公務出國報告
(出國類別：開會)

出席 ISO/TC39/SC2 工具機金屬切削之試驗條件分組委員會議

服務機關：經濟部標準檢驗局

職　稱：技正

姓　名：陳正崑

地　點：德國　德勒斯登

出國期間：112年9月9日至9月17日

報告日期：112年11月28日

摘　要

本次於德國德勒斯登工業大學(Technical University Dresden)，舉行 ISO/TC39/SC2 工具機金屬切削之試驗條件分組委員會議，會議時間為 112 年 9 月 10 日至 9 月 15 日共計 5 天，本次會議由德國標準協會 DIN (Deutsches Institut für Normung)地主國辦理，本次會議為第 93 次會議，參與之國家為瑞士、德國、日本及奧地利等 10 國，共 28 人參加本次會議，TC39 技術委員會目前共有 TC 39/SC2、TC 39/SC4、TC 39/SC6、TC 39/SC8、TC 39/SC10 等共 5 個技術分組委員會，目前 TC 39/SC2 技術分組委員會主要係執掌「工具機金屬切削之試驗條件」相關之國際標準研議新提案、檢討與廢止不適用之標準、檢討目前已公布標準之修訂、補充增修及誤植勘誤、並再確認對現有已公布標準的適用性，以及與其他 ISO 技術領域之技術分組委員會，需本委員會的技術領域相互支援與合作及庶務性事務之聯繫等相關事宜。

TC39/SC2 分組委員會為目前執掌金屬切削工具機相關產品國際標準之制定，包括工具機金屬切削成型動態及靜態精度規定、幾何測試條件及線性軸與旋轉軸之定位精度與重現性允收準則等相關檢測標準，且應用於目前國際工具機市場上多數之重要高精度工具機產品，例如 EDM 放電加工機、切削加工中心機、內外圓研磨床、車削中心機、拉床及銑床等產品。我國在世界之工具機相關產品國際市場中，工具機產品仍然持續保有競爭之優勢，依據目前相關數據顯示我國工具機產品之產值與產量為全球第第七大之國家。

目前先進工業化國家之製造商及使用者，對工具機產品其主要性能之關鍵檢測項目及加工性能指標，多以 TC39/SC2 分組委員會公布之技術標準為性能判定及允收檢測之重要依據，本次會議主要研議項目為應用於精密工業之加工的重要檢測項目，如使用

坐標測量儀允收工具機試驗之指引、工具機在無負載或靜態情況下運轉之幾何精度、龍門式銑床之精度試驗條件、水平主軸內圓磨床準確度之測試條件及切削中心機坐標平面內之輪廓性能評估試驗條件等 ISO 國際標準之制修訂，可藉由本次與會更能深入了解國際標準與工具機主要生產國如義大利、瑞士、日本及德國等技術先進國家，其未來對工具機之加工智能化、性能複合化、減碳化及整機循環再利用化等工具機標準之發展趨勢，將有助於全面規劃我國未來工具機國家標之準制修訂方向，並對我國工具機產品及其相關之精密檢測儀器設備、關鍵零組件提升與國際標準之相容性及競爭力。

出席 **ISO/TC39/SC2**(工具機金屬切削之試驗條件)分組委員會議

目次 頁數

一、背景目的說明

經台灣區工具機暨零組件工業同業公會彙整財政部關稅總局公布 2023 年 6 月份海關進出口貿易統計相關資料顯示，由工具機出口統計得知，2023 年 6 月台灣工具機出口金額 2.22 億美元，相較今年 5 月份減少 2.4%，較去年同(6)月份則減少 16.7%。其中，金屬切削工具機 2023 年 6 月出口金額 1.96 億美元，相較今年 5 月份出口微幅成長 1.1%；金屬成型工具機 2023 年 6 月出口金額為 2,632 萬美元，則較今年 5 月份減少 22.6%。2023 年 1-6 月工具機累計出口金額為 12.72 億美元，較 2022 年同期減少 12.3%，其中金屬切削工具機產品出口金額近 10.92 億美元，較去年同期減少 10.6%，金屬成型工具機產品出口金額近 1.8 億美元，較去年同期減少 21.3%。2023 年 1-6 月台灣工具機出口前十大國家依出口金額排序為中國大陸(含香港)、美國、土耳其、印度、荷蘭、德國、義大利、日本、越南、泰國。[1]

目前全球經濟因新冠疫情期間之影響，全球呈現經濟的成長放緩，美國等各國央行試圖透過提高利率來抑制頑固的通貨膨脹，以及對應疫後的餘波與烏克蘭戰爭所造成的供應鏈動盪。另一方面，中國大陸在景氣不振及投資審慎的影響之下，從生產物價、消費者信心及進出口貿易指標等都持續走弱，這也顯示中國的經濟正在降溫，對於全球經濟穩定亦產生衝擊。

近年來雖受新冠疫情及全球經濟景氣放緩的不利因素影響，由上述資料統計及歷年來之數據指出，我國機械製造業主要整體出口之產品中，以工具機產品出口金額，仍持續成為機械類產品中，具代表性及重要指標標性之關鍵項目，目前工具機可投入加工應用之領域非常多，較常見為應用於航太產業關鍵性零組件之產製、精密機械之零組件加工、機動車輛之傳動系統之製造、自行車變速傳動系統等重要零組件之產製及更為機械自動化加工不可

或缺之工作加工母機設備。

另具高精度加工之高階工具機，目前更被廣泛應用於產製飛彈系統、軍用航空飛行器等國防工業重要裝備關鍵零組件，因此美國已將具高精密度之工具機加以管制並列為戰略物資，並與其他盟國達成共識對高階工具機相關產品輸出至北韓、伊朗及中國大陸等國加以管制，中國大陸為擺脫各國對其實行尖端技術輸出之限制，因此工具機產品目前已成為中國大陸之國家產業重點發展策略優先發展之重點項目。

我國在世界各國之工具機相關產品國際市場中，工具機產品仍然持續保有競爭之優勢。依據目前相關數據顯示工具機產值及產量數據，我國產品之產值與產量為全球第第七大之國家，在我國機械產業出口之產值金屬切削成型工具機等相關產品，已占有極為重要之比例，隨著智慧機械製造需求之增加，未來勢必更有助於智慧工具機產品整體產值之提升，為充份瞭解 ISO 工具機相關技術標準之發展，參與本次於德國德勒斯登所召開之 ISO/TC39/SC2 分組委員會議，更能瞭解工具機技術先進國家其產品加工精度及主要機械性能檢測技術動態，均為未來評估該等產品驗收之重要指標，爰充分瞭解國際標準之發展動向更有其重要性。

本次在德國德勒斯登舉行之第 93 次 ISO/TC39/SC2 分組委員會議，係由德國標準協會 DIN 擔任地主國辦理，本務會議期間所需相關設施之提供、會議場地之安排、協助配合秘書處幕僚所需之庶務性工作、彙整會議所需相關文件及與各會員國代表窗口之聯繫等事宜，均由德國標準協會 DIN 統籌辦理。

目前 ISO/TC39/SC 2 技術分組委員會主要負責制定金屬切削工具機試驗條件之相關試驗要求，目前 TC39/SC 2 分組委員會依其專業技術領域區之架構下組成 6 個專業工作分組其分類如下：

1、WG1 幾何精度相關(第 1 工作組)

2、WG3 切削中心機之允收條件相關(第 3 工作組)

3、WG4 車削中心機之試驗條件相關(第 4 工作組)

4、WG6 熱效應之評估相關(第 6 工作組)

5、WG7 性能、可靠性及相容性相關(第 7 工作組)

6、WG8 工具機振動之評鑑相關(第 8 工作組)

二、會議議程

1、本會議於 112 年 9 月 9 日至 15 日於德國德勒斯登舉行，本次會議參與之國家為美國、義大利、日本、英國、德國、瑞士、奧地利、中國大陸、瑞典及我國等 10 國共 28 人與會。

2、依委員會秘書處所排定之本次會議議程進行討論，本次會議之議程如下：

(1) Opening of the meeting - welcome, attendance and apologies

(2) Roll call of delegates and membership updates

(3) Adoption of the agenda

(4) Appointment of the Drafting Committee

(5) Minutes of the 92nd meeting (hybrid meeting, Aachen in November 2022)

(6) Information from ISO/CS

(6.1) ISO Directives Part 1

(6.2) Appointment of Sustainable Development Goals (SDGs)

(7) Report and follow-up of actions relating to the 92nd meeting

(7.1) ISO 10791-2, Test conditions for machining centres – Part 2: Geometric tests for machines with vertical spindle (vertical Z-axis) (PL: O. Beltrami; M. Tsutsumi)

(7.2) ISO 6779, Test conditions for broaching machines of vertical internal type - Testing of accuracy (PL: M.Vahebi)

(7.3) ISO 2773, Test conditions for pillar type vertical drilling machines – Testing of the accuracy (PL: M.Vahebi)

(8) Discussion on current Drafts and Resolutions

(8.1) ISO 2407, Test conditions for internal cylindrical grinding machines with horizontal spindle – Testing of accuracy, (PL: R. Ottone, M. Tsutsumi)

(8.2) ISO 8636-2, Machine tools – Test conditions for bridge-type milling machines – Testing of the accuracy – Part 2: Travelling bridge (gantry type) machines, (PL: R. Ottone, M. Tsutsumi)

(8.3) ISO 8636-1, Machine tools – Test conditions for bridge-type milling machines – Testing of the accuracy – Part 1: Fixed bridge (portal-type) machines (PL: R. Ottone, M. Tsutsumi)

(8.4) ISO/TS 230-13, Test code for machine tools – Part 13: Guidelines on acceptance tests for machine tools used as coordinate measuring machines, (PL: P. Dahlem)

(8.5) ISO/PWI 10791-6 Amd 1, Test conditions for machining centres – Part 6: Accuracy of speeds and interpolations (PL: W. Mou)

(8.6) ISO 230-6, Test code for machine tools – Part 6: Determination of positioning accuracy on body and face diagonals (Diagonal displacement tests) (PL: M. Dashtizadeh)

(9) Results of the recent Systematic Reviews

(9.1) ISO 4703:2001 (Ed 3, vers 4), Test conditions for surface grinding machines with two columns – Machines for grinding slideways – Testing of the accuracy

(9.2) ISO 230-1:2012 (Ed 3, vers 2), Test code for machine tools – Part 1: Geometric accuracy of machines operating under no-load or quasi-static conditions

(9.3) ISO 1984-1:2001 (vers 4), Test conditions for manually controlled milling machines with table of fixed height - Testing of the accuracy - Part 1: Machines with horizontal spindle

(9.4) ISO 1984-2:2001 (vers 4), Test conditions for manually controlled milling machines with table of fixed height - Testing of the accuracy - Part 2: Machines with vertical spindle

(9.5) ISO 10791-8:2001 (vers 4), Test conditions for machining centres - Part 8: Evaluation of contouring performance in the three coordinate planes

(9.6) ISO 10791-9:2001 (vers 4), Test conditions for machining centres - Part 9: Evaluation of the operating times of tool change and pallet change

(9.7) ISO 14137:2015, ed.2, Test conditions for wire electrical-discharge machines (wire EDM) - Testing of the accuracy

(9.8) ISO 13041-5:2015, ed.2, Test conditions for numerically controlled turning machines and turning centres - Part 5: Accuracy of speeds and interpolations

(9.9) ISO 10791-1:2015, ed.2, Test conditions for machining centres - Part 1: Geometric tests for machines with horizontal spindle (horizontal Z-axis)

(9.10) ISO 1985:2015, Machine tools - Test conditions for surface grinding machines with vertical grinding wheel spindle and reciprocating table - Testing of the accuracy

(10) Items for future work

(11) SC2 Recommendation concerning SC2-chairperson

(12) Date and venue of next meetings

(13) Information from ISO/TC 39 and Liaisons

(14) Any other business

(15) Approval of resolutions

(16) Closure of the meeting

三、會議紀要

(一)本會議重要決議如下列各項(Dresden 2023):

議題 1：Opening of the meeting - welcome, attendance and apologies

決議摘要：

由於本分組委員會(TC39/SC2)主席 Mr. G. Florussen 先生因身體最近出現問題無法參加本次會議，本委員會秘書處 Dr. Jochen Fornather 先生為使本次會議能順利進行，已徵求美國代表 Dr. Alkan Donmez 先生、德國代表 Dr. Alexander Broosm 先生與瑞士代表 Dr. Wolfgang Knapp 先生等三位同意，協助主持本次在德國德勒斯登所舉行相關技術討論會議。後續由提供本次會議場地及各項會議設施支援之德勒斯登工業大學機電工程研究所所長 Dr. Steffen Ihlenfeldt 教授致詞，Dr. Steffen Ihlenfeldt 教授表示歡迎 ISO/TC39/SC2 之各會員國代表到本校進行 5 天之會議，並對該所目前工具機相關研究重點項目進行簡介，並希望未來能有機會與各國進行技術交流，預祝本次會議能順利達成預定的目標。

另 TC39/SC2 委員會秘書處 Dr. Jochen Fornather 先生表示，接獲義大利代表 Mr. Renato Ottone 先生的致歉函，因個人因素他將無法參加本次會議，但是為使議題 8.1 項目至議題 8.3 項目能順利進行討論，仍建議請該項目之專案主持人 Mr. Renato

Ottone 先生使用視訊方式遠端協助主持相關會議之討論。

議題 2：Roll call of delegates and membership updates

決議摘要：

本分組委員會(TC39/SC2)代理主席 Dr. Alexander Broosm，請參加本次會議與會人員逐一自我介紹。

議題 3：Adoption of the agenda

決議摘要：

因本次會議需審查之各項草案與討論提案的議題較多，本分組委員會秘書處，經與會各國代表討論後，為使本次會議之相關技術議題能充份討論，決議本次會議將限縮在所涉加工技術及量測技術等技術層面議題之討論，另若標準草案僅涉之文字用語一致性、誤植及量測設備要求等非技術之議題將不在本次之討論範圍，以避免因本次會議時間不足而影響其他議程，其他原排定議程，本分組委員會同意依本會秘書處所排定之各項討論議程。

議題 4：Appointment of the Drafting Committee

決議摘要：

經 ISO/TC39/SC2 分組委員會議討論後決議，將請義大利代表 Mr. John Ould 先生協助檢視相關草案修飾用語錯誤等事宜，並同意通過秘書處本次提供的各項草案現階段之進度說明等相關資料。

議題 5：Minutes of the 92nd meeting

決議摘要：

ISO/TC39/SC2 分組委員會經審查後，決議核准並同意秘書處，第 92 次會議期間之工作報告。

議題 6：Information from ISO/CS

來自 ISO/CS 中央秘書處訊息

議題 6.1：ISO Directives Part 1

決議摘要：

ISO/TC39/SC2 秘書處報告 ISO/CS 中央秘書處通知本委員會，最新版本的 ISO 指令第 1 部分已於 2023 年 5 月發布，並加以補充說明，詳細相關異動之資料可於各會員國代表窗口及 ISO 之官網查詢，若有其他建議可逕洽中央秘書處。

議題 6.2：Appointment of Sustainable Development Goals (SDGs)

決議摘要：

ISO/TC39 中央秘書處 Mr. Maho Takahashi 先生告知本分組秘書處，對於一些正在進行的項目，缺少提供相關永續發展目標的資訊，本分組秘書處已回復並完成補充填列相關資料。

議題 7：Report and follow-up of actions relating to the 92nd meeting

決議摘要：

由個別專案負責人進行分別報告在 2022 年德國亞琛會議(第 92 次)後，目前草案已進入最終標準草案(FDIS)的後續推動之情況。

議題 7.1：ISO 10791-2, Test conditions for machining centres – Part 2: Geometric tests for machines with vertical spindle (vertical Z-axis)

本分組秘書處報告，ISO 10791-2 立式主軸切削中心機測試條件標準已於 2023 年 4 月 21 日公布。Dr. Jochen Fornather 先生以 ISO/TC39/SC2 秘書處的名義感謝本專案負責人義大利代表 Mr. Oddone Beltrami 先生及 Dr. Masaomi Tsutsumi 先生，在過去幾年中為修訂該標準所付出之辛勞與努力，才能使該標準

能如預訂時程公布。

議題 7.2： ISO 6779, Test conditions for broaching machines of vertical internal type - Testing of accuracy

決議摘要：

本分組秘書處報告 ISO 6779 立式內孔拉床測試條件標準草案因目前正在進行公布前的準備，本專案負責人 Mr. M.Vahebi 先生在最終版本中，發現部分測試條件之規定有數據誤植與文字敘述等錯誤，希望此等錯誤能夠在接下來的幾週內修正解決，並在預定時程內完成公布。

議題 7.3：ISO 2773, Test conditions for pillar type vertical drilling machines – Testing of the accuracy

決議摘要：

本分組秘書處報告 ISO 2773 立式鑽床準確性測試標準，ISO/FDIS 2773 自 2023 年 8 月 31 日起進行最終投票，並將於 2023 年 10 月 26 日結束，並請各會員國踴躍投票。

議題 8：Discussion on current Drafts and Resolutions

決議摘要：

以下將審查目前正進行中之各項草案及相關後續辦理情形之討論，請各項草案之負責人依本次所審查通過之會議議程，開始進行本次會議之審查。

決議摘要：

議題 8.1：ISO 2407, Test conditions for internal cylindrical grinding machines with horizontal spindle – Testing of accuracy, (PL: R. Ottone, M. Tsutsumi)

決議摘要：

本草案負責人 Mr. R. Ottone 先生報告，ISO 6779 標準草案，ISO/DIS 階段投票已於 2023 年 4 月 18 日至 7 月 11 日進

行，雖該草案獲得多數會員國投票通過，但是收到伊朗、日本、義大利、瑞士及美國等 5 個會員之草案修正意見，在本草案中所涉及檢驗 Z 軸運動之真直度時，其局部許可差為在每次 300 mm 量測距離下，其許可差為 0.007 mm，同意英國代表 Mr, John Ould 先生之建議，將對待測工具機之檢測儀器與架設位置加以說明，以降低量測偏差之產生，提升量測結果之準確性。對於本標準中所涉相關檢測設備精度、量測偏差及量測不確定度等相關精度數值修正意見的技術層面之議題，考慮本次會議之議程並無足夠時間，再將各國之後續提出意見逐一進行討論，將利用後續線上會議另案討論相關意見。本分組秘書處要求本案依原既定之規劃時程，於 2023 年 10 月中旬前將本案提送至 ISO/FDIS 階段，以便本分組秘書處在 2023 年 10 月底前啟動本案之 ISO/FDIS 程序，因此決議將於 2023 年 9 月 27 日上午 8 點至 12 點，再次召開線上會議方式進行討論，各國之意見清單及線上會議之連結等資料，將於本次會議後將以電子郵件寄送，提供修正意見之會員國家參與討論，以完成本草案規劃之時程。

議題 8.2：ISO 8636-2, Machine tools – Test conditions for bridge-type milling machines – Testing of the accuracy – Part 2: Travelling bridge (gantry type) machines, (PL: R. Ottone, M. Tsutsumi)

決議摘要：

本草案負責人 Mr. R. Ottone 先生報告，ISO 8636-2 標準草案，ISO/DIS 階段投票已於 2023 年 4 月 20 日至 7 月 13 日進行，雖該草案獲得多數會員國投票通過，但同前案亦接到伊朗、日本、義大利、瑞士及美國等 5 個會員之草案修正意見，但經檢視各國所提之意見後，因較無涉及技術層面之議題，同意依各國之意見修正標準草案，因本分組秘書處要求本案依原既定

之規劃時程，於 2023 年 10 月中旬前將本案提送至 ISO/FDIS 階段，以便本分組秘書處在 2023 年 10 月底前啟動本案之 ISO/FDIS 程序。

議題 8.3：**ISO 8636-1, Machine tools – Test conditions for bridge-type milling machines – Testing of the accuracy – Part 1: Fixed bridge (portal-type) machines (PL: R. Ottone, M. Tsutsumi)**

決議摘要：

本草案負責人 Mr. R. Ottone 先生報告 ISO 8636-1 標準草案，因第 1 版的 WD 標準草案由 2023 年 7 月 1 日起進行第 1 次的討論，雖本人召開多次的線上會議進行討論，但至本次會議前仍未將草案審查完成，本分組秘書處同意由日本、瑞典、瑞士、義大利及美國代表再次進行線上會議審查標準草案，本次會議時間將訂於 2023 年 10 月 23 日至 2023 年 10 月 24 日每日中午 12:30 至下午 2:30 進行會議，兩天的會議預計將所有意見討論完成，本案將依原既定之規劃時程，於 2023 年 12 月中旬前將本案由 ISO/WD 階段提送至 ISO/DIS 階段，以便本分組秘書處在 2024 年 4 月底前啟動本案進入 ISO/DIS 程序。

議題 8.4：**ISO/TS 230-13, Test code for machine tools – Part 13: Guidelines on acceptance tests for machine tools used as coordinate measuring machines**

決議摘要：

本草案負責人 Mr. P. Dahlem 先生報告，ISO/TS 230-13 標準草案，因 ISO/WD 第 1 版由 2023 年 7 月 4 日起進行徵詢意見至 2023 年 9 月 27 日止，因配合本次會議日程，將徵詢意見時間縮短至 2023 年 8 月 30 日止，由於收到各國提出的修正意見超過 400 項，因此本次會議期間僅能進行技術性意見之討論，

為便於進行後續之討論，已非技術性意見將以不同顏色易於識別以提升會議討論效率。

另 Dr. Heinrich Schwenke 先生自願同意參與本提案之準備工作，並協助分析線性軸或旋轉軸與線性軸的平行度測量檢測項目等相關技術意見，本分組秘書處建議任命他為新提案之共同負責人，本分組秘書處後續將要求 ISO/CS(中央秘書處)協助修正本案的專案負責人資料。另經本次會議討論後各國所提之意見，若需再提供相關補充資料之部分，請最遲於請 2023 年 12 月 15 日前提送至本草案負責人 Mr. P. Dahlem 先生後，後續將所有意見併入標準草案中，若有待再協商的技術意見將訂於 2024 年 1 月 29 日至 2024 年 1 月 30 日每日中午 12:30 至下午 2:30 進行線上會議，若兩天的會議可以將所有意見討論完成，本草案負責人會將 ISO/WD 第 2 版之草案，請英國代表協助審視英文用語之正確性後，再提送至本分組秘書處進行 ISO/WD 第 2 版草案之徵詢意見，預計自 2024 年 4 月 1 日至 2024 年 5 月 15 日止，並預定在 2024 年 6 月之會議中進行討論。

議題 8.5：ISO/PWI 10791-6 Amd 1, Test conditions for machining centres – Part 6: Accuracy of speeds and interpolations

決議摘要：

本草案負責人 Dr. W. Mou 先生報告，ISO 10791-6 補充增修標準草案，因日本代表 Dr. Yukitoshi Ihara 先生、Dr. Ryuta Sato 先生、瑞士代表 Dr. Wolfgang Knapp 先生及中國大陸代表 Dr. Wei Wang 先生等四位專家，均對 S 形試件提出相關試驗及研究數據，經討論後意見彙整如下：

1.S 形試件的新定義將奇異點更改為奇異截面，其中取決於 CAM 軟體性能及操作員的技能，另對 C 軸的大幅移動(>180˚)，

由於在大範圍之 C 軸運動期間，切削刀具可能會於相對測試件表面上停止，並在表面上會產生凹痕。依據實驗沿加工表面之進給速度由 1,000 mm/min 降低至 230 mm/min (CAM A)，並沿著奇異截面降低到 70 mm/min (CAM B)，並且在開始時幾乎無進給速度，試件表面的光滑度不應因不同的 CAD 上下曲線之間的連接不同，導致曲線形狀不同。但可藉由提供測試輪廓的 STEP 檔案消除了此種影響，讓 CAD 透過最小化刀具平滑變化行進路徑計算，不適用於任何工具機加工性能之評估。

2.另可將 C 軸運動分佈到多個獨立的區塊(大約 25 個區塊)中，亦可以解決導致連接曲線之問題。然而，目前此僅能透過操作員的手動干預(更改 NC 編碼)來實現。

3.S 試件的切向進給速度設定為 1,000 mm/min，變化範圍為 200 至 1,050 mm/min，如果在 NC 程式中，公差由 0.010 mm 變更為 0.100 mm，則加工表面會發生顯著變化，亦提供公差會隨著刀具之方向的變化而變化之相關數據資料。

4.對於不同的 CAD 系統上下曲線之間的連接不同，導致曲線形狀不同。此處雖提供測試輪廓的 STEP 檔案消除了此等影響，由於不同的表面計算會產生不同的直線表面，因此在不同的讓切情況下，此等影響可能達 0.040 mm(但這約佔公差 0.120 mm 之 33%)，但這樣就產生另一個問題，使用 S 形輪廓的所有不同參數的 STEP 檔案是否可行之疑慮。

5.由於上述 4 項技術意見需再實際之測試加以證明其可行性，本分組秘書處請求 Dr. Wolfgang Knapp 先生協助提出相關技術的可行性評估報告，若 Dr. Wolfgang Knapp 先生於 2024 年 3 月前，也無法提出完整之可行性評估報告，將視情況召開臨時會議解決相關技術問題。

議題 8.6：ISO 230-6, Test code for machine tools – Part 6: Determination of positioning accuracy on body and face diagonals (Diagonal displacement tests) (PL: M. Dashtizadeh)

決議摘要：

本草案負責人伊朗代表 Mr. P. Dahlem 先生報告，ISO 230-6 工具機體與面之對角線的定位精度標準草案，因 ISO/WD 第 1 版由 2022 年 7 月 1 日起進行相關起草任務之分配工作，但由於初期工作推展並不順利且工作進度有所延誤，為符合 ISO/CS 中央秘書處對各案進度時程之管制限制，現已通知 ISO/CS 中央秘書處取消本案之工作項目時程，該處並於 2023 年 6 月通知同意取消有關本案的時程，但本草案負責人 Mr. P. Dahlem 先生仍持續將本草案完成，並將草案寄送各會員國表示意見，由於收到各國提出的修正意見超過 300 項，因此本次會議期間僅能進行技術性意見之討論。

另因本草案涉及的最大改變是增列機身對角線直線度的測量，經過深入討論後，伊朗支持機身對角線直線度測量，但奧地利、中國、日本、瑞典及瑞士皆認為無需額外測試，另美國表示反對，德國及英國棄權，但本草案負責人 Mr. P. Dahlem 先生願協助提供評估報告，並透過以模擬方式檢查不同幾何工具機誤差對端面對角線直線度的影響，包括與不同幾何誤差疊加相關的影響，此等誤差可能會抵消對端面對角線直線度的影響，並將於 2024 年 1 月 19 日中午 12:30 至下午 2:30 召開線上會議進行討論，本草案負責人則將依該次會議之決議修正草案，並於 2024 年 4 月底前完成，由本分組秘書處重新寄發各會員國表示意見，並於下次會議中進行討論，本分組秘書處決議由於 ISO 230-6 修訂的初步工作項目因受時間之限制而暫停，本案將於 2024 年 2 月對 ISO/CS 中央秘書處請求重新啟動修訂本案的工作項目。

議題 9：Results of the recent Systematic Reviews

近期系統性之重新檢視結果

議題 9.1：ISO 4703:2001 (Ed 3, vers 4), Test conditions for surface grinding machines with two columns – Machines for grinding slideways – Testing of the accuracy

決議摘要：

本分組委員會，接受本次審查 ISO 4703 標準資料討論後之決議如下：

1.同意確認本案，將依程序進行確認等事宜，但後續將檢討更新本標準之規範性參考資料。

2.考慮增列有關 X 軸偏移測量的技術意見，並由 Dr. Masaomi Tsutsumi 先生擔任本案負責人，以重新起草修訂草案或增列附錄方式辦理，現已有美國、日本及法國願意加入本案之工作小組成員，亦歡迎其國家成員後續加入本案之草案研擬工作。

議題 9.2：ISO 230-1:2012 (Ed 3, vers 2), Test code for machine tools – Part 1: Geometric accuracy of machines operating under no-load or quasi-static conditions

決議摘要：

本分組委員會，接受本次審查 ISO 230-1 標準資料討論後之決議如下：

同意確認本案，因本標準經檢視後並未涉及技術內容之修訂更新，將依程序進行確認等事宜。將檢討本標準之規範性參考資料之更新，將列入議程提送下次會議進行討論。

議題 9.3：ISO 1984-1:2001 (vers 4), Test conditions for manually controlled milling machines with table of fixed height – Testing of the accuracy – Part 1: Machines with horizontal spindle (N3039)

決議摘要：

本分組委員會，接受本次審查 ISO 1984-1 標準資料討論後之決議如下：

同意確認本案，將依程序進行確認等事宜。雖法國出提意見表示本標準 2001 版修訂後至今，目前已開發出具有控制固定高度工作台及水平主軸銑床之新技術，建議本標準需要與現有技術保持一致，但該國並未提供關於新技術造成對本標準準確度測試之影響，將請法國提供資料，並將本案列入下次會議議程進行討論。

議題 9.4：ISO 1984-2:2001 (vers 4), Test conditions for manually controlled milling machines with table of fixed height – Testing of the accuracy – Part 2: Machines with vertical spindle

決議摘要：

本分組委員會，接受本次審查 ISO 1984-2 標準資料討論後之決議如下：

同意確認本案，將依程序進行確認等事宜。雖法國提意見表示本標準 2001 版修訂後至今，目前已開發出具有控制固定高度工作台及垂直主軸銑床之新技術，建議本標準需要與現有技術保持一致，但該國並未提供關於新技術造成對本標準準確度測試之影響，因此同議題 9.3 案，將請法國提供資料，並將本案列入下次會議議程進行討論。

議題 9.5：ISO 10791-8:2001 (vers 4), Test conditions for machining centres – Part 8: Evaluation of contouring performance in the three coordinate planes

決議摘要：

本分組委員會，接受本次審查 ISO 10791-8 標準資料討論後之決議如下：

同意確認本案，雖目前本標準之檢測技術仍適用於新型之機器，將依程序進行確認等事宜。但對於本標準之規範性參考資料，應進行小幅度之更新，本案將列入下次會議議程進行討論。

議題 9.6：ISO 10791-9:2001 (vers 4), Test conditions for machining centres – Part 9: Evaluation of the operating times of tool change and pallet change

決議摘要：

本分組委員會，接受本次審查 ISO 10791-9 標準資料討論後之決議如下：

同意確認本案，目前標準之檢測技術仍適用於新型之機器，將依程序進行確認等事宜。但對於本標準之規範性參考資料，應進行小幅度之更新，本案將列入下次會議議程進行討論。

議題 9.7：ISO 14137:2015, ed.2, Test conditions for wire electrical-discharge machines (wire EDM) – Testing of the accuracy

決議摘要：

本分組委員會，接受本次審查 ISO 14137 標準資料討論後之決議如下：

同意確認本案，目前標準之檢測技術仍適用，不需進入修訂階段，將依程序進行確認等事宜。

議題 9.8：ISO 13041-5:2015, ed.2, Test conditions for numerically controlled turning machines and turning centres – Part 5: Accuracy of speeds and interpolations

決議摘要：

本分組委員會，接受本次審查 ISO 13041-5 標準資料討論後之決議如下：

同意確認本案，目前標準之檢測技術仍適用，不需進入修訂階

段，將依程序進行確認等事宜。

議題 9.9：ISO 10791-1:2015, ed.2, Test conditions for machining centres – Part 1: Geometric tests for machines with horizontal spindle (horizontal Z-axis)

決議摘要：

本分組委員會，接受本次審查 ISO 10791-1 標準資料討論後之決議如下：

同意確認本案，目前標準之檢測技術仍適用，不需進入修訂階段，將依程序進行確認等事宜。

議題 9.10：ISO 1985:2015, Machine tools – Test conditions for surface grinding machines with vertical grinding wheel spindle and reciprocating table – Testing of the accuracy

決議摘要：

本分組委員會，接受本次審查 ISO 1985 標準資料討論後之決議如下：

同意確認本案，目前標準之檢測技術仍適用，不需進入修訂階段，將依程序進行確認等事宜。

議題 10：Items for future work

決議摘要：

Dr. Philipp Dahlem 介紹了他參加 EUROMET 研究計畫中 2 項可能涉及本分組委員會相關主題項目如下：

1. SRT-F14「機器學習」，解決機器學習模型的不確定性。

2. SRT-F15「數位雙生在先進製造中新興量測技術的應用」，解決應用於工具機的 3D 掃描量測等問題。

本分組委員會經討論後認為此 2 項研究計畫主題與本委員會之技術領域相關，將以本委員會之名義發函 EUROMET 表示支持該 2

項計畫之推動。

議題 11：SC2 Recommendation concerning SC2-chairperson

決議摘要：

由於本分組委員會(TC39/SC2)主席 Mr. G. Florussen 先生因 2023 年 8 月起更換到新的公司任職，但新職位所涉及之工作範圍與本委員會的屬性較無關聯性，將無法持續參加後續之會議，故請辭本分組委員會主席一職。

本分組委員會秘書處報告關於本分組委員會主席的任命已有會員國提名德國代表 Dr. Alexander Broos 先生擔任本分組委員會主席，若在 2023 年 9 月 30 日之前無提名其他候選人，將由德國 Dr. Alexander Broos 先生擔任主席一職，並通知 ISO/TC39 技術委員會更換本委員會主席提案。

議題 12：Date and venue of next meetings

決議摘要：

ISO/TC39/SC2 分組委員會決議接受並感謝本委員會秘書處奧地利之邀請，2024 年 6 月會議將於奧地利維也納舉行，最後會議時間將由本分組委員會秘書處確認後通知各國。

議題 13：Information from ISO/TC 39 and Liaisons

決議摘要：

本分組委員會感謝瑞士代表 Dr. Wolfgang Knapp 協助代表本分組委員會，持續多年出席參與 ISO/TC 39 技術委員會年會之溝通與聯繫。

議題 14：Any other business

本次會議並無其他建議事項。

議題 15：Approval of resolutions

決議摘要：

ISO/TC39/SC2 分組委員會核可本次會議之決議事項。

決議 16：**Closure of the meeting**

決議摘要：

ISO/TC39/SC2 委員會代理主席 Dr. Alexander Broos 先生先生代表參與本次會議之各國，再次由衷感謝本委員會秘書處及本次會議主辦單位德國標準協會，在會議期間提供精實之議程安排、提供各種庶務性之協助及與各國代表之聯絡與協調，更感謝本次各工作組之負責人協調與整合各會員國之意見，並完全對各草案之時程掌控制，使本次會議排訂之各項議題均能充分的討論與審查，並完成所有議題之審查，TC39/SC2 主席代表秘書處邀請各國能持續參與支持後續相關會議，並希望在未來的會議都能與大家再次見面。

四、心得及建議

1、本次 ISO/TC39/SC2 會議是在疫情後第一次舉行的實體會議，本次會議的主辦單位 DIN 德國標準協會，因德國工具產業為國際市場上高精度工具機之主要生產國，其高階工具機之產值與產量更居世界之領先地位，本次會議特別安排於在 2023 年德國漢諾威工具機展(2023 EMO Hannover)前一週舉行，本次會議之協辦單位德國工具機協會(VDW)，亦是德國漢諾威工具機展的主辦單位，故將本此會議排定於此時段辦理，更邀請本此與會國成員前往參觀，其希望藉該展覽展現德國在工具機高精密度加工之軟硬體設備與先進的量測技術，藉此推動德國之工具機先進加工技術及接觸與非接觸式精密量測技術，未來能被 ISO 國際標準所採納並成為 ISO 國際標準，藉此增加該國工具機業者之國際競爭優勢，值得我國業界借鏡學習。

2、本委員會未來之繼任主席 Dr. Alexander Broos 先生任職於德國工具機協會(VDW)金屬加工技術研究部門之主管，他更為德國漢諾威工具機展與萬用工具機介面 UMATI(Universal Machine

Tool Interface)之主要負責人之一，本次有機會與 Dr. Alexander Broos 先生對智慧工具機之未來展交換意見，雙方均認為隨著世界各國人口老化、人力短缺及人員之薪資成本增加等議題之情況日趨嚴重，未來工具機之發展趨勢將朝向以下幾點之方式發展：

(1)工具機與機器人之整合形成連續自動化加工生產線，未來將更廣泛的運用機器人及智慧型引導運輸車(IGV，Intelligent Guided Vehicle)，在不同場域的多種不同機具之加工程序串接連結，以降低產製人力、工時及生產成本。

(2)工具機加工技術之多樣化，未來將有更多的廠商將積層製造(俗稱 3D 列印)之加工技術整合於 5 軸工具機中，包含在工件之加工製程中間接或直接運用 3D 列印技術，達到多工序複雜表面工件之產製，其可提供活化彈性製程、縮短加工時程、減少產製人力之投入與生產成本降低等優勢。

(3)隨著 5G 通訊技術發展逐漸成熟，工具機智慧製造層面之應用已跳脫單機製程訊息管理與應用，著重跨機器、跨不同軟體界面相互通訊連接，並已發展出結合即時通訊技術，形成即時可視化生產流程與加工參數，進而擴展至運用個別機器之聯網功能，將整廠不同場域之工具機等加工機器相關製程數據，在控制中心中鏈結，並將相關數據資料，加以充分集中、整合、運用與管理，建立更彈性製造流程，提升生產效率與競爭力，已成為智慧工具機必備重點發展趨勢。另德國工具機協會(VDW)目前運用其推動之推動萬用工具機介面 UMATI (Universal Machine Tool Interface)，讓介面管理者或使用者在遠端可在線上即時查看製程中或受委託之製造商，對產品之生產的加工製程、控制參數及量測數據等產品訂單相關資訊，目前已有許多業者包含臺灣工具機暨零組件工業同業公會在內的國內業者加

入，另諸多國際之工具機大廠都已成為 UMATI 的夥伴聯盟，深信未來在 5G 設備與環境的建置與發展下，工具機產品將搭配智能化或機器學習功能等人工智慧技術功能，將可提高工具機加工效率及價值，也是我國業者必須儘早投入研發及準備的技術發展趨勢。

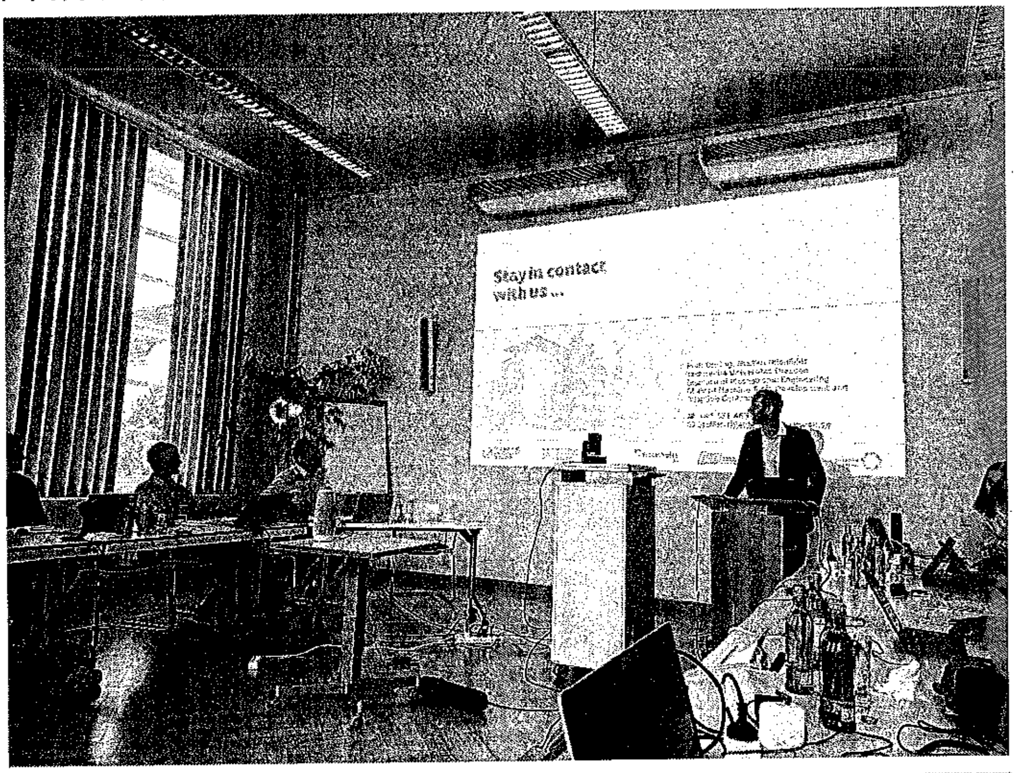
4、本次英國代表 Mr, John Ould 先生為國際知名的量測設備製造商 Renishaw 工具機部門的資深經理，他並持續代表英國參加本委員會議，在本次會議中多次運用其公司的設備為例，說明校正安裝之經驗，並對設置量測設備之程序提出實務操作的修正建議，也使原標準草案中可能產生量測不確定度之影響因子降低，更有助於工具機整機量測精度之提升，提升整體量測之準確度，並獲各國認同其相關建議並納入標準中，目前該公司已逐漸成為全球工具機產品量測設備供應鏈之主要供應商，更以其生產之精度檢測設備均可滿足並符合 ISO 工具機標準之規定為利基，對工具機之製造者、研究機構、檢測實驗室等全球客戶進行行銷，發揮標準引領產業之優勢，強化其產品競爭力，且持續投入參與標準化活動，並強化相關實務技術經驗與標準之鏈結，值得我國相關產業參考。

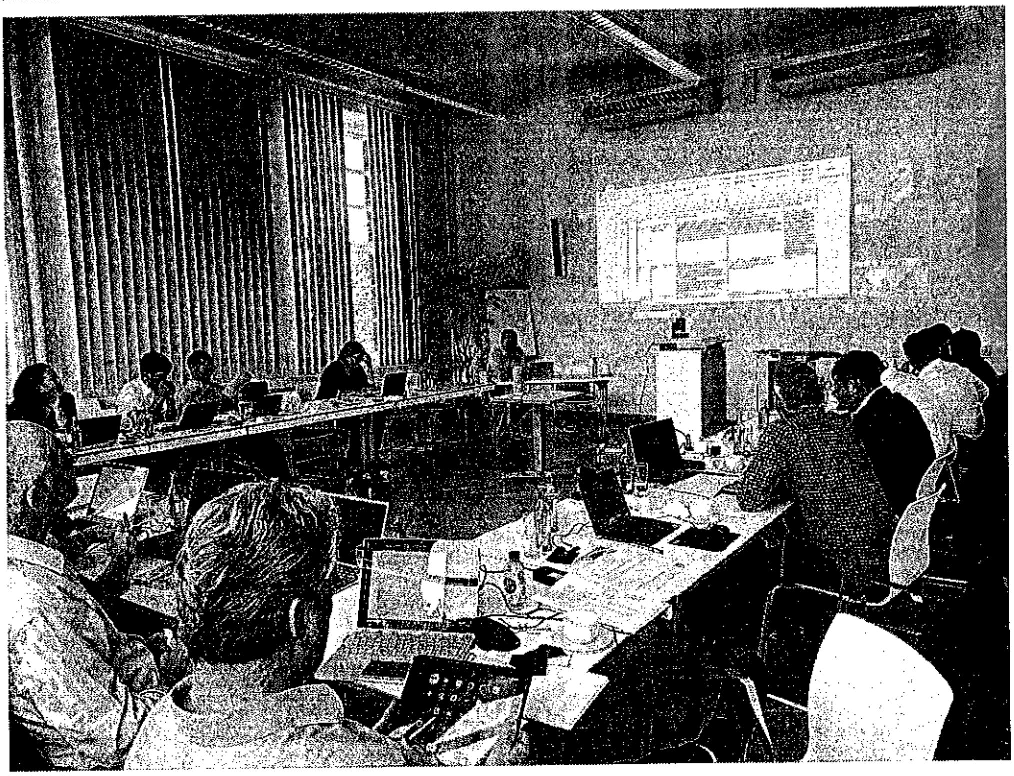
5、我國雖為世界工具機生產之第七大國，由於國際現實之政治環境等因素，目前我國仍未獲准加入 ISO 國際標準組織成為會員，因 ISO/TC39/SC2 工具機金屬切削之試驗條件分組委員會議，較一般常見之 WG 工作組會議限制與會之資格，僅會員國才可參與，ISO/TC39/SC2 分組委員會是我國目前少數可實際參與國際標準活動之會議，本次參與會議係經由在以往國際會議場合結識對我國友好之國外相關單位友人之協助下，才能順利參加本次 ISO TC 39/SC2 會議，在此建議本局同仁未來若有機會參與區域性或國際標準活動或會議，應儘可能出席會議，不但

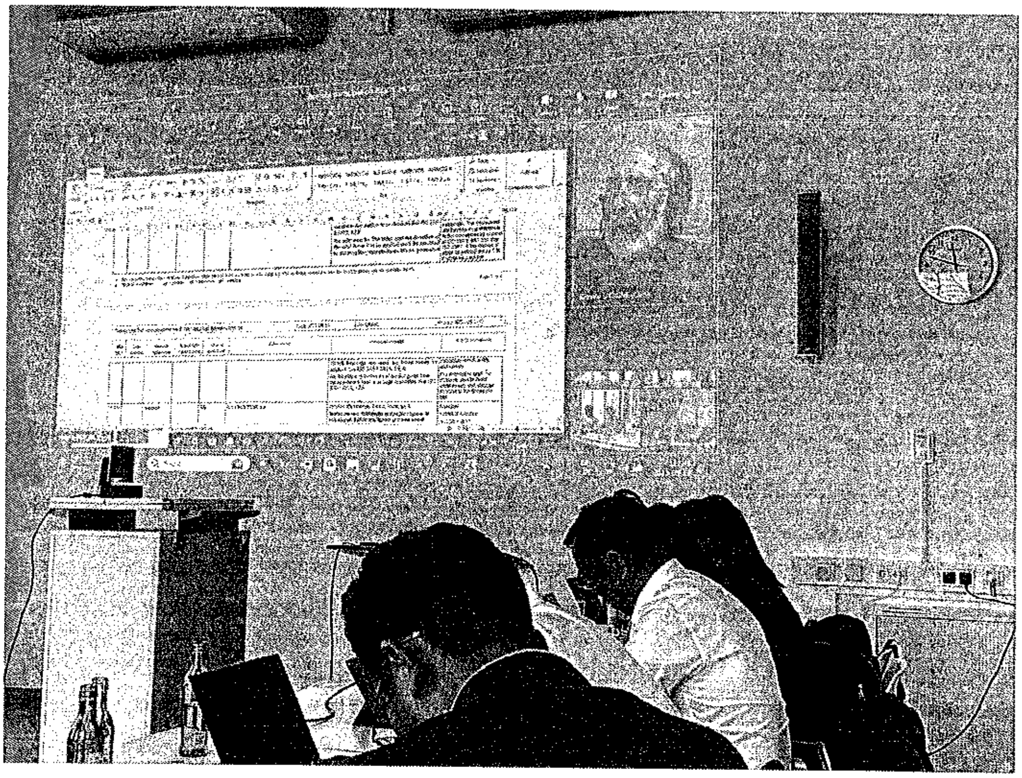
可與各國專家增進彼此之情誼擴增人脈，並有助於我國未來國際會議的參與。

6、參加本次 ISO/TC39/SC2 分組委員會議與各國金屬切削成型工具機專業領域相關之學者、研究單位及專家等進行技術意見交流，除可增進彼此之情誼外，並可成為我國後續參與國際標準化活動之助力，且更能深入了解國際標準與工具機主要生產國如日本、德國及瑞士等國家，未來工具機標準發展規劃之趨勢，有助於未來我國 CNS 國家標準制、修訂之籌劃，更能切合與世界工具機先進國家技術發展之趨勢，以提升我國工具機產業之產品及關鍵性零組件在國際市場之優勢與競爭力。

本次分組委員會議照片







五、會議文件（如附件）

*、ISO CD2 2407, Test conditions for internal cylindrical grinding machines with horizontal spindle － Testing of accuracy

*、Studying the influence of the machining process on the geometrical defects of the standardized S-shape test part

*、ISO WD 8636-1, Machine tools － Test conditions for bridge-type milling machines － Part 1 : Testing of the accuracy of fixed bridge (portal-type) machines

*、ISO WD TS 230-13, Test code for machine tools — Part 13: Guidelines for the determination of the measuring performance of machine tools used as coordinate measuring machines

*、Influence of NC Program Quality and Geometric Errors of Rotary Axes on S-Shaped Machining Test Accuracy

*、Feed speed fluctuation in simultaneous five axis machining using an end mill

六、參考資料

[1] 台灣區工具機暨零組件工業同業公會網站。

七、附件

ISO CD2 2407:2022 (E)

ISO TC 039/SC 02

Secretariat: ASI

Test conditions for internal cylindrical grinding machines with horizontal spindle — Testing of accuracy

CD2 stage

Contents

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 39, *Machine tools*, Subcommittee SC 2, *Test conditions for metal cutting machine tools.*

This fourth edition cancels and replaces the third edition (ISO 2407:1997), which has been technically revised. The main changes compared to the previous edition are as follows:

- Corrections in Amendment 1:2016 have been applied;
- References to ISO 230 series have been updated;
- Tests for optional B1-axis have been added;
- A new Annex A (Informative), *Error motions of axes of rotation* has been added.

In addition to text written in ISO official languages, this document gives, in informative Annex B, Table B.1, the equivalent terms in German, Italian, Japanese and Persian; these are published under the responsibility of the member body for Germany (DIN), Italy (UNI), Japan (JISC) and Iran (INSO) and are given for information only. Only the terms given in the official languages can be considered as ISO terms.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Test conditions for internal cylindrical grinding machines with horizontal spindle — Testing of accuracy

1 Scope

This document specifies, with reference to ISO 230-1, 230-2 and ISO 230-7, geometric tests, positioning tests and machining tests on general purpose and normal accuracy internal cylindrical grinding machines with horizontal spindle, whether fitted with a facing wheelhead slide or not. It also specifies the applicable tolerances corresponding to the above-mentioned tests.

This document deals only with the verification of the accuracy; it applies neither to the testing of the machine operation (vibrations, abnormal noise, stick-slip motion of components, etc.), nor to the checking of its characteristics (such as speeds, feeds, etc.), which should generally be checked before the testing of the accuracy.

This document provides the terminology used for the principal components of the machine and the designation of the axes with reference to ISO 841.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 230-1:2012, *Test code for machine tools -- Part 1: Geometric accuracy of machines operating under no-load or quasi-static conditions*

ISO 230-2:2014, *Test code for machine tools -- Part 2: Determination of accuracy and repeatability of positioning of numerically controlled axes*

ISO 230-7:2015, *Test code for machine tools -- Part 7: Geometric accuracy of axes of rotation*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 230-1:2012 and ISO 230-7:2015 apply.

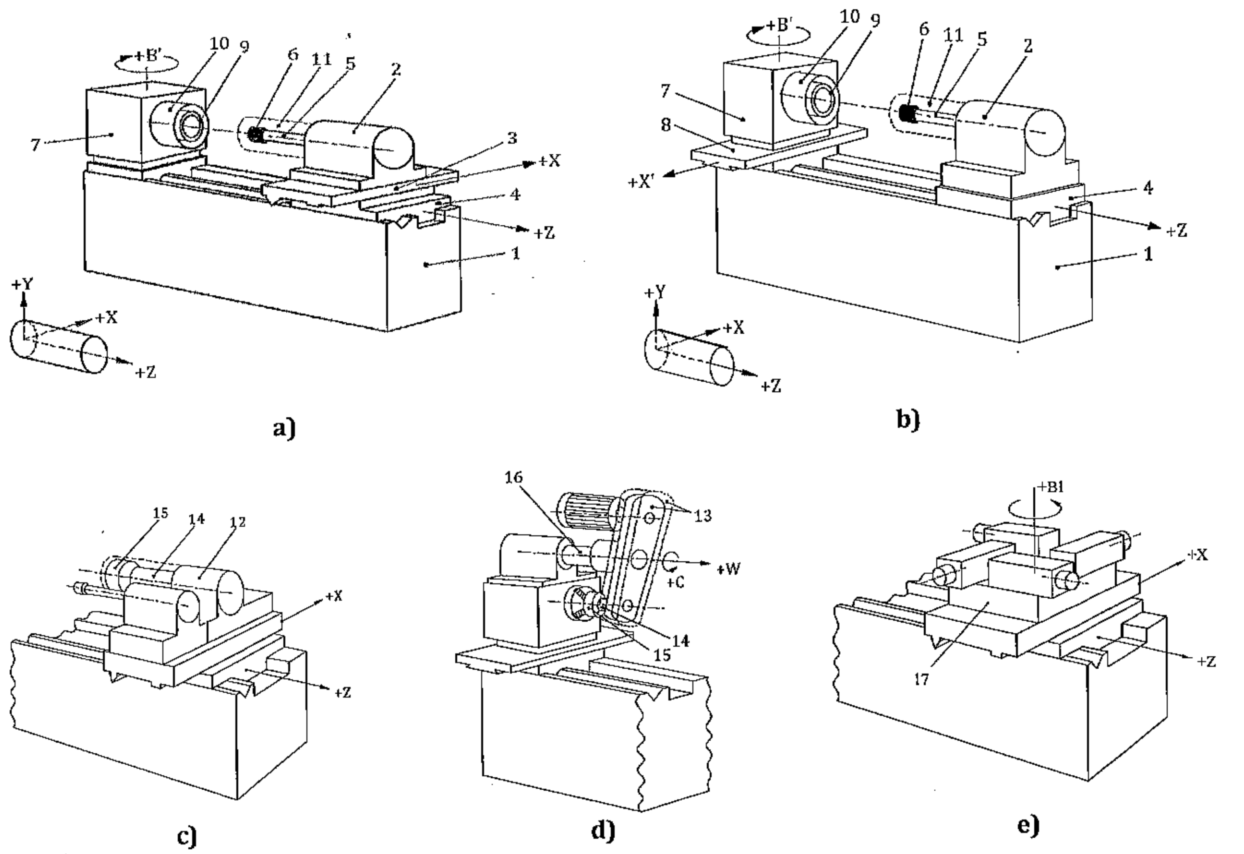
ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

4 Machine configurations

The common characteristic of all internal cylindrical grinding machines with horizontal spindle is that they have at least one horizontal workhead and one wheelhead on the bed and the spindles are facing each other. The workhead can swivel around a vertical axis (B'-axis) for grinding conical surfaces.



Key

	English	French
1	bed	banc
2	wheelhead	poupée porte-meule
3	wheelhead cross slide (X-axis)	chariot transversal de poupée porte-meule (axe X)
4	wheelhead carriage (Z-axis)	chariot de poupée porte- meule (axe Z)
5	wheel spindle ((C1)-axis)	broche porte-meule (axe (C1))
6	internal grinding wheel	meule intérieure
7	workhead (swivelling) (including B'-axis and C'-axis)	poupée porte-pièce (pivotante) (incluant l'axe B' et l'axe C')
8	workhead cross slide (X'-axis)	chariot transversal de poupée porte-pièce
9	workholding spindle	broche porte-pièce
10	workpiece guard	protecteur de la pièce
11	wheel guard	carter de meule
12	facing wheelhead	poupée porte-meule à surfacer
13	swivel arm (with drive and guard) (C3-axis)	bràs pivotant (avec dispositif d'entraînement et protecteur) (axe C3)
14	facing spindle ((C2)-axis)	broche porte-meule à surfacer (axe (C2))
15	facing wheel	meule à surfacer
16	facing wheel quill (W-axis)	coulant de meule à surfacer (axe W)
17	B1-axis	axe B1

Figure 1 — Machine configurations

Depending upon the machine design, one of the two heads (workhead or wheelhead) can move along the X-axis. The wheelhead usually can move along the Z-axis (see Figures 1a) and 1b)).

In some cases, these machines are equipped with a facing wheel. This can be accomplished by means of the second wheelhead as shown in Figure 1c) or by an additional swivelling wheelhead attachment. This attachment is usually mounted on the workhead with a linear motion (W-axis) parallel to Z-axis and a swivelling motion (C3-axis) around the W-axis (see Figure 1d)).

In some cases, these machines are equipped with a B1-axis that is mounted on the wheelhead cross slide (X-axis) and allows a fast tool change (2 to 4 axes). In some machine tools, B1-axis is a continuous axis.

5 Preliminary remarks

5.1 Measuring units

In this document, all linear dimensions, deviations and corresponding tolerances are expressed in millimetres; angular dimensions are expressed in degrees, and angular deviations and the corresponding tolerances are expressed in ratios but in some cases microradians or arcseconds are used for clarification purposes. The equivalence of the following expressions should always be kept in mind:

$$0{,}010/1\,000 = 10\ \mu\text{rad} \approx 2'' \qquad (1)$$

5.2 Reference to ISO 230-1, ISO 230-2 and ISO 230-7

To apply this document, reference shall be made to ISO 230-1 when required, especially for the installation of the machine tool before testing, warming up of the spindle and other moving components, description of measuring methods and recommended accuracy of testing equipment.

In the "Observations" block of the tests described in the following clauses, the instructions are followed by a reference to the corresponding clause in ISO 230-1, ISO 230-2 and ISO 230-7, in cases where the test concerned is in compliance with the specifications of that part of ISO 230.

5.3 Machine levelling

Prior to conducting tests on a machine tool, the machine tool should be levelled according to the recommendations of the supplier/manufacturer (see ISO 230-1:2012, 6.1).

5.4 Temperature conditions

The temperature conditions throughout the tests shall be specified by agreement between the manufacturer/supplier and user.

5.5 Testing sequence

The sequence in which the tests are presented in this document in no way defines the practical order of testing. In order to make the mounting of instruments or measuring easier, tests may be performed in any order.

5.6 Tests to be performed

When testing a machine, it is not always necessary or possible to carry out all the tests described in this document. When the tests are required for acceptance purposes, it is up to the user to choose, in agreement with the supplier/manufacturer, those tests relating to the components and/or the properties of the machine which are of interest. These tests are to be clearly stated when ordering a machine. Mere reference to document for the acceptance tests, without specifying the tests to be carried out, and without agreement on the relevant expenses, cannot be considered as binding for any contracting party.

5.7 Measuring instruments

Measuring instruments indicated in the tests described in the following clauses are examples only. Other instruments capable of measuring the same quantities and having the same, or a smaller, measurement uncertainty can be used. Reference shall be made to ISO 230-1:2012, Clause 5, which indicates the relationship between measurement uncertainties and the tolerances.

When a "dial gauge" is referred to, it can mean not only dial test indicators (DTI), but any type of linear displacement sensor such as analog or digital dial gauges, linear variable differential transformer (LVDTs), linear scale displacement gauges, or non-contact sensors, when applicable to the test concerned.

Similarly, when a "straightedge" is referred to, it can mean any type of straightness reference artefact, such as a granite or ceramic or steel or cast-iron straightedge, one arm of a square, one generating line on a cylindrical square, any straight path on a reference cube, or a special, dedicated artefact manufactured to fit in the T-slots or other references.

In the same way, when a "square" is mentioned, it can mean any type of squareness reference artefact, such as a granite or ceramic or steel or cast-iron square, a cylindrical square, a reference cube, or, again, a special, dedicated artefact.

When a "precision level" is referred to, it can mean any type of level such as bubble tube, digital and analogue electronic levels.

Valuable information on measuring instruments is available in ISO/TR 230-11.

5.8 Software compensation

When built-in software facilities are available for compensating geometric, positioning, contouring and thermal deviations, their use during these tests should be based on agreement between manufacturer/supplier and user, with due consideration to the machine tool intended use, e.g. if the intended use of the machine tool is with or without software compensation for geometric errors. When the software compensation is used, this shall be stated in the test report. It shall be noted that when software compensation is used, some machine tool axes cannot be locked for test purposes.

Valuable information on numerical compensation of geometric errors can be gathered in ISO/TR 16907.

5.9 Machining tests

Machining tests shall be made with finishing cuts only, not with roughing cuts which are liable to generate appreciable cutting forces.

5.10 Minimum tolerance

By mutual agreement, manufacturer/supplier and user can establish the tolerance for a measuring length different from that given in the tests described in the following clauses. However, it shall be considered that the minimum value of tolerance is 0,005 mm unless otherwise specified.

In specifying the minimum tolerance, measurement uncertainty associated with the test and the recommended instrument, shall be taken into account, see 5.7.

5.11 Diagrams

For reasons of simplicity, the diagrams in clauses 6, 7 and 8 of this document illustrate only one type of machine.

6 Geometric tests

6.1 Linear axes motions

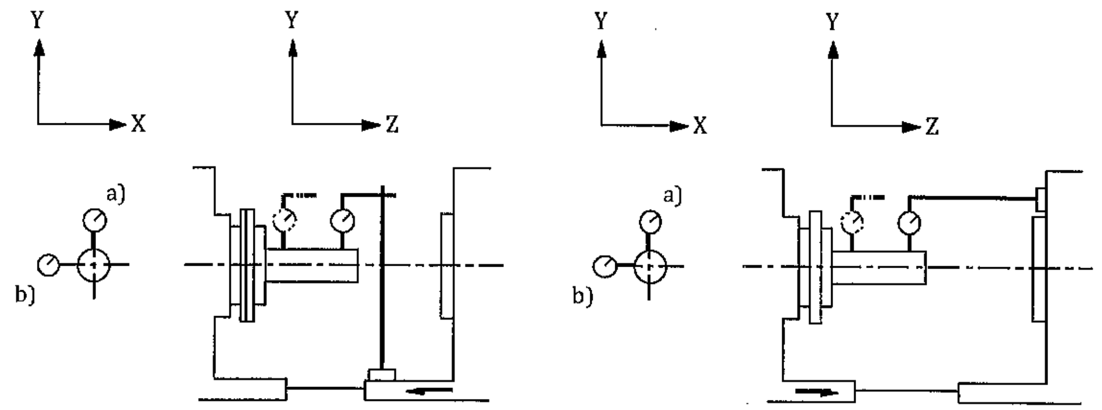
Object — **G1**

Checking of straightness of the wheelhead (or workhead) slide motion along the Z-axis:

a) in the vertical plane, E_{YZ};

b) in the horizontal plane, E_{XZ}.

Diagram



Tolerance

a) 0,015 for a measuring length of 250

b) 0,008 for a measuring length of 250

Measurement results

a)

b)

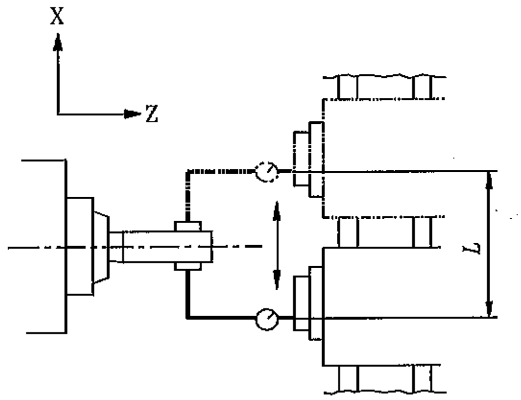
Measuring instruments

Dial gauge and test mandrel or straightedge, or optical instruments

Observations and references to ISO 230-1: 8.2

When a test mandrel is used, the dial gauge support shall be placed on the wheelhead and the test mandrel in the workholding spindle.

When a straightedge is used, the dial gauge support shall be placed on a fixed part of the wheelhead, the stylus touching a straightedge laid approximately parallel to the Z-axis motion.

Object	**G2**
Checking of squareness of the motion of the wheelhead cross slide or workhead cross slide (X-axis) to the Z-axis motion, $E_{B(0Z)X}$.	
Diagram	
	
Key	
L distance between the two points touched	
Tolerance	
0,020/300 (0,066/1 000) where 300 is the distance between the two points touched, *L*.	
Measurement results	
Measuring instruments	
Test mandrel and dial gauge support or optical instruments	
Observations and references to ISO 230-1: 10.3.2 and 10.3.3	
Set a test mandrel on the workholding spindle and adjust the workhead (B'-axis) so that the spindle axis is parallel to the Z-axis motion. Fix the dial gauge support on the test mandrel, with the stylus of the dial gauge touching a point of the wheel spindle. Turn the workholding spindle through 180° and move the X-axis until the stylus again touches the same point. The difference in readings of the dial gauge divided by the distance between the two points touched is the squareness error to be reported.	

6.2 Workholding spindle

Object | **G3**

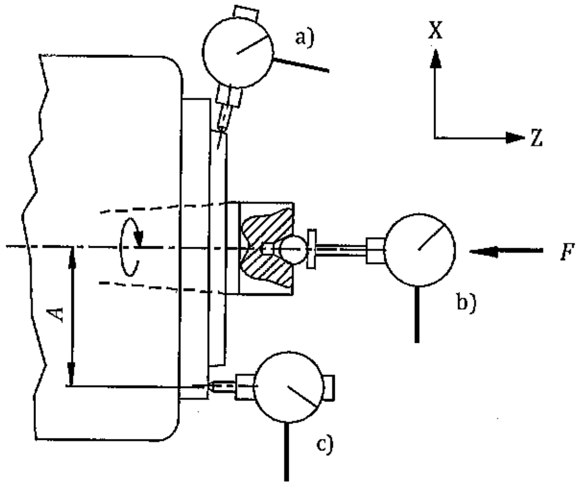
Checking of the workholding spindle rotation:

a) run-out of the external centring surface;

b) axial error motion, $E_{ZC'}$;

c) face run-out of the front resting surface

Diagram



Key

A distance from the spindle axis

F axial force

Tolerance

a) 0,005

b) 0,005

c) 0,010

Measurement results

a)

b)

c)

Measuring instruments

Dial gauge for a) and c) and dial gauge with flat-ended stylus tip for b)

Observations and, for a) and c), reference to ISO 230-1:2012, 12.5; For b), reference to ISO 230-7:2015, 5.4.4

For a): In the case of a tapered spindle nose, the stylus of the dial gauge shall be set normal to the surface to be checked.

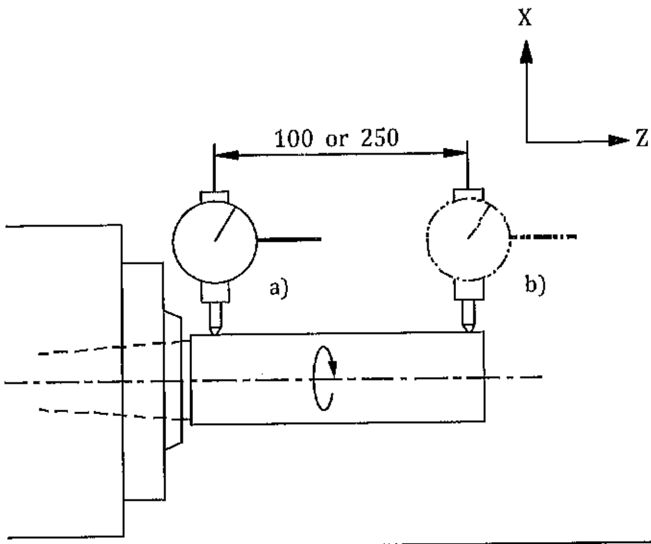
For b): The value and the direction of the axial force *F* to be applied shall be specified by the supplier/manufacturer. Where preloaded thrust bearings are used, no force needs be applied.

For c): Distance *A* of the dial gauge from the spindle axis shall be as large as possible.

See also test AR1 in Annex A

Object	**G4**
Checking of run-out of the internal taper of the workholding spindle a) near the spindle nose; b) at a distance of 100 or 250	

Diagram



Tolerance

a) 0,005

b) 0,010 for a measuring distance of 100

0,015 for a measuring distance of 250

Measurement results

Measured distance:

a)

b)

Measuring instruments

Test mandrel and dial gauge

Observations and references to ISO 230-1: 12.5

In the case of an internal taper, the test shall be made with the aid of a test mandrel.

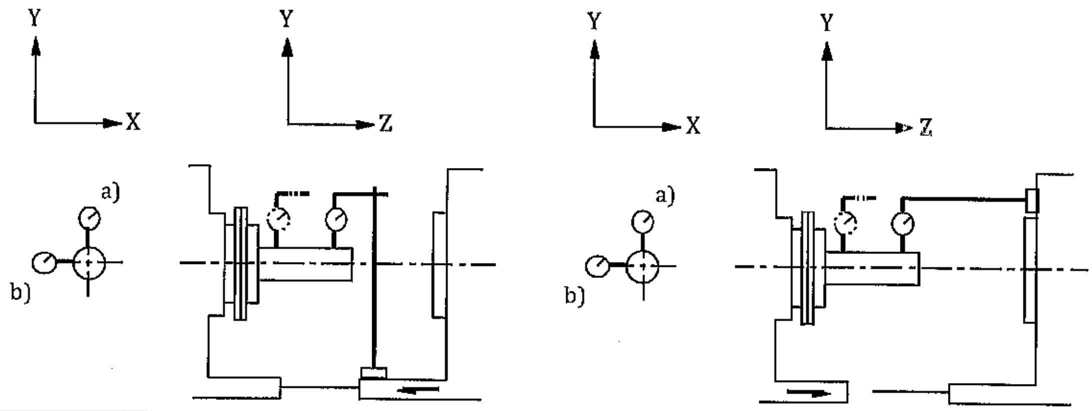
Object | **G5**

Checking of parallelism of the workholding spindle axis, (C′), to the Z-axis motion of the wheelhead (or of the workhead):

a) in the vertical plane, $E_{A(0Z)(C')}$;

b) in the horizontal plane, $E_{B(0Z)(C')}$.

Diagram



Tolerance

a) 0,008/100, 0,020/250 (0,080/1 000); test mandrel end directed upwards

b) 0,003/100, 0,008/250 (0,032/1 000)

Measurement results

a)

b)

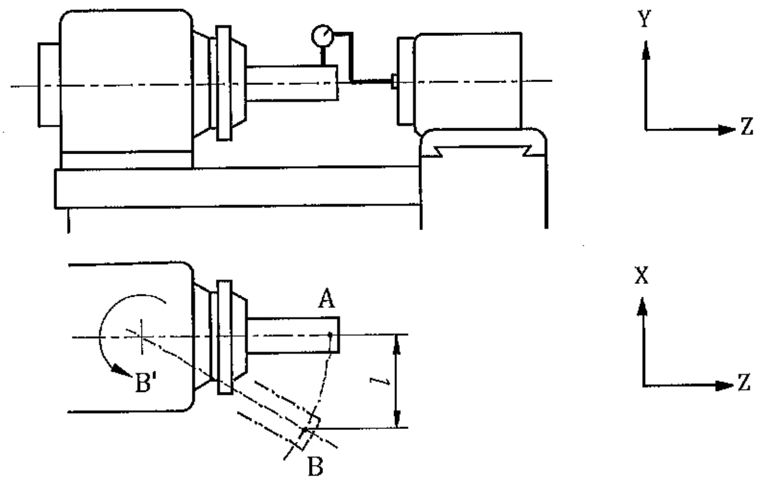
Measuring instruments

Test mandrel and dial gauge or optical instruments

Observations and references to ISO 230-1: 12.5

The checking shall be done first at one angular position of the workholding spindle and then repeated after rotating the spindle through 180°. Mean values shall be taken at each measuring point in order to evaluate the parallelism error.

Object	G6
Checking of parallelism of the workhead swivelling plane to the X-axis.	
Diagram	



Key

l difference in X-axis positions between measuring points A and B

Tolerance

0,010/100 (0,100/1 000)

Measurement results

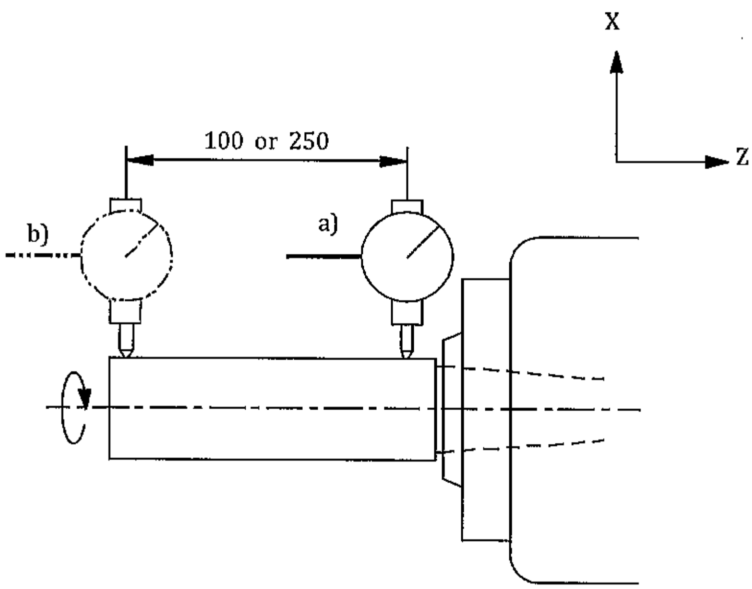
Measuring instruments

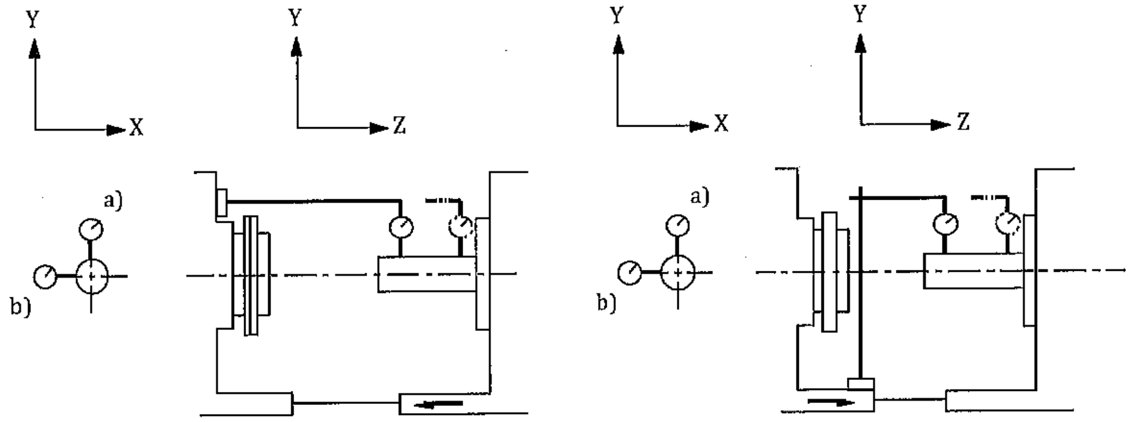
Test mandrel and dial gauge

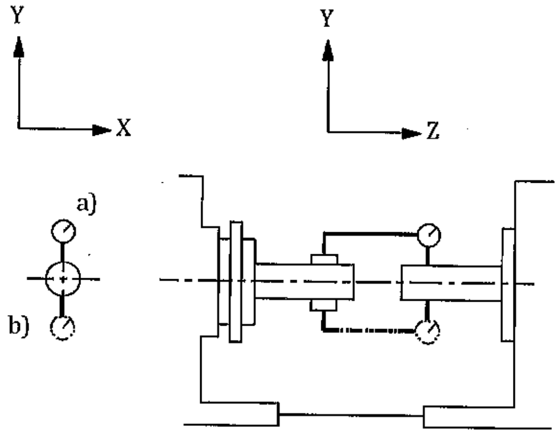
Observations and references to ISO 230-1: 12.3.3.2

A reading shall be taken when the workhead is locked in position A. Swivel the workhead towards its external position B and touch the stylus of the dial gauge to the same point of the test mandrel as in position A, moving the cross slide and the Z-axis. The difference between the readings at positions A and B is the value to be reported.

6.3 Wheel spindle

Object	**G7**
Checking of run-out of internal taper of the wheel spindle (wheel mounting diameter): a) near the spindle nose; b) at a distance of 100 or 250 This test is applicable to all available wheel spindles.	
Diagram	
	
Tolerance a) 0,005 b) 0,010 for a measuring distance of 100 0,015 for a measuring distance of 250	
Measurement results Measured distance: a) b)	
Measuring instruments Test mandrel according to the type of spindle nose and dial gauge	
Observations and references to ISO 230-1: 12.5.3 In the case of an internal taper, the test shall be made with the aid of a test mandrel. See also test AR2 in Annex A.	

Object	**G8**
Checking of parallelism of the wheel spindle axis, (C1), to the Z-axis motion of the wheelhead (or of the workhead):	
a) in the vertical plane, $E_{A(0Z)(C1)}$;	
b) in the horizontal plane, $E_{B(0Z)(C1)}$.	
This test is applicable to all available wheel spindles.	
Diagram	
	
Tolerance	
a) 0,007/100, 0,020/300 (0,065/1 000); test mandrel end directed upwards	
b) 0,004/100, 0,010/300 (0,035/1 000)	
Measurement results	
a)	
b)	
Measuring instruments	
Test mandrel and dial gauge or optical instruments	
Observations and references to ISO 230-1: 10.1.3	
The checking shall be done first at one angular position of the wheel spindle, C1, and then repeated after rotating the spindle through 180°. Mean values shall be taken at each measuring point in order to evaluate the parallelism error.	

Object	**G9**
Checking of the equidistance (difference in height) of the workholding spindle axis, C', and the grinding spindle axis, (C1), in the vertical plane. This test is applicable to all available wheel spindles.	
Diagram	
	
Tolerance	
0,025	
Measurement results	
Measuring instruments	
Dial gauge and dial gauge support, or optical instruments	
Observations and references to ISO 230-1: 12.3.3	
The test shall be carried out in the vertical plane after having obtained alignment in the horizontal plane. Specific care shall be devoted to minimize the compliance of the dial gauge support.	

6.4 Facing wheelhead

G10

Object

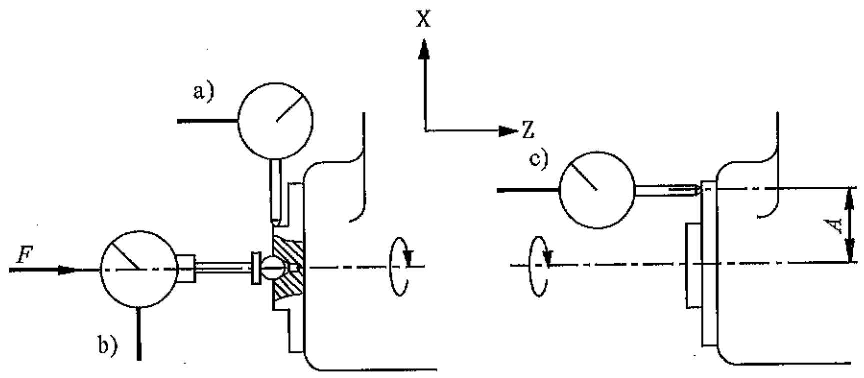
Checking of the facing spindle:

a) run-out of the external centring surface;

b) axial error motion, $E_{Z(C2)}$;

c) face run-out of the front resting surface.

Diagram



Key

A distance from the spindle axis

F axial force

Tolerance

a) 0,005

b) 0,005

c) 0,010

Measurement results

a)

b)

c)

Measuring instruments

Dial gauge for a) and c) and dial gauge with flat-ended stylus tip for b)

Observations and, for a) and c), reference to ISO 230-1:2012, 12.5; For b), reference to ISO 230-7:2015, 5.4.4

For a):

In the case of a tapered spindle nose, the stylus of the dial gauge shall be set normal to the surface to be checked.

For b):

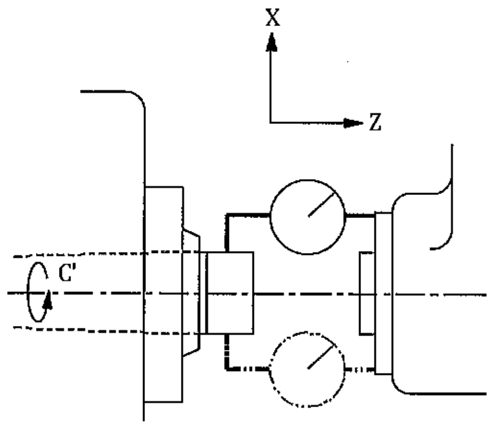
The value and the direction of the axial force *F* to be applied shall be specified by the supplier/manufacturer.

Where preloaded thrust bearings are used, no force needs be applied.

For c):

Distance *A* of the dial gauge from the spindle axis shall be as large as possible.

See also test AR2 in Annex A.

Object	G11
Checking of perpendicularity of the flange face of the facing spindle, (C2), to the workholding spindle axis, C'	
Diagram	
	
Tolerance 0,020 over 300 where 300 is the distance between the two points touched.	
Measurement results	
Measuring instruments Dial gauge and dial gauge support	
Observations and references to ISO 230-1:12.4.1 and 12.4.8 The dial gauge is rotated through 360° and the largest variation in the readings is the squareness error to be reported	

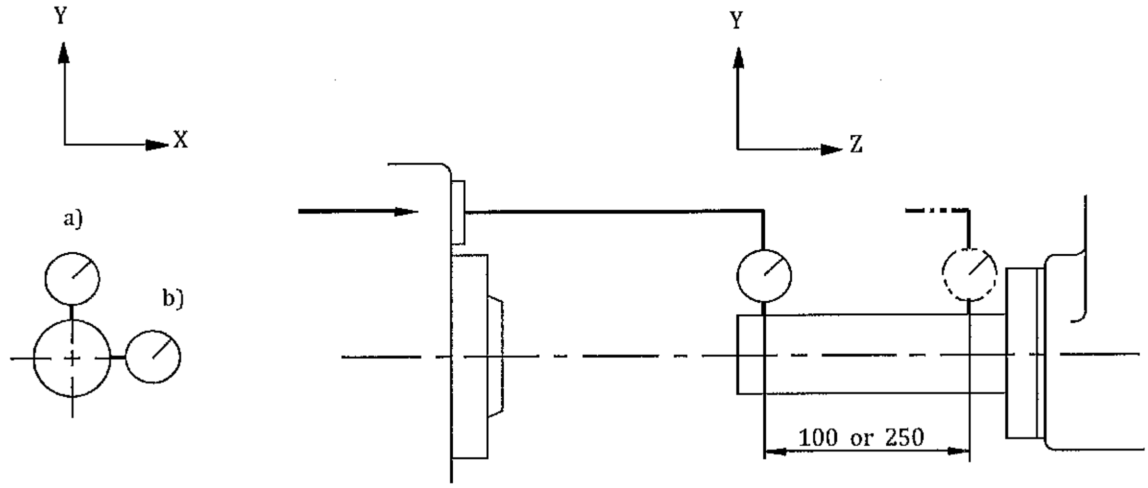
Object — **G12**

Checking of parallelism of the facing spindle axis, (C2), to the Z-axis motion (of the wheelhead or of the workhead):

a) in the vertical plane, $E_{A(0Z)(C2)}$;

b) in the horizontal plane, $E_{B(0Z)(C2)}$.

Diagram



Tolerance

a) 0,008/100, 0,020/250 (0,080/1 000); test mandrel end directed upwards

b) 0,003/100, 0,008/250 (0,032/1 000)

Measurement results

a)

b)

Measuring instruments

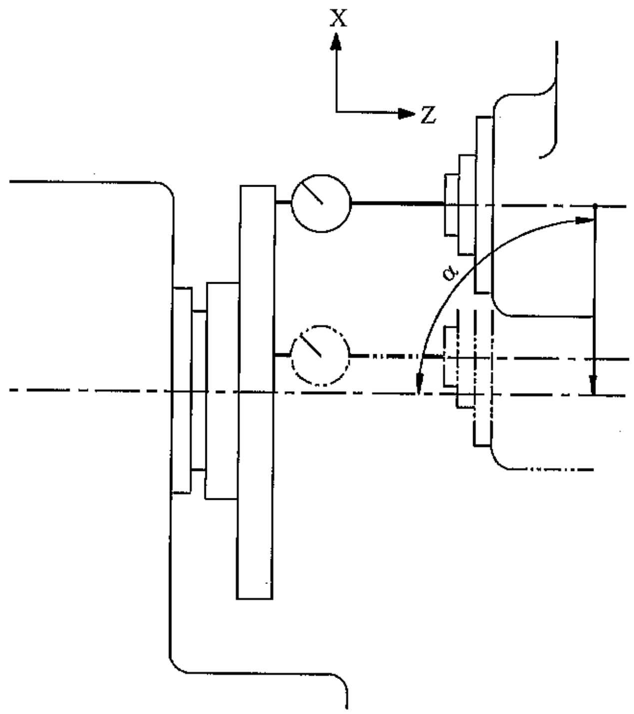
Dial gauge and test mandrel

Observations and references to ISO 230-1: 10.1.3

The checking shall be done first at one angular position of the facing spindle, (C2), and then repeated after rotating the spindle through 180°. Mean values shall be taken at each measuring point in order to evaluate the parallelism error.

Object	**G13**
Checking of squareness of the motion of the facing wheelhead, (swivelling around C3-axis or linear along the X-axis), to the workholding spindle axis.	

Diagram



Key

α swivelling angle

Tolerance

0,010/300 (0,035/1 000) with $\alpha \geq 90°$

Measurement results

Measuring instruments

Dial gauge and flat disc or straightedge

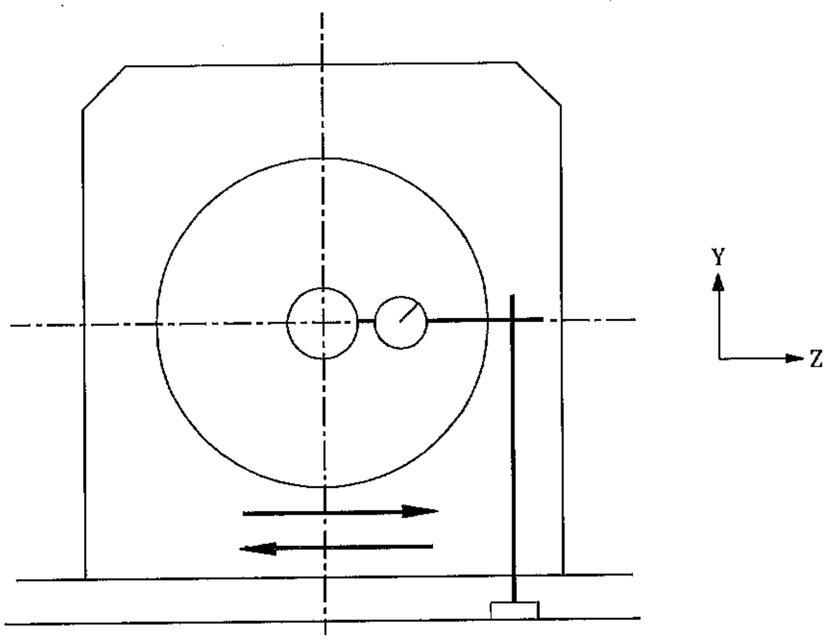
Observations and references to ISO 230-1: 12.4.1 and 12.4.6

The disk is nominally flat and perpendicular to the C'-axis.

The dial gauge is rigidly mounted on the facing wheelhead and it is brought to contact the disk. The C3-axis is swivelled and a new reading of the dial gauge is taken.

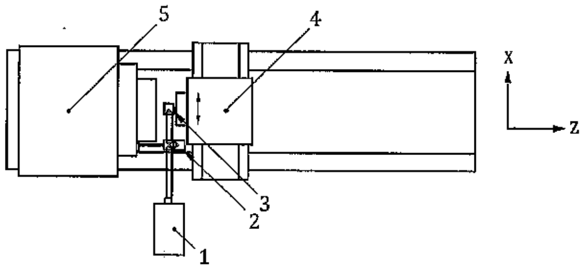
The difference between the two readings divided by the distance between the two measurement points is the squareness error to be reported.

7 Positioning tests

Object	P1
Checking of the repeatability of the finishing approach of the wheelhead cross slide (or the workhead cross slide).	
Diagram	
	
Tolerance	
0,002	
Measurement results	
Measuring instruments	
Dial gauge	
Observations and references to ISO 230-1	
Carry out five consecutive tests for the wheelhead cross slide positioning (or workhead slide positioning), the motion being obtained by a quick approach followed by a slow approach. The range of individual positioning measurements is the measurement result to be reported.	

Object				**P2**
Checking of the accuracy and repeatability of the X-axis motion of the wheelhead cross slide, E_{XX}.				

Diagram



Key

1 laser head 2 interferometer 3 retro-reflector 4 wheelhead carriage 5 workhead

Tolerance For axes up to 1 000		**Measuring length** ≤ 500	**Measuring length** ≤ 1 000	**Measurement results** Measured length
Unidirectional positioning accuracy of X-axis [a]	$E_{XX,A\uparrow}$; $E_{XX,A\downarrow}$	0,016	0,020	
Unidirectional positioning repeatability of X-axis [a]	$E_{XX,R\uparrow}$; $E_{XX,R\downarrow}$	0,006	0,008	
Mean reversal value of X-axis	$E_{XX,\bar{B}}$	0,010	0,013	
Unidirectional systematic positioning error of X-axis [a]	$E_{XX,E\uparrow}$; $E_{XX,E\downarrow}$	0,008	0,013	

[a] Possible basis for machine acceptance.

Measuring instruments

Laser measurement equipment or linear scale.

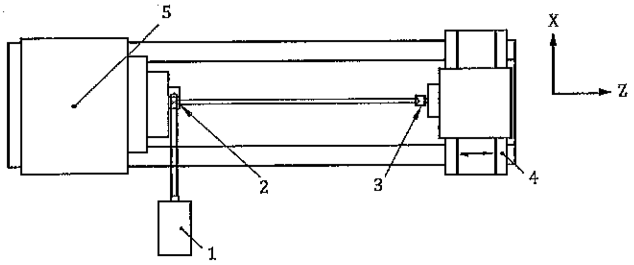
Observations and references to ISO 230-2:2014, 3, 5.3.2 and 5.3.3

Relative measurement between the tool position and work-piece position is desired. When a linear scale is used, it shall be set on the table parallel to the Z-axis, the scale reader being on the tool position. When laser equipment is used, the reflector shall be set on the spindle head and the interferometer on the workhead.

Concerning the test conditions, test program and presentation of results, ISO 230-2:2014, Clauses 3, 4 and 7 shall be referred to. The starting point of measurement shall be stated.

Object					**P3**
Checking of the accuracy and repeatability of the Z-axis motion of the wheelhead carriage, E_{ZZ}.					

Diagram



Key

1 laser head 2 interferometer 3 retro-reflector 4 wheelhead carriage 5 workhead

Tolerance For axes up to 2 000		**Measuring length** ≤ 500	≤ 1 000	≤ 2 000	**Measurement results** Measured length:
Bi-directional positioning accuracy of Z-axis [a]	$E_{ZZ,A}$	0,025	0,032	0,040	
Unidirectional positioning accuracy of Z-axis [a]	$E_{ZZ,A\uparrow}$; $E_{ZZ,A\downarrow}$	0,015	0,019	0,024	
Unidirectional positioning repeatability of Z-axis [a]	$E_{ZZ,R\uparrow}$;$E_{ZZ,R\downarrow}$	0,008	0,010	0,013	
Mean reversal value of Z-axis	$E_{ZZ,\bar{B}}$	0,010	0,013	0,016	
Bi-directional systematic positioning error of Z-axis [a]	$E_{ZZ,E}$	0,016	0,020	0,025	
Unidirectional systematic positioning error of Z-axis [a]	$E_{ZZ,E\uparrow}$; $E_{ZZ,E\downarrow}$	0,008	0,010	0,013	
Mean bi-directional positioning error of Z-axis [a]	$E_{ZZ,M}$	0,010	0,013	0,016	
For axes exceeding 2 000					
Bi-directional systematic positioning error of Z-axis [a]	$E_{ZZ,E}$	0,032 + 0,008 for each additional 1 000			
Mean bi-directional positioning error of Z-axis [a]	$E_{ZZ,M}$	0,025 + 0,005 for each additional 1 000			

[a] Possible basis for machine acceptance.

Measuring instruments

Laser measurement equipment or linear scale.

Observations and references to ISO 230-2:2014, 3, 5.3.2 and 5.3.3

Relative measurement between the tool position and work-piece position is desired. When a linear scale is used, it shall be set on the table parallel to the Z-axis, the scale reader being on the tool position. When laser equipment is used, the reflector shall be set on the spindle head and the interferometer on the workhead.

For axes exceeding 2 000, one or more segments of 2 000 with 5 runs forward and backward each. Tolerances for axis lengths ≤ 2 000 shall be applied.

For axes up to 4 000 one measurement over one 2 000 segment is recommended, for axes over 4 000 and up to 8 000 two 2 000 segments are recommended, and so forth.

Test segments shall be equally spaced along the full axis length, with any excess length equally divided at the beginning, in between, and at the end of the test segments.

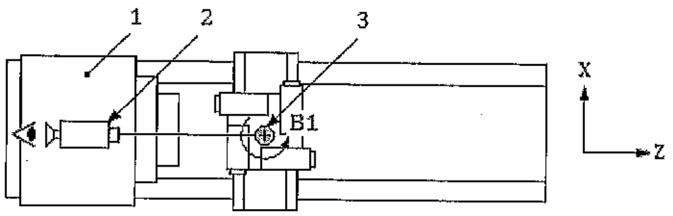
Other number of 2 000 mm segments, other lengths of segments, as well as the positions of the segments within the working area can be subject to agreement between manufacturer/supplier and user. Additionally, one test over the total travel of the axis (once forward and once backward) shall be performed.

Concerning the test conditions, test program and presentation of results, ISO 230-2:2014, Clauses 3, 4 and 7 shall be referred to. The starting point of measurement shall be stated.

Object — **P4**

Checking of the accuracy and repeatability of the B1-axis of rotation, E_{BB1}.

Diagram



Key

1 workhead 2 autocollimator 3 polygon

Tolerance (30° or 45° interval positioning)		For 360°		Measurement results
		"	µrad	
Bi-directional positioning accuracy of C'-axis [a]	$E_{BB1,A}$	11	55	
Unidirectional positioning repeatability of C'-axis [a]	$E_{BB1,R\uparrow}$; $E_{BB1,R\downarrow}$	6	30	
Bi-directional positioning repeatability of C'-axis	$E_{BB1,R}$	8	40	
Mean reversal value of C'-axis	$E_{BB1,\bar{B}}$	6	30	
Bi-directional systematic positioning error of C'-axis [a]	$E_{BB1,E}$	6	30	
Mean bi-directional positioning error of C'-axis [a]	$E_{BB1,M}$	4	20	

[a] Possible basis for machine acceptance.

Measuring instruments

Laser angle measuring equipment or polygon and autocollimator.

Observations and references to ISO 230-2:2014, 3, 5.3.4 and 5.3.5

Fix the autocollimator on the workhead side of the machine tool and fix the polygon near the centre of the B1-axis of rotation, in alignment with the autocollimator at the first measuring rotary position.

Target positions shall be selected according to ISO 230-2:2014, Table 1.

Angular positioning feed speed shall be agreed between manufacturer/supplier and user.

Concerning the test conditions, test program and presentation of results, ISO 230-2:2014, Clauses 3, 4 and 7 shall be referred to.

8 Machining tests

M1

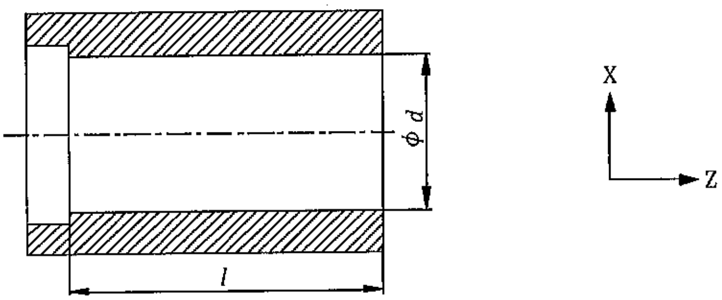
Object

Checking of the accuracy of the bore of a test piece ground by internal grinding

a) roundness

b) consistency of diameters

Diagram



D = maximum admissible diameter for grinding (mm) [a]	d (mm)	l (mm)
$D \leq 40$	15	25
$40 < D \leq 80$	30	50
$80 < D \leq 150$	60	100
$150 < D$	100	150

Key

d test bore diameter

l test bore length

[a] Refer to M2 Diagram

Tolerance

a) 0,003

b) 0,005 for $l = 25$

0,005 for $l = 50$

0,010 for $l = 100$

0,015 for $l = 150$

Measurement results

Maximum admissible diameter D:

a)

b)

Measuring instruments

Bore gauge and roundness measuring machine

Observations and references to ISO 230-1:2012, B.1.1 and B.1.2

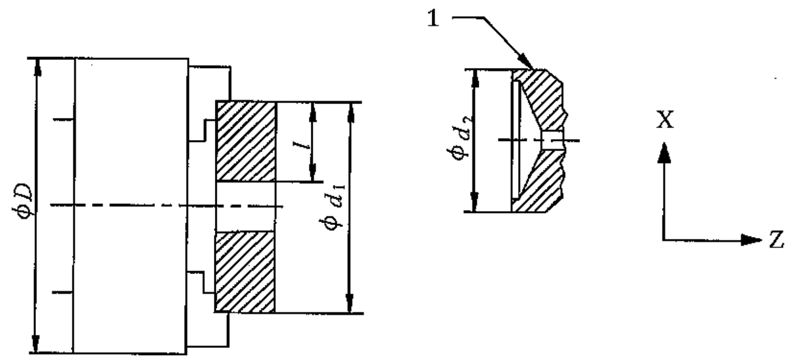
Grinding of the test piece shall be conducted along the whole length l, without arbor support.

For a): Measurements for roundness shall be made at several positions of the test piece and the greatest measured value shall be recorded.

For b): Variation of diameter shall be measured at both ends and in the middle of the test piece. The measurements shall be carried out in a single axial plane. Any taper should be such that the largest diameter is near the workhead.

Object	**M2**
Checking of the flatness of the ground face of a disk	

Diagram



Key

1 grinding wheel

D maximum admissible diameter for grinding

d_1 outer diameter of the disk

d_2 outer diameter of the grinding wheel

l width of ground face

Tolerance

0,010 for $d_1 = 300$

The ground test piece shall be flat or concave

Measurement results

Measuring instruments

Straightedge and gauge blocks for surface plate and dial gauge or CMM

Observations and references to ISO 230-1: B.1.1 and B.1.2

The test piece shall be mounted on a face plate or chuck.

The workhead spindle axis is set parallel to the Z-axis motion. Facing of a flat surface perpendicular to the workhead spindle.

The outer diameter $d_1$of the disc and the width l of the ground face shall be conforming to the following formulae:

$$d_1 = \frac{2}{3} \times D, \qquad l = \frac{2}{3} \times d_2$$

Annex A
(informative)

Error motions of axes of rotation

A.1 Rotational accuracy of workholding spindle, C'

AR1

Object

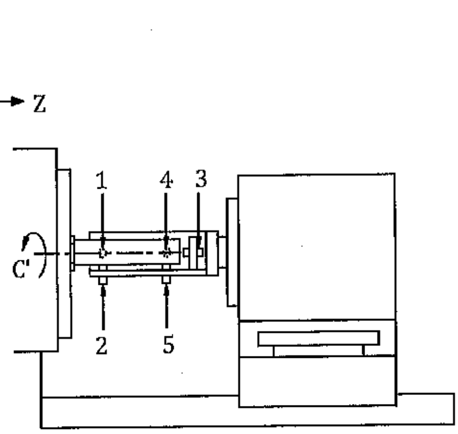
Axis of rotation error motion for workholding spindle C':

a) radial error motion in direction of X, $E_{XC'}$;

b) axial error motion, $E_{ZC'}$;

c) tilt error motion around the Y-axis, $E_{BC'}$.

Diagram



Key

1 to 5 linear displacement sensors

Tolerance

		At percentage of maximum speed		
		10%	50%	100%
a) radial error motion in X direction	$E_{XC'}$	0,005 at all speeds		
b) axial error motion	$E_{ZC'}$	0,003 at all speeds		
c) tilt error motion around the Y-axis	$E_{BC'}$	to be defined between manufacturer/supplier and user		

If the minimum speed is larger than 10 % of the maximum speed, then the spindle should be operated at minimum speed instead.

Warning: Maximum rotational speed defined by measurement equipment manufacturer and ISO 16089 safety requirements shall be considered.

Measurement results

	At percentage of maximum speed		
	10%	50%	100%
a)			
b)			
c)			

Measuring instruments

Test mandrel, non-contacting linear displacement sensors and angular measuring device or two precision spheres located slightly eccentric to the spindle axis average line and non-contacting linear displacement sensors.

Observations and references to ISO 230-7

This test is a spindle test with fixed sensitive direction (ISO 230-7:2015, 5.4).

After setup of the measuring instrument, the spindle should be warmed up at 50 % of the maximum spindle speed for a time period of 10 min, if not otherwise agreed between manufacturer/supplier and user.

a) Total radial error motion value, $E_{XC'}$, (using sensors 1 and 2).

Total radial error motion measurement is described in ISO 230-7:2015, 5.4.3. The radial error motion should be measured as close as possible to the spindle nose.

For the total radial error motion, $E_{XC'}$, an error motion polar plot with a least square circle (LSC) centre should be provided.

b) Total axial error motion value, $E_{ZC'}$ (using sensor 3).

Axial error motion measurement is described in ISO 230-7:2015, 5.4.4.

For the axial error motion $E_{ZC'}$, a total error motion polar plot with a polar chart (PC) centre should be provided.

c) Tilt error motion values, $E_{BC'}$ (using sensors 1, 2, 4 and 5).

Tilt error motion measurement is described in ISO 230-7:2015, 5.4.5. The tilt error motion can also be checked with just one non-contacting sensor (see ISO 230-7:2015, 5.4.5.2 and 5.4.5.4).

For the tilt error motion, $E_{BC'}$, an error motion polar plot with a polar chart (PC) centre should be provided.

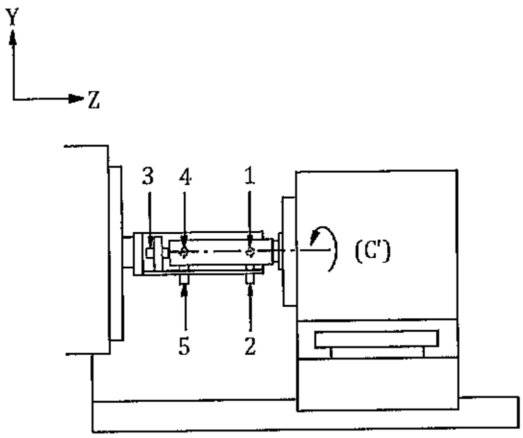
For these tests the following parameters should be stated:

1) the radial, axial or face locations at which the measurements are made;
2) identification of all artefacts, targets and fixtures used;
3) the location of the measurement setup;
4) the position of any linear or rotary positioning stages that are connected to the device under test;
5) the direction angle of the sensitive direction, e.g. axial, radial or intermediate angles, as appropriate;
6) presentation of the measurement result, e.g. error motion value, polar plot, time-based plot, frequency-content plot;
7) the rotational frequency of the spindle (zero for static error motion);
8) the time duration in seconds or number of spindle rotations;
9) appropriate warm-up or break-in procedure;
10) the frequency response of the instrumentation, given in Hertz or cycles per revolution, including roll-off characteristics of any electronic filters — in the case of digital instrumentation, the displacement resolution and sampling rate;
11) the structural loop, including the position and orientation of sensors relative to the spindle housing from which the error motion is reported, specified objects with respect to which the spindle axes and the reference coordinate axes are located and the elements connecting these objects;
12) time and date of measurement;
13) type and calibration status of all measurement instrumentation;
14) any other operating conditions which can influence the measurement such as ambient temperature.

If the tilt measurements are not needed (by agreement between the supplier and the user) then only three displacement sensors are used (1, 2, and 3) and the test mandrel may be replaced by a precision test sphere.

A.2 Rotational accuracy of wheel spindle (C1) and of facing spindle (C2)

Text references and symbols in AR2 refer to the wheel head spindle (C1). For testing the facing spindle, references to (C1) shall be replaced with (C2). All additional wheel spindles axes (where present) shall be identified and tested. Symbols shall be adapted accordingly.

Object				**AR2**
Axis of rotation error motion for the wheel head spindle, (C1): a) radial error motion in rotating sensitive direction, $E_{XY(C1)}$; b) axial error motion, $E_{Z(C1)}$; c) tilt error motion in rotating sensitive direction $E_{AB(C1)}$.				
Diagram  **Key** 1 to 5 linear displacement sensors				
Tolerance		At percentage of maximum speed		
		10%	50%	100%
a) total radial error motion value	$E_{XY(C1)}$	0,005 at all speeds		
b) total axial error motion value	$E_{Z(C1)}$	0,003 at all speeds		
c) total tilt error motion value	$E_{AB(C1)}$	to be defined between manufacturer/supplier and user		
If the minimum speed is larger than 10 % of the maximum speed, then the spindle should be operated at minimum speed instead. Warning: Maximum rotational speed defined by measurement equipment manufacturer and ISO 16089 safety requirements shall be considered.				
Measurement results		At percentage of maximum speed		
		10%	50%	100%
	a)			
	b)			
	c)			

Measuring instruments

Test mandrel, non-contacting linear displacement sensors and angular measuring device or two precision spheres located slightly eccentric to the spindle axis average line and non-contacting linear displacement sensors.

Observations and references to ISO 230-7

This test is a spindle test with rotating sensitive direction (ISO 230-7:2015, 5.3).

After setup of the measuring instrument, the spindle should be warmed up at 50 % of the maximum spindle speed for a time period of 10 min, if not otherwise agreed between manufacturer/supplier and user.

a) Total radial error motion value, $E_{XY(C1)}$, (using sensors 1 and 2).
Radial error motion measurement is described in ISO 230-7:2015, 5.3.2. The radial error motion should be measured as close as possible to the spindle nose.

For the radial error motion, $E_{XY(C1)}$, a total error motion polar plot with a least square circle (LSC) centre should be provided.

b) Total axial error motion value $E_{Z(C1)}$ (using sensor 3).
Axial error motion measurement is described in ISO 230-7:2015, 5.3.4.

For the axial error motion $E_{Z(C1)}$, a total error motion polar plot with a polar chart (PC) centre should be provided.

c) Total tilt error motion values, $E_{AB(C1)}$ (using sensors 1, 2, 4 and 5).
Tilt error motion measurement is described in ISO 230-7:2015, 5.3.3. The tilt error motion can also be checked with just two non-contacting sensors (see ISO 230-7:2015, 5.3.3.2).

For the tilt error motion, $E_{AB(C1)}$, a total error motion polar plot with a polar chart (PC) centre should be provided.

For these tests the following parameters shall be stated:

1) the radial, axial or face locations at which the measurements are made;
2) identification of all artefacts, targets and fixtures used;
3) the location of the measurement setup;
4) the position of any linear or rotary positioning stages that are connected to the device under test;
5) the direction angle of the sensitive direction, e.g., axial, radial or intermediate angles, as appropriate;
6) presentation of the measurement result, e.g. error motion value, polar plot, time-based plot, frequency-content plot;
7) the rotational frequency of the spindle (zero for static error motion);
8) the time duration in seconds or number of spindle rotations;
9) appropriate warm-up or break-in procedure;
10) the frequency response of the instrumentation, given in Hertz or cycles per revolution, including roll-off characteristics of any electronic filters — in the case of digital instrumentation, the displacement resolution and sampling rate;
11) the structural loop, including the position and orientation of sensors relative to the spindle housing from which the error motion is reported, specified objects with respect to which the spindle axes and the reference coordinate axes are located and the elements connecting these objects;
12) time and date of measurement;
13) type and calibration status of all measurement instrumentation;
14) any other operating conditions which can influence the measurement such as ambient temperature.

If the tilt measurements are not needed (by agreement between the supplier and the user) then only three displacement sensors are used (1, 2, and 3) and the test mandrel may be replaced by precision test sphere.

Annex B
(informative)

Terms in other languages

See Table B.1

Table B.1 — Terms in other than official ISO languages for Figure 1

Key	German	Italian	Japanese	Persian
1	Bett	banco	ベッド	بستر
2	Schleifspindelstock	testa porta-mola	といし軸頭	کلگی چرخ سنگ
3	Schleifspindel-querschlitten (...)	slitta trasversale della testa porta-mola (asse X)	といし軸頭クロススライド	کشویی عرضی کلگی چرخ سنگ (محور X)
4	Schleifspindel-längsschlitten (...)	slitta longitudinale della testa porta-mola (asse Z)	といし軸頭往復台	کشویی طولی کلگی چرخ سنگ (محور Z)
5	Schleifspindel (...)	mandrino porta-mola (asse (C1))	といし軸	اسپیندل سنگ (محور C1)
6	Innenschleifscheibe	mola per interni	内面研削といし	چرخ سنگ داخلی
7	Werkstückspindelstock (schwenkbar) (...)	testa porta-pezzo orientabile (comprende l'asse B' e l'asse C')	工作主軸台（旋回式）(B'軸及び C'軸を含む)	کلگی کارگیر (چرخان) (شامل محور B' و محور C')
8	Werkstückspindel-stockschlitten (...)	slitta trasversale della testa porta-pezzo (asse X')	工作主軸台クロススライド(X'軸)	کشویی عرضی کلگی کارگیر (محور X')
9	Werkstückspindel-Aufnahme	attrezzo del mandrino porta-pezzo	工作主軸	اسپیندل کارگیر
10	Werkstück-Schutzeinrichtung	dispositivo di protezione del pezzo	工作物覆い	محافظ قطعه کار
11	Werkzeug-Schutzeinrichtung	riparo della mola	といし覆い	محافظ چرخ سنگ
12	Planschleifeinrichtung	testa porta-mola a sfacciare	端面研削といし軸頭	کلگی چرخ سنگ پیشانی تراش
13	Schwenkarm (...) (mit Antrieb und Antriebsabdeckung)	braccio orientabile (asse (C3)) con trasmissione e riparo	旋回アーム(駆動装置及び覆い付き)(C3 軸)	بازوی چرخان (با محرک و محافظ) (محور C3)
14	Planschleifspindel (...)	mandrino porta-mola a sfacciare (asse (C2))	端面研削といし軸((C2)軸)	اسپیندل پیشانی تراش (محور C2)
15	Planschleifscheibe	mola a sfacciare	端面研削といし	چرخ سنگ پیشانی تراش
16	Schwenkarmachse (...)	cannotto della mola a sfacciare (asse W)	端面研削用旋回・切込み軸(W 軸)	کوبیل چرخ سنگ پیشانی تراش (محور W)
17		asse B1	B1 軸	محور B1

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[2] ISO 841, *Industrial automation systems — Physical device control — Coordinate system and motion nomenclature*

[3] ISO/TR 16907, *Machine tools — Numerical compensation of geometric errors*

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Studying the influence of the machining process on the geometrical defects of the standardized S-shape test part

H. Chanal *, E. Duc, A. Chevalier

Université Clermont Auvergne, CNRS, Clermont Auvergne INP, Institut Pascal, F-63000, Clermont-Ferrand, France

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ABSTRACT

In 2020, an S-shape part was proposed as a 5-axis reception test part in the new version of ISO 10791–7:2020. This test part enables the testing of machine-tool behavior that involves a high variation in tool axis orientation. This test part is formed of an S-shape fillet which is machined in flank milling with an endmill of Ø20 mm. Any defects of the machined part are influenced by the accuracy of the CAD model, the CAM tool path computation, the measurement uncertainty of the free-formed surface by a coordinate measurement machine (CMM), and machine-tool geometric behavior. This article aims to quantify the influence of all these steps on the final defects of machined parts. The proposed conclusion to our work is based on analytical and numerical study and experimental analysis. Finally, we propose an identification process for machine-tool architecture geometrical defects pertaining to the measurement of the machined S-shape part.

1. Introduction

Continuous 5-axis machining enables the manufacture of parts with complex shapes and uses a cutting tool deployed across a number of industrial settings, such as mold making or aeronautics. Two machining modes are generally used: end machining with a cylindrical, toroidal, or hemispherical cutter; and flank machining with a cylindrical or conical cutter. The machined parts must meet cost and time requirements while machining a final geometry that conforms to the geometric specifications.

During the execution of a 5-axis machining operation, several classes of defects may influence the machined part [1,2]:

- #1 Geometrical defects due to positions of axes.
- #2 Defects of the guidance of the translation axes (roll, yaw, pitch).
- #3 Inverse transformation defects due to the direct and inverse kinematic models of the machine-tool.
- #4 Errors in the machining path calculation.
- #5 Tool path tracking errors due to the control loop performances of the axes.
- #6 Errors related to the rotation of the cutting tools during machining (spindle runout, tool bending, vibration, etc.).

The influence of thermal defects is not covered in this study.

The geometrical behavior measurement of machine tools is a critical issue, as it influences the geometrical conformity of the machined parts. The purpose of the acceptance or certification of a machine tool is to validate the ability of the machine tool to carry out machining operations in conformity, i.e., with the required accuracy. Several methods can be used to test a machine, depending on the defects to be evaluated:

- Static methods can be used to evaluate defects #1, #2, and #3 using for example lasers, ball bars, or linear scales [3];
- Kinematic methods ensure the evaluation of machine movement accuracy, to quantify, in addition, defect #5 using laser trackers, for example [4];
- Measurement of a machined part ensures an evaluation of the combination of all the defect classes. The machined part can be a test part which is standardized or not. A classical test part for 3-axis machining is introduced in the ISO standard [5].

The problem of defining machine-tool acceptance tests therefore comprises the quantifying of machine-tool accuracy in a configuration close to the future machining configuration. Static and kinematic methods are excellent for setting up machines and evaluating their intrinsic accuracy performance. Generally, they follow requirements defined by a particular standard. However, they do not evaluate the machine-tool behavior during machining; for example, they do not

* Corresponding author.
E-mail address: Helene.chanal@sigma-clermont.fr (H. Chanal).

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consider the influence of numerical controller behavior in the tool path following defect.

The problem of experimental error evaluation remains complex, and a number of studies are moving toward the implementation of better models for predicting these errors. In this vein, Shneor proposes a piece of software that evaluates the accuracy of a machine-tool for the purpose of 5-axis positional machining [6]. The kinematic model of a machine structure is used to calculate an error matrix. The proposed model can be used to modify a theoretical machining path and deduce the standard errors on the machined surface. The model developed is relatively simple and generic and does not consider the specific kinematic behavior of the machine.

The machining of a part reproduces a machining configuration but induces the appearance of defects #4 and #6. They may affect the quality of the machined part, making this quality a result of factors beyond geometric machine-tool behavior alone. Moreover, further defects can appear as a consequence, for example, of CAD modeling.

The literature proposes different studies for the definition of a test part. For example, Thiebaut defines a particular part for 3 axes free-form machining [7]. Wiessner et al. dedicate part of their study to the influence of machine-tool thermal deformations [8]. Florussen proposes the use of a torus-shaped test part with a hemispherical tool for evaluating the accuracy of the machine tool during machining [9]. This method can thus assess defects #1 to #5 while minimizing defect #6 because the machining load is reduced. In addition, the surface is geometrically simple to measure. On the other hand, the process is not faithful to the operations generally used on this type of machine tool.

To clarify the reception process, ISO offers a reception part to qualify 5-axis machine tools, introduced in the new version of ISO 10791–7:2020. This test part enables the testing of machine-tool behavior that involves a high variation in tool axis orientation [10]. This new part is called the S-shape test part. This test part is formed of an S-shape fillet and a rectangular base (Fig. 1) [11]. It is machined in flank milling with an endmill of Ø20 mm and generally manufactured from aluminum alloy raw material.

A number of recent studies have quantified the dynamic solicitation of each machine-tool axis [12–14]. Su compares the movement of the rotary axes of the NAS 979 test part (first piece defined in the standard to test a 5-axis machine-tool) and the S-shape test part [11]. This comparison shows an increase of the rotary axis acceleration load for the S-shape test part (Fig. 2). Thus, this S-shape test part aims to qualify the 5-axis geometrical behavior of a machine-tool and Numerical Controller (NC) behavior.

The fillet is composed of two free-form ruled surfaces A and B defined from fourth-order quasi-uniform rational B-splines (Fig. 1). The test result is therefore influenced by the accuracy of the CAD model, the CAM tool path computation, the measurement uncertainty of free form surface by a coordinate measurement machine (CMM), and the machine-tool geometric behavior [15]. Sato's first study investigates the influence of the CAM software and geometrical machine defects on machined S-shape part defects [16]. In Sato's work, the study of CAM software is limited to setting up trajectory computation tolerance.

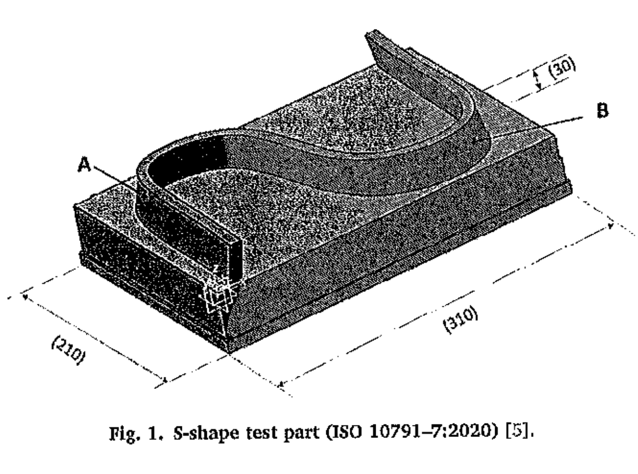

Fig. 1. S-shape test part (ISO 10791–7:2020) [5].

This paper therefore aims to study the influence of each step of the machining process on the part defect in order to improve the acceptance testing process of machine tools. The idea is to separate all geometrical defects occurring in the machining process including modeling parts, calculating the tool path, and the kinematic behavior of the machine tool. In so doing, by measuring the machined S-shape test part, we can be sure to identify the behavior that is detrimental to geometric quality.

After an introduction of the S-shape test part, a first analytical study is undertaken in order to identify overcut and undercut resulting from tool path computation. A second study shows the influence of CAM software with an analysis of the tool path computation process. In a third step, the influence of the kinematic behavior of the machine tool is studied. Finally, an S-shape test part is machined, and the measurement results are presented. In the light of both these measurements and the findings of previous studies, we propose correction actions to improve the accuracy of machining of part similar to S-shape test pieces. These correction actions should ensure the improvement of machine-tool accuracy during the 5-axis machining of free-form surfaces.

2. S-shape test part introduction with associated mathematical means

The two fillet surfaces machined in flank milling of the S-shape test part can be analytically described according to the standard model.

In the following, the geometry of the S-shape test part is introduced. Following this, we provide the definitions of the four fourth-order (cubic) quasi-uniform rational B-splines and the two ruled surfaces.

2.1. Geometrical S-shape test part definition

The S-shape test part is composed of two ruled surfaces. Each surface follows two fourth-order quasi-uniform rational B-splines. The table in Fig. 3 gives the control point positions for each fourth-order quasi-uniform rational B-spline used to define ruled surfaces A and B, as given in the ISO standard.

Each fourth-order quasi-uniform rational B-spline is computed according to the degree m (3 in this case), the set of weighted control points (Fig. 3), and the given knot vector. In this case, the knot vector is:

$$U=\left\{0,0,0,0,\frac{1}{13},\frac{2}{13},\frac{3}{13},\frac{4}{13},\frac{5}{13},\frac{6}{13},\frac{7}{13},\frac{8}{13},\frac{9}{13},\frac{10}{13},\frac{11}{13},\frac{12}{13},1,1,1,1\right\}$$
$$=\{u_1,u_2,u_3,u_4,u_5,u_6,u_7,u_8,u_9,u_{10},u_{11},u_{12},u_{13},u_{14},u_{15},u_{16},u_{17},u_{18},u_{19},u_{20}\}$$

The basic functions $N_{i,m}$ used to compute B-spline equations are then deduced from the recursion formula:

$$N_{i,0}(u)=\begin{cases}1 & \text{if } u_i\le u\le u_{i+1}\\ 0 & \text{otherwise}\end{cases}$$

And $N_{i,a}(u)=\frac{u-u_i}{u_{i+a}-u_i}N_{i,a-1}(u)+\frac{u_{i+a+1}-u}{u_{i+a+1}-u_{i+1}}N_{i+1,a-1}(u)$ for $a=1$ to m with $u\in[u_i,u_{i+1}]$.

Finally, for example, the B-spline curve with P_i control points can be computed from:

$$\mathbf{C_P}(u)=\sum_{i=0}^{n}N_{i,m}(u)\mathbf{P_i} \text{ with } n=15 \text{ and. } u\in[0,1]$$

In the standard, the ruled surface is computed from (Fig. 7):

$$\mathbf{S}(u,v)=(1-v)\times\mathbf{C_0}(u)+v\times\mathbf{C_1}(u)(u\in[0,1],v\in[0,1]) \tag{1}$$

where for surface A, $\mathbf{C_0}(u)=\mathbf{C_Q}(u)$ and $\mathbf{C_1}(u)=\mathbf{C_P}(u)$ and for surface B, $\mathbf{C_0}(u)=\mathbf{C_N}(u)$ and $\mathbf{C_1}(u)=\mathbf{C_M}(u)$.

Thus, the analytical definition of surfaces A and B is computed using equation (1). The machining tool path is derived from these two

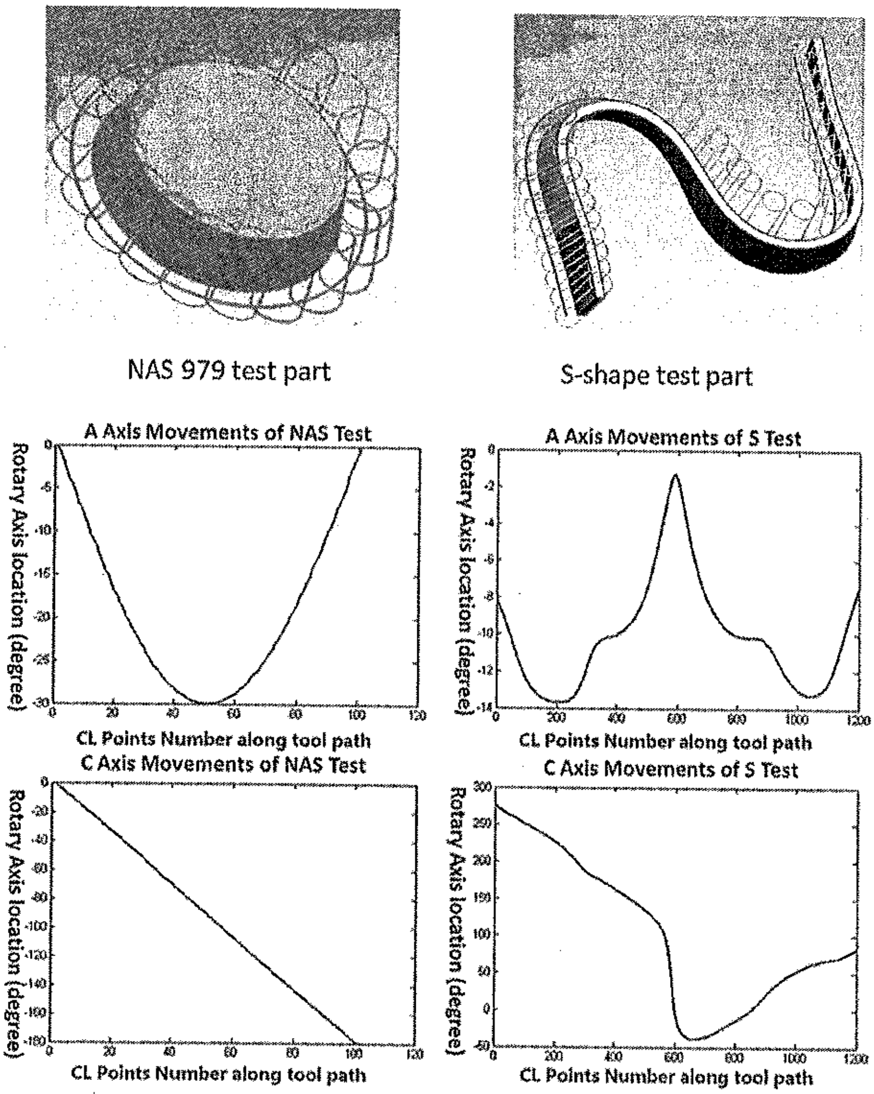

Fig. 2. Comparison of rotary axes of NAS 979 test piece and S-shape test piece [11].

surfaces. The measurement process of the S-shape test part is described in the ISO standard.

The measurement of the S-shape part is realized in a hundred given points distributed equally on four curves. Two curves are located on surface A and two curves are located on surface B at two different heights 11 mm (named BOTTOM curve) and 25 mm (named TOP curve) (Fig. 4).

In the following, we discuss the impact of the geometrical definition of the S-shape test part on the machining of these surfaces.

2.2. Curve and ruled surface definition in a CAD software

A curve is an application that associates a parameter value to a 3D point. Each S-shape test part surface is defined from an upper curve and a lower curve. Each curve is defined from a fourth-order quasi-uniform rational B-spline. The quasi-uniform knot sequence indicates the structure of the curve setting. This point is particularly critical as it will impact the orientation of the tools and therefore the geometric quality of the machined surface. Traditionally, two types of setting exist: the setting on the curvilinear abscissa (i.e., all along the curve, the parameter is equal to the length ratio from the beginning of the curve, $u = 0.5$ = middle of the curve) and the quasi-uniform setting.

Mathematically, a ruled surface is calculated by connecting a point on the upper curve to a point on the lower curve which has the same parameter (Fig. 7). In CAD software, a ruled surface is constructed by connecting a point on the upper curve to a point on the lower curve. As the two curves are independent, there is not necessarily consistency between the settings of these two curves. Therefore, CAD systems tend to compute point pairs according to a geometric method and not according to the curve setting. The fundamental issue is that curve setting is not always specifiable in CAD software. Thus, the same curve definition can lead to different curve shapes according to the particular CAD software in use.

Fig. 5 shows an example of ruled surface computation from the same two curves. The two computed surfaces S1 and S2 are different as the straight line generatrix orientation evolves strongly.

In the context of S-shape test part machining, the exact definition of the surfaces and the deduced orientation of the tool play a key role in the accuracy of the surface model. Indeed, a defect in tool axis orientation leads to a machining defect. To avoid the impact of CAD software, ISO experts choose to attach to ISO 10791–7:2020 a.stp file that defines S-shape part geometry. In the following study, we base our analysis on the analytical definition of the surfaces.

a) Control points of ruled surface A

P_i	POS_X	POS_Y	POS_Z
P_0	-131	-95.5	30
P_1	-126	-41	30
P_2	-131	23	30
P_3	-116	78	30
P_4	-51	77	30
P_5	-20	46	30
P_6	-11	10	30
P_7	-9	2	30
P_8	-7	-6	30
P_9	-5	-14	30
P_{10}	3	-46	30
P_{11}	32	-80	30
P_{12}	103	-81	30
P_{13}	116	-13	30
P_{14}	110	43	30
P_{15}	115	99.5	30

Q_i	POS_X	POS_Y	POS_Z
Q_0	-137	-95.5	0
Q_1	-134	-41	0
Q_2	-138	23	0
Q_3	-118	87	0
Q_4	-49	84	0
Q_5	-23	58	0
Q_6	-11	10	0
Q_7	-9	2	0
Q_8	-7	-6	0
Q_9	-5	-14	0
Q_{10}	3	-46	0
Q_{11}	36	-88	0
Q_{12}	111	-84	0
Q_{13}	119	-13	0
Q_{14}	118	43	0
Q_{15}	121	99.5	0

b) Control points of ruled surface B

M_i	POS_X	POS_Y	POS_Z
M_0	-121	-95.5	30
M_1	-117	-29	30
M_2	-121	30	30
M_3	-107	68	30
M_4	-62	67	30
M_5	-31	48	30
M_6	-22	12	30
M_7	-20	4	30
M_8	-18	-4	30
M_9	-16	-12	30
M_{10}	-7	-48	30
M_{11}	26	-88	30
M_{12}	95	-91	30
M_{13}	129	-42	30
M_{14}	118	28	30
M_{15}	125	99.5	30

N_i	POS_X	POS_Y	POS_Z
N_0	-127	-95.5	0
N_1	-124	-29	0
N_2	-128	30	0
N_3	-108	76	0
N_4	-62	74	0
N_5	-33	56	0
N_6	-22	12	0
N_7	-20	4	0
N_8	-18	-4	0
N_9	-16	-12	0
N_{10}	-7	-48	0
N_{11}	30	-95	0
N_{12}	100	-97	0
N_{13}	132	-46	0
N_{14}	127	27	0
N_{15}	131	99.5	0

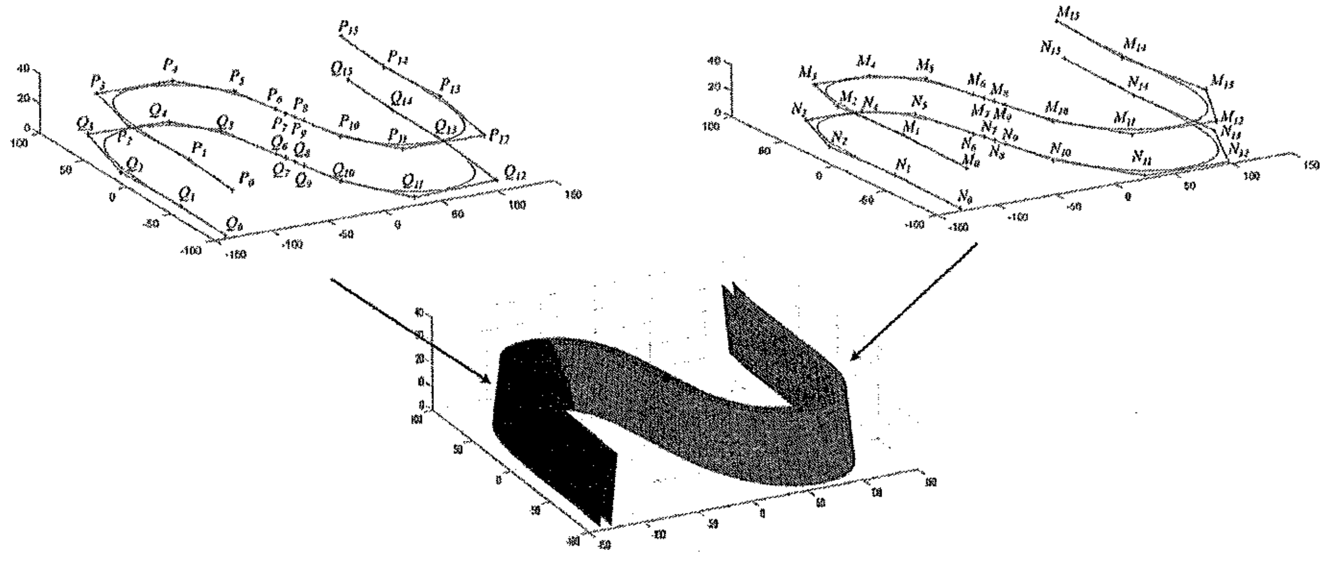

Fig. 3. Definition of S-shape part geometry [5].

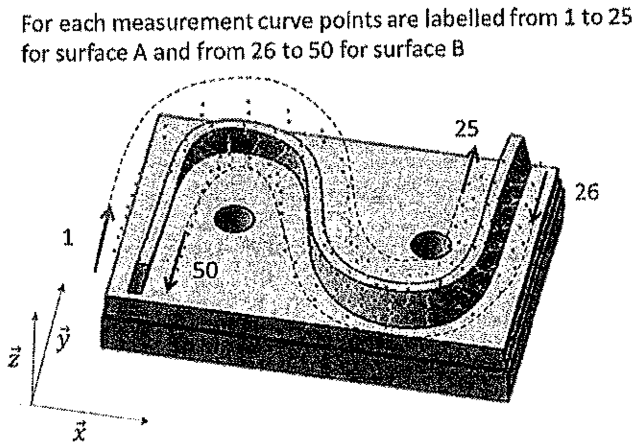

Fig. 4. Measured points on S-shape test part.

3. Undercut and overcut for non-developable ruled surfaces

A number of studies research tool path computation for non-developable ruled surfaces, particularly in the aeronautical context [17–19]. The main problem of 5-axis flank milling concerns the contact line between the tool and the surface. The presence of a non-zero twist angle makes it impossible to define a machining tool path by the flank allowing the nominal surface to be machined without "overcut" or "undercut" (Fig. 6).

3.1. *Flank tangent position of a tool on a surface - undercut and overcut*

The issue of computing the tool position tangent to a surface is complex. The contact is not punctual, but rather as a curve along the tool flank [17]. Only developable ruled surfaces can be machined precisely by a cylindrical or conical tool because the contact curve is equal to a line. Non-developable ruled surfaces lead to interferences between the tool and the part surface which lead to overcut and undercut [19].

To quantify overcut and undercut, a first computation of the theoretical tool path is realized with a strict application of equation (1). Several vectors are defined from the S-shape test part (Fig. 7):

- $\mathbf{R}(u)$ is a normalized vector as $\mathbf{R}(u) = \frac{\mathbf{C}_1(u)-\mathbf{C}_0(u)}{\|\mathbf{C}_1(u)-\mathbf{C}_0(u)\|}$. $\mathbf{R}(u)$ is along a straight line generatrix of the surface.
- $\mathbf{T}(u,v)$ is the tangent vector of a $\mathbf{S}(u,v)$ curve obtained for a constant v and a variable parameter u. $\mathbf{T}(u,v)$ is therefore perpendicular to $\mathbf{R}(u)$ and can be computed as: $\mathbf{T}(u,v) = \frac{\frac{d\mathbf{S}(u,v)}{du}}{\|\frac{d\mathbf{S}(u,v)}{du}\|}$ avec $\frac{d\mathbf{S}(u,v)}{du} = (1-v)\frac{d\mathbf{C}_0(u)}{du} + v\frac{d\mathbf{C}_1(u)}{du}$. Note that $\frac{d\mathbf{C}_k(u)}{du} = \sum_{i=0}^{n}\frac{dN_{i,m}(u)}{du}\mathbf{P}_i$.
- $\mathbf{N}(u,v)$ is defined as $\mathbf{N}(u,v) = \pm\mathbf{R}(u)\times\mathbf{T}(u,v)$ to be oriented toward the outside of the part.

The tool path computation is realized from the assumption that the tool is guided by the curve $\mathbf{C}_0(u)$ and $\mathbf{C}_1(u)$. The axial position of the tool is given by curve $\mathbf{C}_1(u)$ as we consider that the tool section is always in contact with $\mathbf{C}_1(u)$. The tool radius $R_{tool} = 10$ mm and the tool length $L_{tool} = 35$ mm. Thus, the tool path equation is:

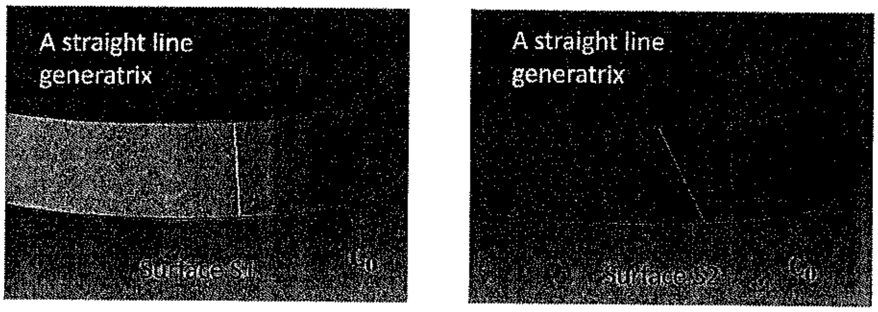

Fig. 5. Variation of a straight line generatrix according to surface computation method S1 (Left) & S2 (right).

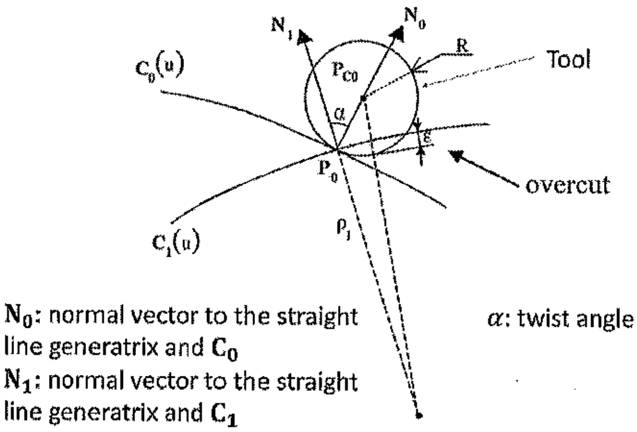

Fig. 6. Definition of "overcut" [19].

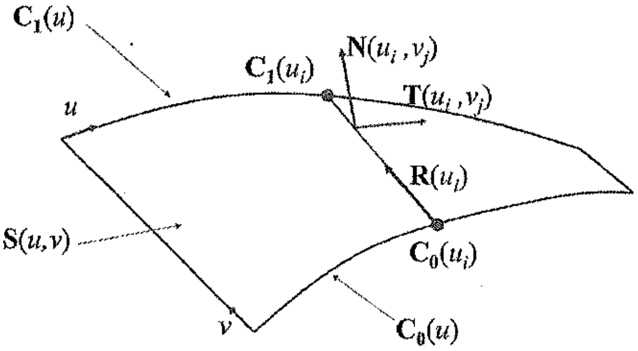

Fig. 7. Vector definition to compute analytical tool path.

$$\mathbf{T}_{tool}(u) = \mathbf{C}_1(u) + R_{tool}\mathbf{N}(u,1) - L_{tool}\mathbf{R}(u) \tag{2}$$

Thus, $\mathbf{R}(u)$ is the tool axis orientation.

The machined surface is the tool envelope surface during the movement along the path [17]. The tool envelope surface can be computed from the property that a point M of the tool belongs to the envelope surface if the normal $\mathbf{n}_M$ to the tool surface at M is perpendicular to the speed of the point M:

$$\mathbf{V}_{M\in tool/0} \cdot \mathbf{n}_M = 0 \tag{3}$$

As the tool is cylindrical, $\mathbf{n}_M$ is always perpendicular to the tool axis (Fig. 8).

However,

$$\mathbf{V}_{M\in tool/0} = \left(\frac{d\mathbf{OM}}{dt}\right)_0 = \left(\frac{d\mathbf{OE}}{dt}\right)_0 + \boldsymbol{\Omega} \times (h\mathbf{w} + R_{tool}\mathbf{n}_M) \tag{4}$$

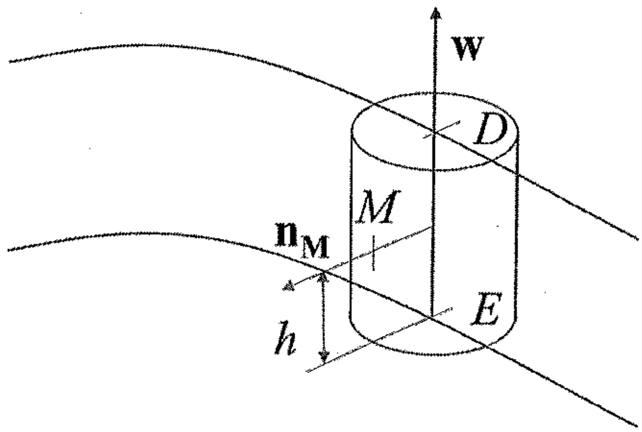

Fig. 8. Tool envelope surface computation.

where O is the center of a fixed coordinate system, E is the tool control point, $\mathbf{OE}$ is the vector from O to E, $\boldsymbol{\Omega}$ is the instantaneous rotation speed of tool axis as $\boldsymbol{\Omega} \times \mathbf{w} = \frac{d\mathbf{w}}{dt}$, $\mathbf{w}$ is the unit vector of the tool axis, h is the height of point M and R_{tool} is the tool radius.

In our case study, $\mathbf{OE} = \mathbf{T}_{tool}(u)$ and $\mathbf{w} = \mathbf{R}(u)$.

Thus, the point M, which belongs to the tool surface envelop, is given by the following equation according to the S-shape test part setting and equation (4):

$$\frac{d\mathbf{T}_{tool}(u)}{du} \cdot \mathbf{n}_M + h\frac{d\mathbf{R}(u)}{du} \cdot \mathbf{n}_M = 0 \tag{5}$$

To solve equation (5), as $\mathbf{n}_M$ is perpendicular to $\mathbf{R}(u)$, it can be written as $\mathbf{n}_M(u,h) = \cos(\theta(u,h))\mathbf{T}(u,1) + \sin(\theta(u,h))\mathbf{N}(u,1)$. Thus, a point M belongs to the tool surface envelope if:

$$\tan(\theta(u,h)) = \pm\frac{\frac{d\mathbf{T}_{tool}(u)}{du} \cdot \mathbf{T}(u,1) + h\frac{d\mathbf{R}(u)}{du} \cdot \mathbf{T}(u,1)}{\frac{d\mathbf{T}_{tool}(u)}{du} \cdot \mathbf{N}(u,1) + h\frac{d\mathbf{R}(u)}{du} \cdot \mathbf{N}(u,1)}$$

Overcut values are then computed from:

$$Overcut(u,h) = R_{tool}(1 - \sin(\theta(u,h))) \tag{6}$$

Fig. 9 shows the overcut on surface A and surface B (the two sides of the S-shape test part (Fig. 3)). A maximum of 0.0387 mm is visualized for surface A and 0.0125 mm for surface B. Such errors should not be blamed on the machine tool. Note that these values are important but lower than the surface profile tolerance of 0.12 mm defined in the standard.

3.2. Influence of the tool radius defect

The tool path is computed from a tool diameter of 20 mm. However, the real tool diameter is not strictly 20 mm. From equation (6), the

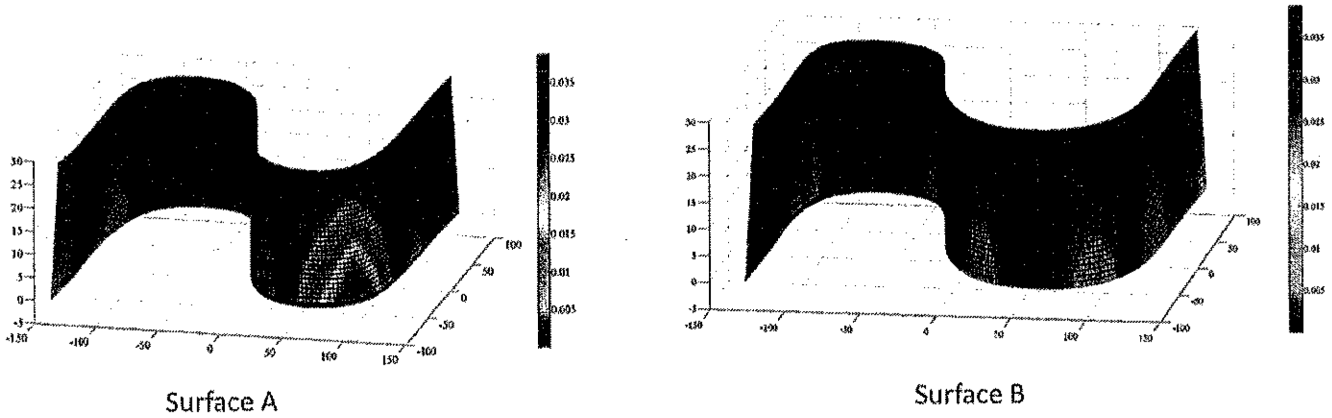

Fig. 9. Overcut computation for surface A and surface B of S-shape test part.

defect produced on the machined surface due to the tool radius defect can be computed:

$$Def_{tool}(u,h) = \left(R'_{tool} - R_{tool}\right)\sin(\theta(u,h))$$

where R'_{tool} is the real tool radius. Fig. 10 illustrates the defect due to a tool radius defect of −0.01 mm. The defect produced on the machined surface is close to the tool radius defect.

4. Influence of S-part tool path computation

4.1. Tool path computation

A number of studies have researched how to modify the tool path to decrease the extent of undercut and overcut [20,21].

Castagnetti proposes a method of tool path smoothing that can be used in flank milling [22]. A first path is calculated and transformed in the machine coordinate system. For each position, an envelope is also calculated in the machine coordinate system to ensure that tolerances are maintained. Then a new tool path is calculated by minimizing the acceleration variations under the constraints of respecting the envelopes.

The latest methods currently being developed are based on a surface approach that allows tool paths to be smoothed. Path optimization is

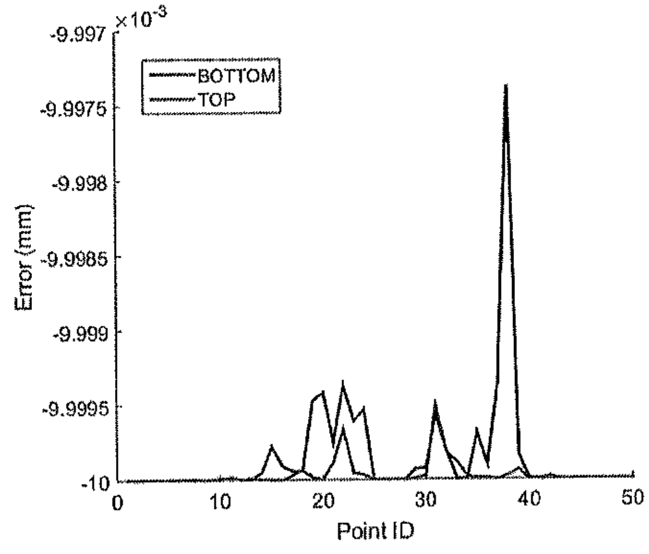

Fig. 10. Geometric defect due to a tool radius defect of 0.01 mm.

performed by controlling the distance between the path envelope surface and the surface to be machined. For example, Bo calculates the envelope of a tool of any shape and compares it to the local second-order approximation of the surface to obtain the most favorable directions [23]. The integration of these directions allows tool paths to be calculated.

During machining, adapting the feed rate is also a method of reducing kinematic errors. For example, Chu reduces the errors associated with linear interpolation in the case of flank machining [24]. The author calculates the envelope surface of the tool path and estimates the error induced. He then reduces the feed rate until the error is less than a given tolerance.

These studies involve the implementation of complex computing outside of the CAM environment. However, it is important to propose a method that can be carried out in a CAM environment to allow a large number of manufacturers to achieve this type of test while mastering overcut and undercut without the need for complex numerical computation. In CAM systems, the most robust solution is to calculate the position of the tool tangent to the bottom curve. In a second step, the tool is oriented according to the isoparametric curve or the main direction (Fig. 11).

In this case, the straight line generatrix distribution plays a very important role in the occurrence of interference. Indeed, the angle between vectors normal to the surface along the contact line has more or less twist angle which generates more or less interference (Fig. 6). In the following figure, the steeply inclined straight line generatrix (surface S2) produces an interference of 0.037 mm, whereas it is zero for surface S1 (Fig. 11).

In this paper, four part programs are calculated from the original surfaces, using a conventional CAM system, as in an industrial process of machine tool acceptance. The calculation algorithm and the calculation parameters are identical:

- Tool diameter: 20 mm
- Machining tolerance: 0.002 mm
- Distance between points: 0.5 mm

The path calculation algorithm computes the position of the tool tangent to a curve or to both curves and orients the tool according to the isoparametric curve of the tangent surface.

The first program TP1S1 is based on the S1 surface and is computed to be tangential to the top curve to be consistent with the tool path computed in section 3.1. The second TP2S2 is based on the S2 surface which is computed with a different straight line generatrix distribution. For the third program TP3CR, the intersection curves between the surfaces and two planes located at Z11 and Z25 are calculated (Fig. 12). These new curves are used to calculate the tangent position of the tool.

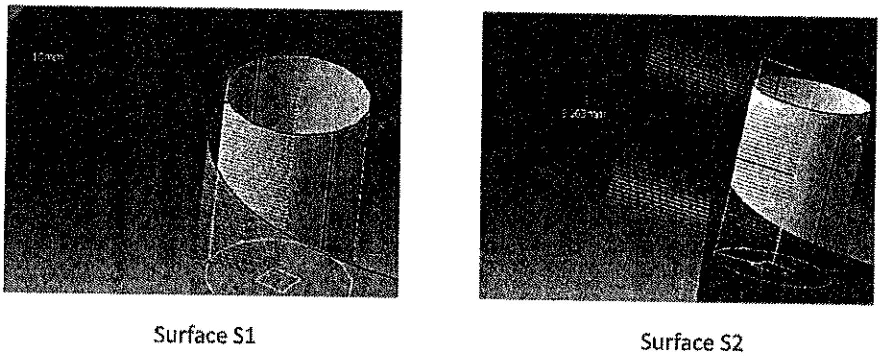

Fig. 11. Interference apparition according to the straight line generatrix inclination on surface S1 & S2.

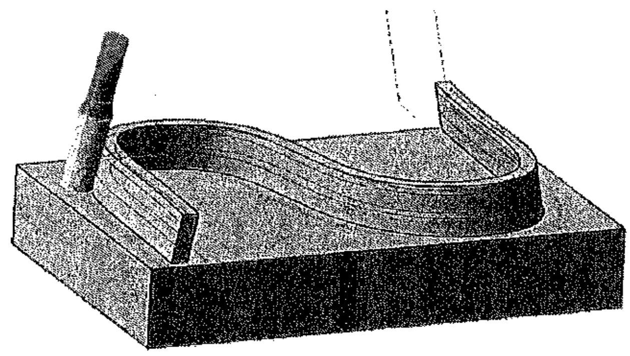

Fig. 12. Extracted curves for defining TP3CR.

Note, that these two curves pass through all the measurement points defined in the standard. The tool axis is oriented along the isoparametric curve of the surface. The TP4S1 path is based on surface 1 and the bottom of the part. The tool is oriented along the isoparametric curve of the surface. The contact is located 11 mm from the tool tip along the tool axis.

The comparison of the calculated tool paths is based on the calculation of the geometric deviations at the measurement points specified by the standard (Fig. 12). For each point P_s, a vector $\mathbf{n}_s$ is computed regarding the normal to the surface. The vector is oriented outwards from the surface and defines a line (n_s). The tool path is discretized with a step less than 0.1 mm. The intersection is calculated between each line (n_s) and each tool position defined by the tool tip and the axis of the tool. The smallest abscissa along the straight line (n_s) of all existing intersections is retained. This calculation follows an opposite approach to the calculation of the envelope area. In Fig. 13, the line (n_s) is printed in orange, both intersection points are represented in cyan.

The discretization of the tool path induces an error in the calculation of the geometrical deviation according to equation (7). Equation (7) is the taylor expension of the chord error equation [25]. A discretization *step* of less than 0.1 mm results in an *error* of less than 0.000125 mm.

$$error \approx step^2 / 8R_{tool} \quad (7)$$

The method presents the advantage of being independent of a CAD environment and does not use surface definitions. The error computation is directly linked to the standard points. Then again, estimating deviations can be greater because the distance is computed between two points projected in one direction and not between a point projected on a surface.

Fig. 14 presents geometric deviation for the 4 proposed tool paths. Geometrical deviations are computed for the measurement curves. The TOP curve is located at Z25, and the BOTTOM curve is located at Z11. Fig. 14 illustrates the position of maximal geometrical deviations on the

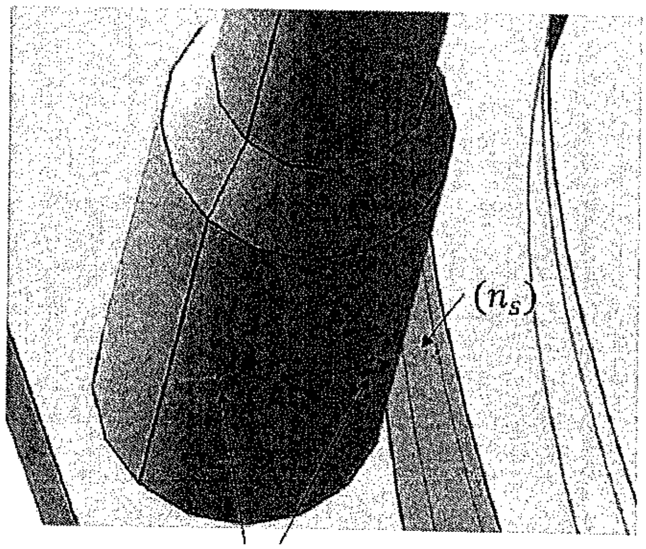

Fig. 13. Geometrical deviation calculation.

tool paths TP1S1 and TP2S2. In these figures, all tool positions are merged to illustrate the tool movement.

The computed geometrical deviation for TP1S1 is close to the one computed in Fig. 9 as the main difference is the discretization of the TP1S1 tool path. In the case of TP2S2, the straight line generatrix distribution used to compute the surface S2 is modified which modified the orientation of the tool axis and increase the overcut value (Fig. 11). For TP3CR, the use of the two curves which pass through the measurement points allows decreasing the measure of defect due to interference. In the case of TP4S1, the tool path computation is realized to be tangential to a curve close to one of the measure curves, thus the measurement of the defect due to interference decreases too.

Despite the tool path accuracy, the geometrical deviations can reach 0.01 mm in the best case, which is an significant value compared to the tolerance expected by the standard (0.12 mm). The TP3CR path, computed from two curves, reduces the value of the geometric deviations to a maximum acceptable value of 0.005 mm.

The analysis shows that in the TP2S2 case, the particular orientation of the isoparametric curve induces very significant errors incompatible with the specifications of the standard. The accuracy of TP4S1 is better than TP1S1 because the computed tool path reduces great variation in tool orientation. Thus, the construction of the surface and the

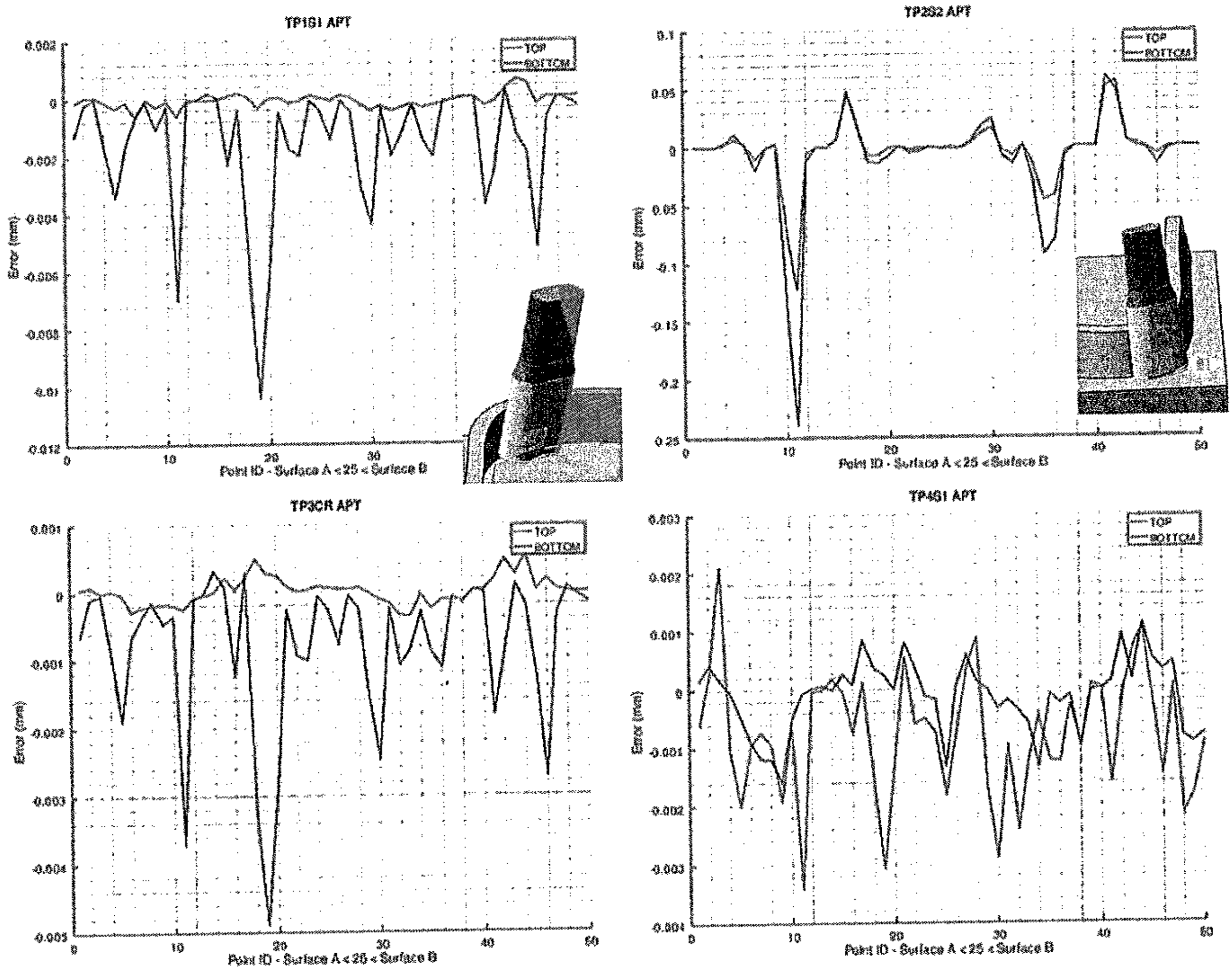

Fig. 14. Geometrical deviation results.

calculation of the tool path play a significant role in the accuracy of the surface. Geometrical deviations affect the quality of the machined surface and it is necessary to separate the errors to identify only machine-related errors.

4.2. *B-spline tool path computation*

Numerical controls currently offer two interesting features: polynomial interpolation; and space correction of the tool geometry. Thus, it is possible to calculate the tool path without using a CAM system. The problem of calculating the tangent position of the tool and the orientation of the tool axis is directly dealt with by the numerical control without any a priori control.

For the Siemens 840D CNC, using the CUT3DC function gives the program named TP5C1 (Table 1).

It is also possible to calculate mathematically, using equation (1), the equations of the two measurement curves located at Z11 and Z25 (program TP6C2). The equations of these curves are exact and there are no approximations. The program of Table 2 is obtained.

These two programs present the opportunity to preclude the defect induced by CAM software. To respect the classical numerical chains, we choose to machine and to measure a part with the TP4S1 tool paths.

5. Defect due to machine-tool kinematic behavior

This test part aims to evaluate the behavior of machine-tools during 5-axis machining. It is therefore important to study the impact of the machine-tool on the machining defect regarding CAM tool path computation.

In this section, we begin by assessing the impact of tool path computation realized by the numerical controller. We then discuss the impact of inverse transformation errors.

5.1. *Geometrical defect due to numerical controller*

The next step concerns the behavior of the machine tool without real machining, i.e., assessing defects due to the numerical controller. The objective is to capture the control tool positions during movements to calculate the associated geometrical deviations. The latest version of the Siemens 840D numerical controller ensures the position of the 5 axes to be captured in the Work Coordinate System (WCS) (i.e., part programming coordinate). The sampling period is 0.008 s. Geometrical deviations are calculated using the same algorithm as in section 4. Fig. 15 gives the geometric deviation extract from the numerical controller for the calculated path for the 4 calculated paths. These figures illustrate the geometrical processing of the path performed by the NC manager during tool movement. The processing includes corrections related to the

Table 1
Program TP5C1.

ORICURVE								
G1	G42							
	X-137	Y-95.5	Z0	XH = −131	YH = −95.5	ZH = 30		
BSPLINE SD = 3								
	X-134	Y-41	Z0	XH = −126	YH = −41	ZH = 30	PL = 0	
	X-138	Y23	Z0	XH = −131	YH = 23	ZH = 30	PL = 51.4077	;arc1
	X-118	Y87	Z0	XH = −116	YH = 78	ZH = 30	PL = 51.4077	;arc2
	X-49	Y84	Z0	XH = −51	YH = 77	ZH = 30	PL = 51.4077	;arc3
	X-23	Y58	Z0	XH = −20	YH = 46	ZH = 30	PL = 51.4077	;arc4
	X-11	Y10	Z0	XH = −11	YH = 10	ZH = 30	PL = 51.4077	;arc5
	X-9	Y2	Z0	XH = −9	YH = 2	ZH = 30	PL = 51.4077	;arc6
	X-7	Y-6	Z0	XH = −7	YH = −6	ZH = 30	PL = 51.4077	;arc7
	X-5	Y-14	Z0	XH = −5	YH = −14	ZH = 30	PL = 51.4077	;arc8
	X3	Y-46	Z0	XH = 3	YH = −46	ZH = 30	PL = 51.4077	;arc9
	X36	Y-88	Z0	XH = 32	YH = −80	ZH = 30	PL = 51.4077	;arc10
	X111	Y-84	Z0	XH = 103	YH = −81	ZH = 30	PL = 51.4077	;arc11
	X119	Y-13	Z0	XH = 116	YH = −13	ZH = 30	PL = 51.4077	;arc12
	X118	Y43	Z0	XH = 110	YH = 43	ZH = 30	PL = 51.4077	;arc13
	X121	Y99.5	Z0	XH = 115	YH = 99.5	ZH = 30	PL = 0	
ORICURVE								
G1	X-127	Y-95.5	Z0	XH = −121	YH = −95.5	ZH = 30		
BSPLINE SD = 3								
	X-124	Y-29	Z0	XH = −117	YH = −29	ZH = 30	PL = 0	
	X-128	Y30	Z0	XH = −121	YH = 30	ZH = 30	PL = 51.2397	;arc1
	X-108	Y76	Z0	XH = −107	YH = 68	ZH = 30	PL = 51.2397	;arc2
	X-62	Y74	Z0	XH = −62	YH = 67	ZH = 30	PL = 51.2397	;arc3
	X-33	Y56	Z0	XH = −31	YH = 48	ZH = 30	PL = 51.2397	;arc4
	X-22	Y12	Z0	XH = −22	YH = 12	ZH = 30	PL = 51.2397	;arc5
	X-20	Y4	Z0	XH = −20	YH = 4	ZH = 30	PL = 51.2397	;arc6
	X-18	Y-4	Z0	XH = −18	YH = −4	ZH = 30	PL = 51.2397	;arc7
	X-16	Y-12	Z0	XH = −16	YH = −12	ZH = 30	PL = 51.2397	;arc8
	X-7	Y-48	Z0	XH = −7	YH = −48	ZH = 30	PL = 51.2397	;arc9
	X30	Y-95	Z0	XH = 26	YH = −88	ZH = 30	PL = 51.2397	;arc10
	X100	Y-97	Z0	XH = 95	YH = −91	ZH = 30	PL = 51.2397	;arc11
	X132	Y-46	Z0	XH = 129	YH = −42	ZH = 30	PL = 51.2397	;arc12
	X127	Y27	Z0	XH = 118	YH = 28	ZH = 30	PL = 51.2397	;arc13
	X131	Y99.5	Z0	XH = 125	YH = 99.5	ZH = 30	PL = 0	

kinematic solicitations, corrections related to the geometrical model of the inverse kinematic transformation according to the selected model.

TP1S1, TP3CR, and TP4S1 deviations are very similar. The kinematic behavior of the machine tool is predominant compared to the error profile generated by the tool path. By contrast, in the case of TP2S2, the kinematic error profile is very close to the geometrical error profile. In this case, the error of the tool path calculation is predominant.

The behavior of the machine-tool numerical controller can reach 0.034 mm. It is predominant compared to the error profile generated by the tool path computed by CAM software.

Programs TP5C1 and TP6C2 are also tested. The kinematic behavior of these programs is measured on the machine with the following setting of Cycle 832 (Sinumerik 840D): Ori_Finish, path tolerance = 0.03 mm, angle orientation tolerance = 0.5° (Fig. 16).

A second test is performed on the machine with the following Cycle 832 setting: Ori_Finish, path tolerance = 0.001 mm, angle orientation tolerance = 0.01°.

Although the curves describe the S-shape surfaces more accurately, there are significant errors on the tool path following of the TOP curve (at points 14 and 43 for program TP5C1, and at point 10 for program TP6C2). It is therefore a tool orientation error, the calculation of which does not seem to be handled perfectly by the numerical control. Whatever the method used, it is necessary to determine the position and orientation of the tool tangent to the attempted surface. For programs TP5C1 and TP6C2 we cannot control the accuracy of the numerical calculation algorithms realized by the numerical controller.

5.2. *Geometrical defect due to inverse transformation errors*

Five-axis machine-tools are controlled with a kinematic model. This kinematic model enables the computation of the machine-tool tool path regarding attempted tool path in WCS. Thus, errors in this model lead to defects in the machining part. Moreover, this model should be consistent with the machine-tool geometric defect.

In this study, the part is machined on Five Machining Flexiax V. This machine-tool has a rotating table around C-axis and a rotating head around B-axis (Fig. 17). (x,y,z) and (i,j,k) are the tool center point and tool axis coordinates in the table coordinate system $(\vec{x}_p, \vec{y}_p, \vec{z}_p)$. (X,Y,Z,B,C) are the axis values. L_0 is the distance between the rotation axis B and the tool center point. $(\vec{x}_T, \vec{y}_T, \vec{z}_T)$ is the tool coordinate system.

The nominal kinematic model can be computed according to transformation matrices from equation (8) [26].

$$ {}^{O}T_X\,{}^{X}T_Z\,{}^{Z}T_B\,{}^{B}T_T \begin{bmatrix} 0\\0\\0\\1 \end{bmatrix} = {}^{O}T_Y\,{}^{Y}T_C \begin{bmatrix} x\\y\\z\\1 \end{bmatrix} \tag{8} $$

where ${}^{O}T_X = \begin{bmatrix} 1&0&0&X\\0&1&0&0\\0&0&1&0\\0&0&0&1 \end{bmatrix}$, ${}^{X}T_Z = \begin{bmatrix} 1&0&0&0\\0&1&0&0\\0&0&1&Z\\0&0&0&1 \end{bmatrix}$, ${}^{Z}T_B = \begin{bmatrix} \cos(B)&0&\sin(B)&0\\0&1&0&0\\-\sin(B)&0&\cos(B)&0\\0&0&0&1 \end{bmatrix}$, ${}^{B}T_T = \begin{bmatrix} 1&0&0&0\\0&1&0&0\\0&0&1&-L_0\\0&0&0&1 \end{bmatrix}$, ${}^{O}T_Y = \begin{bmatrix} 1&0&0&0\\0&1&0&-Y\\0&0&1&0\\0&0&0&1 \end{bmatrix}$, ${}^{Y}T_C = \begin{bmatrix} \cos(C)&\sin(C)&0&0\\ \sin(C)&\cos(C)&0&0\\0&0&1&0\\0&0&0&1 \end{bmatrix}$.

Table 2
Program TP6C2.

ORICURVE								
G1	G42							
	X-134.8	Y-95.5	Z11	XH = −132	YH = −95.5	ZH = 25		
BSPLINE SD = 3								
	X-131.067	Y-41	Z11	XH = −127.333	YH = −41	ZH = 25	PL = 0	
	X-135.433	Y23	Z11	XH = −132.167	YH = 23	ZH = 25	PL = 51.4077	;arc1
	X-117.267	Y83.7	Z11	XH = −116.333	YH = 79.5	ZH = 25	PL = 51.4077	;arc2
	X-49.733	Y81.433	Z11	XH = −50.667	YH = 78.167	ZH = 25	PL = 51.4077	;arc3
	X-21.9	Y53.6	Z11	XH = −20.5	YH = 46	ZH = 25	PL = 51.4077	;arc4
	X-11	Y10	Z11	XH = −11	YH = 10	ZH = 25	PL = 51.4077	;arc5
	X-9	Y2	Z11	XH = −9	YH = 2	ZH = 25	PL = 51.4077	;arc6
	X-7	Y-6	Z11	XH = −7	YH = −6	ZH = 25	PL = 51.4077	;arc7
	X-5	Y-14	Z11	XH = −5	YH = −14	ZH = 25	PL = 51.4077	;arc8
	X3	Y-46	Z11	XH = 3	YH = −46	ZH = 25	PL = 51.4077	;arc9
	X34.533	Y-85.067	Z11	XH = 32.667	YH = −81.333	ZH = 25	PL = 51.4077	;arc10
	X108.067	Y-82.9	Z11	XH = 104.334	YH = −81.5	ZH = 25	PL = 51.4077	;arc11
	X117.9	Y-13	Z11	XH = 116.5	YH = −13	ZH = 25	PL = 51.4077	;arc12
	X115.067	Y43	Z11	XH = 111.333	YH = 43	ZH = 25	PL = 51.4077	;arc13
	X118.8	Y99.5	Z11	XH = 116	YH = 99.5	ZH = 25	PL = 0	
ORICURVE								
G1	X-124.8	Y-95.5	Z11	XH = −122	YH = −95.5	ZH = 25		
BSPLINE SD = 3								
	X-121.433	Y-29	Z11	XH = −118.167	YH = −29	ZH = 25	PL = 0	
	X-125.433	Y30	Z11	XH = −122.167	YH = 30	ZH = 25	PL = 51.2397	;arc1
	X-107.633	Y73.067	Z11	XH = −107.167	YH = 69.333	ZH = 25	PL = 51.2397	;arc2
	X-62	Y71.433	Z11	XH = −62	YH = 68.167	ZH = 25	PL = 51.2397	;arc3
	X-32.267	Y53.067	Z11	XH = −31.333	YH = 49.333	ZH = 25	PL = 51.2397	;arc4
	X-22	Y12	Z11	XH = −22	YH = 12	ZH = 25	PL = 51.2397	;arc5
	X-20	Y4	Z11	XH = −20	YH = 4	ZH = 25	PL = 51.2397	;arc6
	X-18	Y-4	Z11	XH = −18	YH = −4	ZH = 25	PL = 51.2397	;arc7
	X-16	Y-12	Z11	XH = −16	YH = −12	ZH = 25	PL = 51.2397	;arc8
	X-7	Y-48	Z11	XH = −7	YH = −48	ZH = 25	PL = 51.2397	;arc9
	X28.533	Y-92.433	Z11	XH = 26.667	YH = −89.167	ZH = 25	PL = 51.2397	;arc10
	X98.167	Y-94.8	Z11	XH = 95.833	YH = −92	ZH = 25	PL = 51.2397	;arc11
	X130.9	Y-44.533	Z11	XH = 129.5	YH = −42.667	ZH = 25	PL = 51.2397	;arc12
	X123.7	Y27.367	Z11	XH = 119.5	YH = 27.834	ZH = 25	PL = 51.2397	;arc13
	X128.8	Y99.5	Z11	XH = 126	YH = 99.5	ZH = 25	PL = 0	
G1								

Thus, the direct and inverse nominal kinematic models are given by:

$$\begin{cases} x = Xcos(C) + Ysin(C) - L_o\cos(C)\sin(B) \\ y = -Xsin(C) + Ycos(C) + L_0\sin(B)\sin(C) \\ z = Z - L_0\cos(B) \end{cases} \tag{9}$$

With $\tan(C) = -\frac{j}{i}$ and $\tan(B) = \frac{\sqrt{i^2+j^2}}{k}$.

Thus, the articular nominal tool path necessary to machine the S-shape test part can be computed from equation (9) as:

$$\mathbf{X_{tool}}(\mathbf{u}) = \begin{bmatrix} X_{tool}(u) \\ Y_{tool}(u) \\ Z_{tool}(u) \end{bmatrix} = \begin{bmatrix} cos(C_{tool}(u)) & -\sin(C_{tool}(u)) & 0 \\ \sin(C_{tool}(u)) & \cos(C_{tool}(u)) & 0 \\ 0 & 0 & 1 \end{bmatrix} \mathbf{T_{tool}}(u) + \begin{bmatrix} L_0\sin(B_{tool}(u)) \\ 0 \\ L_0\cos(B_{tool}(u)) \end{bmatrix}. \tag{10}$$

With $\tan(C_{tool}(u)) = -\frac{R(u)\cdot\overrightarrow{y_p}}{R(u)\cdot\overrightarrow{x_p}}$ and $\tan(B_{tool}(u)) = \frac{\sqrt{(R(u)\cdot\overrightarrow{x_p})^2+(R(u)\cdot\overrightarrow{y_p})^2}}{R(u)\cdot\overrightarrow{z_p}}$.

In ISO 230–1, several defects are introduced in order to qualify machine-tool geometric accuracy [2]. Errors are of different natures: errors of the zero position of linear and rotary axes, positioning errors along the direction of motion, straightness errors of translation motion, and angular motion errors. In this study, we focus on the geometric errors which are constant regarding tool pose in the machine-tool workspace. Note that these errors can be introduced in the machine-tool geometrical model which can be implemented in its numerical controller.

For each axis, the reference straight line associated with the axis joint is defined by zero position and orientation errors (Fig. 18). According to ISO 230–1, if the machine tool coordinate system is chosen with X-axis is the primary axis, Y-axis is the secondary axis, and the machine-tool origin is chosen to be along the C-axis average line at the height (Z coordinate) where the B-axis average line intersects with the ZX plane when all axes are commanded to zero. Then, only 8 parameters would remain to characterize a 5-axis machine-tool (Table 3) [27].

In order to develop a geometrical model with these 8 defects, we introduced error transformation matrices into equation (7). These matrices can be written as equation (11), as the error values are small [26]:

$$\mathbf{D}_i = \begin{bmatrix} \sqrt{1 - E_{B0i}^2 - E_{C0i}^2} & -E_{C0i} & E_{B0i} & E_{X0i} \\ E_{C0i} & \sqrt{1 - E_{A0i}^2 - E_{C0i}^2} & -E_{A0i} & E_{Y0i} \\ -E_{B0i} & E_{A0i} & \sqrt{1 - E_{A0i}^2 - E_{B0i}^2} & E_{Z0i} \\ 0 & 0 & 0 & 1 \end{bmatrix}_{R_{i-1}} \tag{11}$$

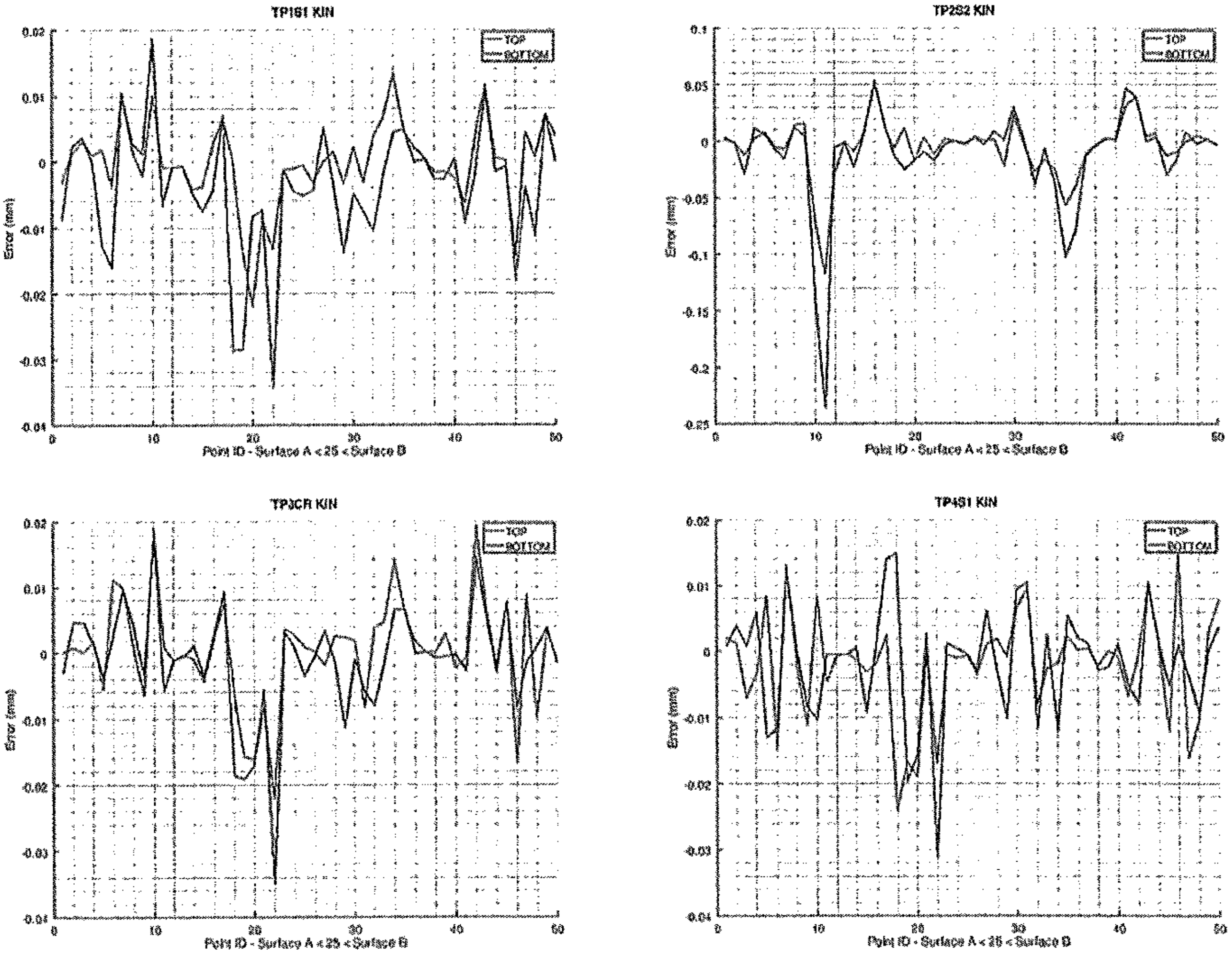

Fig. 15. Geometric deviation due to numerical controller.

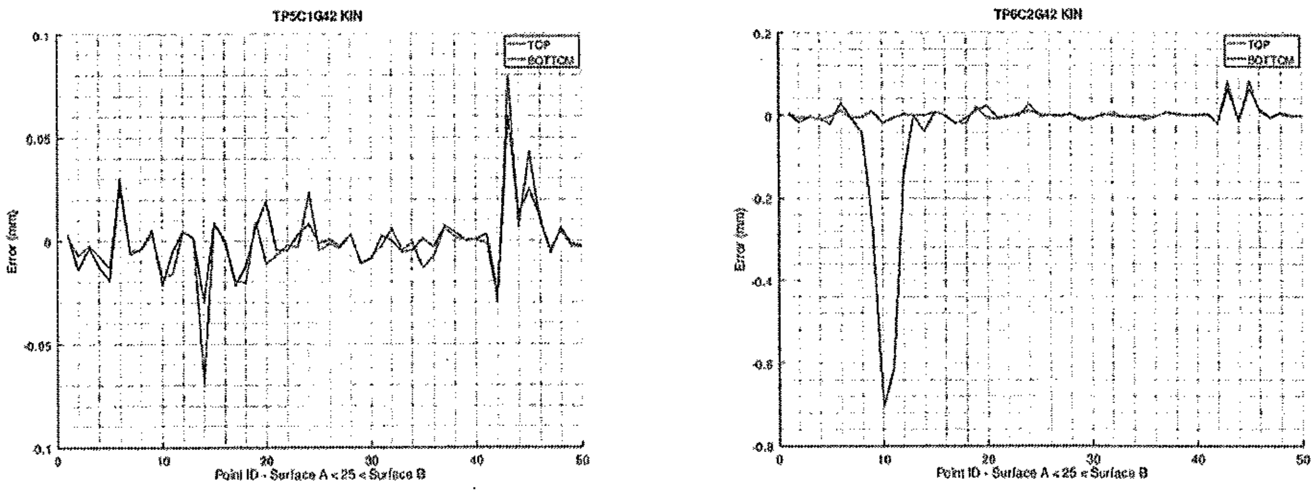

Fig. 16. Geometric deviation due to numerical controller for TP5C1 and TP6C2 with the first setting of Cycle 832.

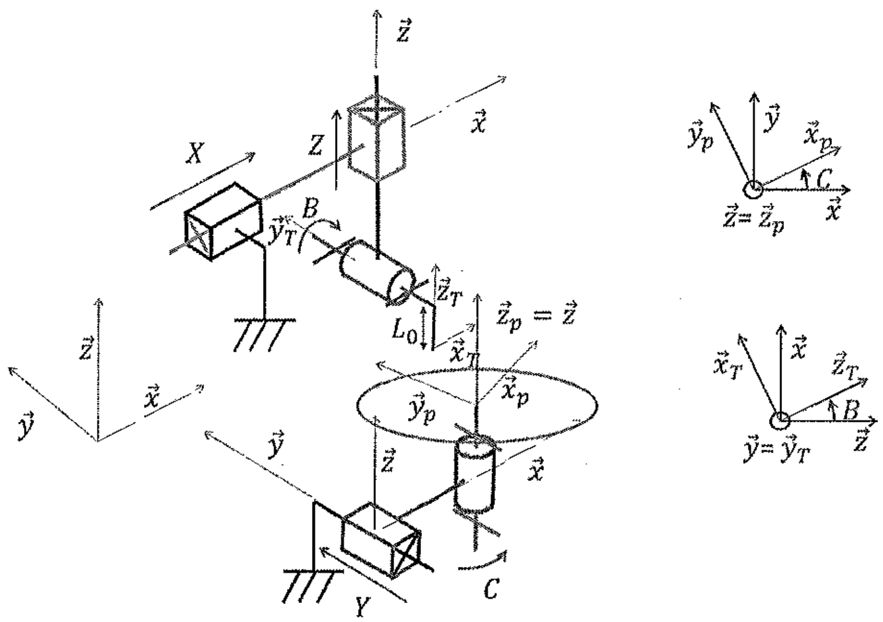

Fig. 17. Kinematic diagram of machine tool studied.

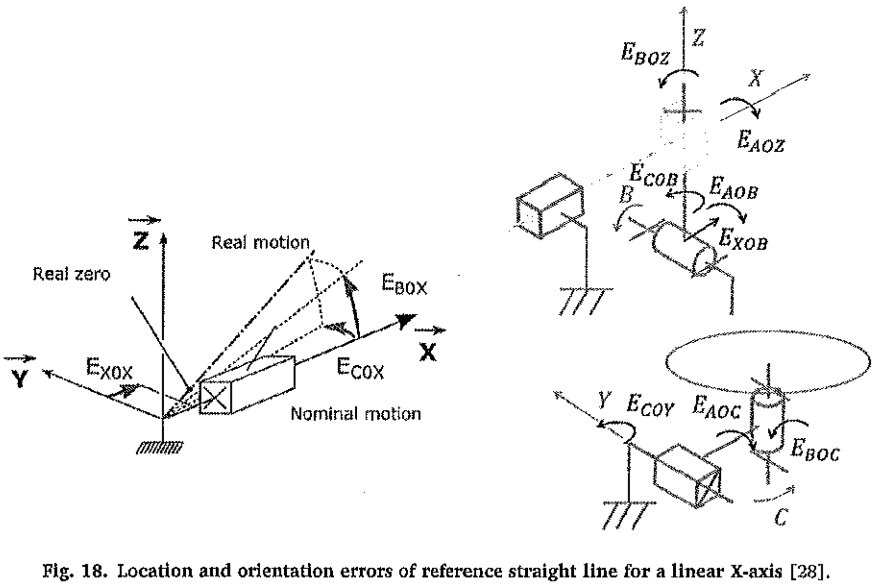

Fig. 18. Location and orientation errors of reference straight line for a linear X-axis [28].

Table 3
Minimum number of error parameters to fully characterize a 5-axis machine tool [2].

	X-axis	Y-axis	Z-axis	C-axis	B-axis
E_{XOi}	0	–	–	0	E_{XOB}
E_{YOi}	–	0	–	0	–
E_{ZOi}	–	–	0	–	0
E_{AOi}	–	0	E_{AOZ}	E_{AOC}	E_{AOB}
E_{BOi}	0	–	E_{BOZ}	E_{BOC}	0
E_{COi}	0	E_{COY}	0	0	E_{COB}

where i is the studied axis and i-1 is the previous axis.

Thus, the direct kinematic model with defects can be computed from equation (12).

$$\begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} = DKM(\mathbf{X},\xi) = \left(\mathbf{D_Y}{}^{O}\mathbf{T_Y}\mathbf{D_C}{}^{Y}\mathbf{T_C}\right)^{-1}\mathbf{D_X}{}^{O}\mathbf{T_X}\mathbf{D_Z}{}^{X}\mathbf{T_Z}\mathbf{D_B}{}^{Z}\mathbf{T_B}{}^{B}\mathbf{T_T}\begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} \tag{12}$$

where $\mathbf{X} = (X,Y,Z,B,C)^t$ and $\xi = (E_{COY},E_{AOZ},E_{BOZ},E_{AOC},E_{BOC},E_{XOB},E_{AOB},E_{COB})^t$.

Finally, the induced tool position defect can be computed from a sensitivity analysis with differentiation and linearization of equation (12) [29]:

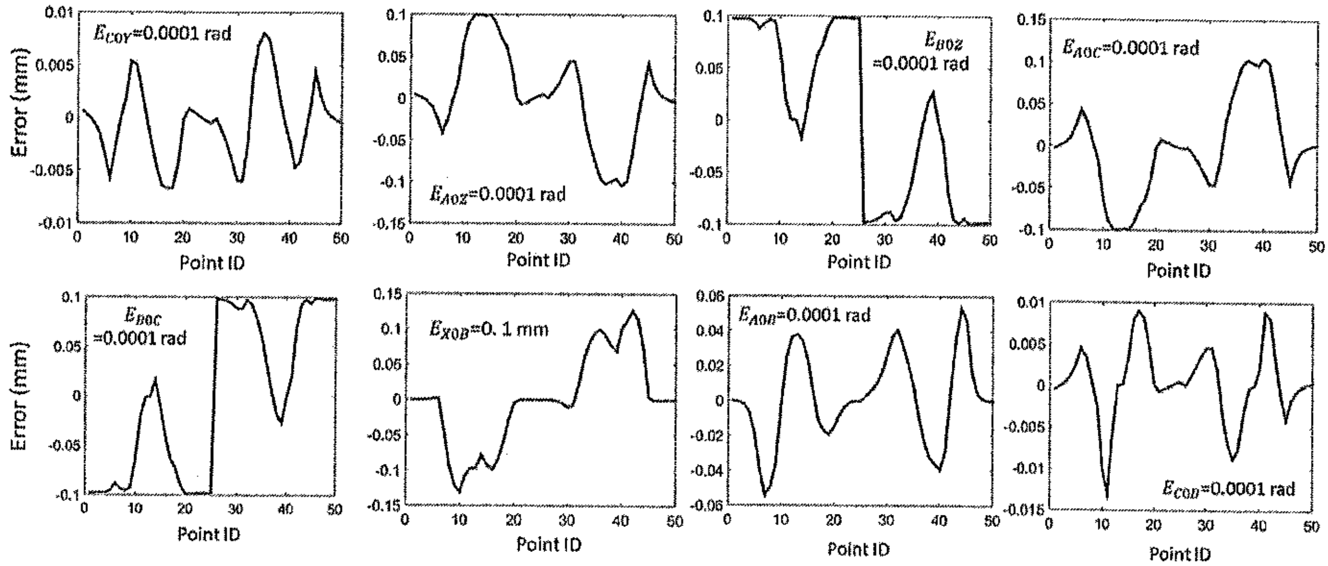

Fig. 19. Machining defect induced by a single defect on table position.

$$\begin{bmatrix} dx \\ dy \\ dz \end{bmatrix} = \frac{dDKM(\mathbf{X},\xi)}{d\xi}\xi \quad (13)$$

$\frac{dDKM(\mathbf{X},\xi)}{d\xi}$ is detailed in Appendix A.

With regard to the machined part, the machined defects are computed by subtracting the tool position defect of each point of the tool path and tool position defect on the origin of WCS (the middle of the table in this case). The machining defect on the S-shape test part is then enumerated using a projection of these errors computed from the tool path $\mathbf{X}_{tool}(u)$ along $\mathbf{N}(u,1)$.

$$Mdef(u) = \left(\frac{dDKM(\mathbf{X}_{tool}(u),\xi)}{d\xi} - \frac{dDKM((0,0,0,0,0),\xi)}{d\xi}\right)\xi \cdot \mathbf{N}(u,1) \quad (14)$$

Fig. 19 illustrates the simulated machining defects due to a single defect on $E_{C0Y}, E_{A0Z}, E_{B0Z}, E_{A0C}, E_{B0C}, E_{X0B}, E_{A0B}$ and E_{C0B} at each measurement point. This simulation is conducted with $L_0 = 499.889$ mm, which is consistent with the experimental setup presented in the following section.

These graphs can help to detect machine-tool influent defects according to the machining part measurement. Indeed, the machined defect due to inverse transformation errors is a composition of graphs proposed in (Fig. 19). However, from the measure of an S-shape test part, defect E_{A0Z} and E_{A0C} cannot be identified separately as their influence on the machined defect is similar except for the sign. This is the same conclusion for defect E_{B0Z} and E_{B0C}.

As a final step in our study, an S-shape test part was machined in Five Machining Flexiax V with program TP4S1.

6. S-shape test part machining and measurement

The S-shape test part is machined in an aluminum alloy according to the standard recommendation with the program TP4S1. For this program, the geometrical deviation due to tool path computation is between [−0.0034 mm; 0.0021 mm] (Fig. 14), and the geometrical defect due to numerical controller is between [−0.031 mm; 0.015 mm] (Fig. 15).

After machining, the S-shape test part is measured. The measurement process consists of measuring the hundred points defined in the standard (Fig. 4). This measure is realized using a CMM (Fig. 20). The CMM model is a Trimesure with a maximum permissible error of length measurement $MPEE = \pm\left(3+\frac{L}{75}\right)$ µm with L in mm and a maximum permissible limit of the repeatability range $R_{0,MPL} = 3$ µm (ISO 10360–2 : 2010).

As Fig. 20 illustrates, the measurement shows that the defects on the top and bottom curves are similar. Thus, the machined defect may be principally due to a tool position defect. The defect measures between −0.18 mm and 0.21 mm which is, unfortunately, greater than expected by the standard, which is 0.12 mm. Moreover, it is a hundred times greater than the defect due to overcut and undercut. In our case, the influence of this defect can be neglected. The defect due to the NC

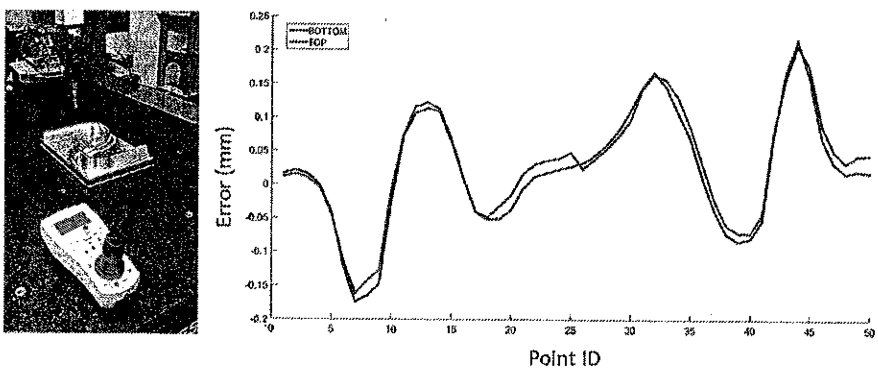

Fig. 20. Measurement of S-shape test part.

Table 4
Identified values of machine-tool error parameters from S-shape measurement.

Error parameters	Identified values	Values for simulation
$x_1 = E_{AOC} = -E_{AOZ}$	$-7.0883.10^{-7}$ rad	0 rad
$x_2 = E_{BOC} = -E_{BOZ}$	$-1.2581.10^{-7}$ rad	0 rad
$x_3 = E_{COY}$	$-1.0654.10^{-5}$ rad	0 rad
$x_4 = E_{XOB}$	0.0294 mm	0.0294 mm
$x_5 = E_{AOB}$	$3.2419.10^{-4}$ rad	$3.2419.10^{-4}$ rad
$x_6 = E_{BOZ}$.	$1.2581.10^{-7}$ rad	0 rad

controller is ten times smaller than the measured defect.

However, a comparison between Figs. 19 and 20 shows that the measured defect seems to be caused mostly by E_{AOB}. The shape of the influence curve of a defect about E_{AOB} is similar to the measurement defect curve of the S-shape test part. Moreover, a defect near 0.02 mm appears at point 1 which can be due to a tool radius defect of 0.02 mm.

Thus, we can conclude that the measured defect is mostly due to inverse transformation errors. This conclusion and the size of the obtained defect are consistent with other published research on the subejct [1]. Our aim is therefore to use this measure defect on the S-shape test part to identify the machine tool geometric defects that, when their values are implemented in the numerical controller of the machine-tool,

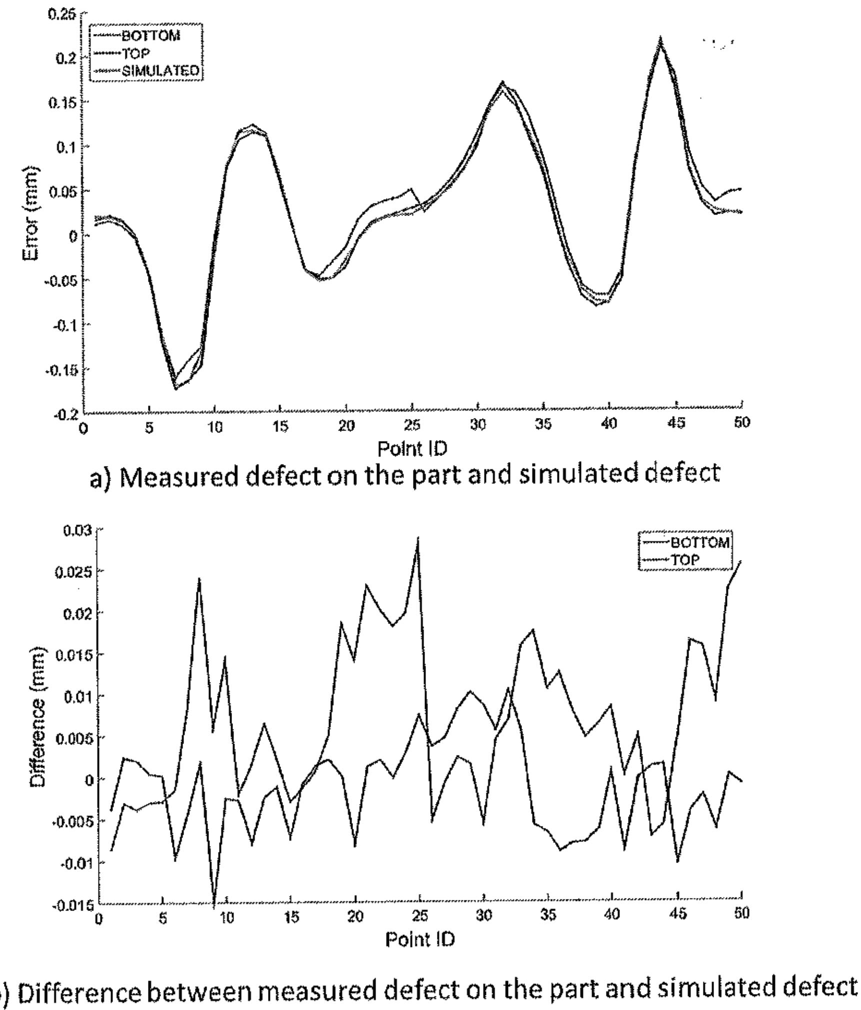

Fig. 21. Identification of machine-tool axis errors from machined defect measurements.

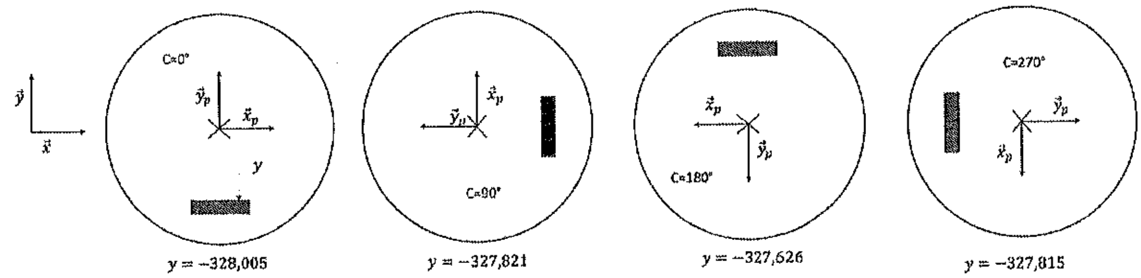

Fig. 22. Measurement of position defect of the table rotation axis.

are not consistent with the real machine tool geometric behavior.

Thus, an optimization process is realized with the Matlab® lsqnonlin algorithm and by taking into account a tool radius defect of 0.02 mm. The cost function is the difference between the measurement errors at each point and the simulated error from equation (14). To consider that defect E_{A0Z} and E_{A0C}, and defect E_{B0Z} and E_{B0C} cannot be identified separately from the S-shape test part measurement. Six optimization variables replace the machine-tool error parameters in the geometrical model of equation (12) as $x_1 = E_{AOC} = -E_{AOZ}$, $x_2 = E_{BOC} = -E_{BOZ}$, $x_3 = E_{C0Y}$, $x_4 = E_{XOB}$, $x_5 = E_{AOB}$ and $x_6 = E_{BOZ}$.

The obtained values are given in Table 4 and are coherent with the previous observation.

Fig. 21 shows a comparison between measured defects on each measurement point of the S-shape test part and the simulated defects. The residual errors after the optimization process are less than 0.045 mm which respects the standard requirement. These errors are in the same magnitude order of deviation due to the numerical controller (Fig. 15 TP4S1 KIN). The identified values of machine-tool error parameters from the S-shape measurements do not ensure the accurate identification of the geometric behavior of the used machine tool as dynamic behaviors are involved during machining, but it gives a first estimation [30,31]. A static measurement process should further be undertaken in order to identify these influent parameters more accurately.

To validate this result, a measurement of a gauge block position in WCS is realized for four positions around axis-C with a probe (in this case $L_0 = 533.889$ mm). Measurement results are given in Fig. 22. The idea of this test is to measure the same physical points in the table coordinate system using a probe positioned in the machine tool spindle. As the measure is realized in the table coordinate system, we can highlight the inverse transformation error.

From equation (12), the machine-tool defect can be identified for each table position measurement:

$$\begin{cases} y_{C=0} = -X_{C=0}E_{C0Y} - (Z_{C=0} - L_0)E_{A0Z} + (Z_{C=0} - L_0)E_{A0C} + L_0 E_{A0B} = -328.005 \\ y_{C=90} = -(Z_{C=90} - L_0)E_{B0Z} + (Z_{C=90} - L_0)E_{B0C} - E_{X0B} = -327.821 \\ y_{C=180} = X_{C=180}E_{C0Y} + (Z_{C=180} - L_0)E_{A0Z} - (Z_{C=180} - L_0)E_{A0C} - L_0 E_{A0B} = -327.626 \\ y_{C=270} = (Z_{C=270} - L_0)E_{B0Z} - (Z_{C=270} - L_0)E_{B0C} + E_{X0B} = -327.815 \end{cases} \quad (15)$$

However, $X_{C=0} = X_{C=180} = 0$ and $Z_{C=0} = Z_{C=90} = Z_{C=180} = Z_{C=270} \approx L_0$. Thus,

$$y_{C=180} - y_{C=0} = -2L_0 E_{A0B} \text{ and } y_{C=270} - y_{C=90} = 2E_{X0B} \quad (16)$$

Finally, from this test, $E_{A0B} = \frac{0.1895}{L_0} = 3.549.10^{-4}$ rad $= 0.020°$ and $E_{X0B} = 0.003$ mm.

The error E_{A0B} found with this test is close (less than 8%) to the one found from the optimization based on the measure of the S-shape test part (Table 4). At the same time, the error E_{X0B} is not the same as that derived from the optimization based on the measure of the S-shape test part. However, the measure on the machine-tool studied is not as accurate as of the measurement on a CMM. The machine-tool studied here is reputed to have a linear position accuracy of the Y-axis of the order of a millimeter hundredth. However, an error E_{X0B} of 0.01 mm generates a maximum machined defect of the S-shape test part of 0.015 mm, which is less than expected by the standard (Fig. 19).

This test shows the difficulty of estimating machine-tool geometric defects from direct measurement on the machine tool described in ISO 3655:2006 and ISO 8636–1:2000.

Moreover, we realized the measurement of the parallelism of the tool housing axis with C-axis in plan Y-Z on the assumption that this defect might be similar to E_{A0B}. This test is one of the tests proposed in ISO 3655:2006 for testing the accuracy of a machine-tool. The measured defect is 0.010 mm for a length of 300 mm, i.e. an angular defect of $3.333.10^{-5}$ rad. The measured defect is ten times lower than that identified from the measure of the S-shape. Indeed, the measured defect is not E_{A0B}, i.e., the orientation defect of B-axis around X-axis; it is in fact the orientation defect of B-axis around. $\vec{x}_p$.

The comparison of tests introduced in ISO 3655:2006 and the defect extracted from the measurement of the S-shape test part illustrates the benefits of the measurements of the S-shape test part in identifying the geometric behavior of a 5-axis machine-tool. Moreover, in the case of the S-shape test part, rotating axes move during the part machining, thus ensuring a reception process adapted to 5-axis continuous machining.

7. Conclusion

In this paper, we studied the evolution of the geometry of the S-shape test part during each step of machining in order to quantify the associated impact on the final machined part.

As the S-shape test part is defined from two non-developable ruled surfaces, an overcut appears that can reach 0.0387 mm. This is joined by a defect resulting from CAM software tool path computation. The maximum computed deviation is 0.01 mm. The movement of the machine-tool axis is imposed by the numerical controller. This step generates a supplementary maximum deviation of 0.034 mm. Finally, we analyzed the influence of inverse transformation errors resulting from the gap between the geometric model implemented in the numerical controller and the real geometric behavior of the machine-tool studied. Developing a geometric model which integrates error parameters used by the standard to characterize a 5-axis machine tool shows the significant influence of inverse transformation errors in continuous 5- axis machining. Moreover, the sensitivity analysis of the machine-tool geometric parameters on the machined defect of the S-shape test part shows that defect E_{A0Z} and E_{A0C} have a similar influence on the machined defect as for defect E_{B0Z} and E_{B0C}.

To this day, there is still no standard test for identifying all defects, as some of them are only influent during 5-axis continuous machining. The standard is not yet completely developed for a continuous 5-axis machine-tool.

The use of a geometric model ensures the identification of the defects that had detrimental effects on the quality of the S-shape test part. In this light, future research may benefit from studying the accuracy benefit for 5-axis continuous machining of the implementation of an identified geometric model with defects in the numerical controller.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

9 Appendix A

$$\begin{bmatrix} dx \\ dy \\ dz \end{bmatrix} = \frac{dDKM(X,\xi)}{d\xi} \cdot d\xi \Rightarrow \begin{bmatrix} dx \\ dy \\ dz \end{bmatrix}$$

$$= \begin{bmatrix} (L_0\sin(B) - X)\sin(C) & -(Z - L_0\cos(B).)\sin(C) & (Z - L_0\cos(B).)\cos(C) & (Z - L_0\cos(B).)\sin(C) & -(Z - L_0\cos(B).)\cos(C) & \cos(C) & L_0\cos(B)\sin(C) & -L_0\sin(B)\sin(C) \\ (L_0\sin(B) - X)\cos(C) & -(Z - L_0\cos(B).)\cos(C) & -(Z - L_0\cos(B).)\sin(C) & (Z - L_0\cos(B).)\cos(C) & (Z - L_0\cos(B).)\sin(C) & -\sin(C) & L_0\cos(B)\cos(C) & -L_0\sin(B)\cos(C) \\ 0 & 0 & L_0\sin(B) & -Y & X - L_0\sin(B) & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} E_{C0Y} \\ E_{A0Z} \\ E_{B0Z} \\ E_{A0C} \\ E_{B0C} \\ E_{X0B} \\ E_{A0B} \\ E_{C0B} \end{bmatrix}$$

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ISO WD 8636-1(E)

ISO TC 39/SC 2

Secretariat: ASI

Machine tools – Test conditions for bridge-type milling machines – Part 1: Testing of the accuracy of fixed bridge (portal-type) machines

WD stage

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For the convenience of the reader, this first working draft reports the extracts of original test tables from ISO 8636:2000. These tables will be deleted at subsequent development stages.

Contents

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

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This document was prepared by Technical Committee ISO/TC 39 *Machine tools*, Subcommittee SC 2, *Test conditions for metal cutting machine tools*

This third edition cancels and replaces the second edition (ISO 8636-1:2000), which has been technically revised.

The main changes compared to the previous edition are as follows:

— References in Observations have been updated to ISO 230-1:2012 and to ISO 230-2:2014.

— The original Clause 3 "Definitions and descriptions" has been renamed "Terms and definitions" to comply with current prescriptions of ISO/IEC Directives Part 2.

— The content of the original subclause 3.2 has been moved to a new Clause 4 "Classification and description of fixed bridge-type milling machines", which now also includes the content of original Clause 4 "Terminology and designation of axes" which has been revised to better represent current technology.

— Preliminary remarks sub-clauses have been revised to be consistent with the latest revisions of machine-tool specific standards.

— Tolerances for tests related to long axes (with travel lengths up to 10 000) have been introduced.

— Tests for straightness and angular errors of Z-axis motion have been added.

— Tests for straightness and angular errors of cross-rail W-axis motion have been added.

- Tests for geometric accuracy of axis of rotation have been added in Annex A (Informative).
- A new Annex B provides additional information related to tests for straightness of the X'-axis motion in the vertical ZX plane, $E_{ZX'}$, to account for non-rigid body behaviour of large tables.
- Test for table flatness (formerly G9) has been deleted because the table surface is not normally used as a reference for the orientation of the workpiece, and, for tests made during the working life of the machine tool, the surface might no longer be suitable for accurate measurements on these large machine tools.
- Tests for tilting spindle heads (formerly G15 and P7) have been deleted as such heads are not available any more.
- Machining tests have been excluded considering that such tests are typically the object of agreement between manufacturer/supplier and user, (possibly) including tests that are specified in ISO 10791-7.

In addition to the terms in Key of Figure 1, written in English and French, this document gives, in informative Annex C, Table C.1, the equivalent terms in German, Italian, Japanese and Persian; these are published under the responsibility of the member body for Germany (DIN), Italy (UNI), Japan (JISC) and Iran (INSO) and are given for information only. Only the terms given in the official languages can be considered as ISO terms.

A list of all parts in the ISO 8636 series can be found on the ISO website.

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Machine tools – Test conditions for bridge-type milling machines – Part 1: Testing of the accuracy of fixed bridge (portal-type) machines

1 Scope

This document specifies, with reference to ISO 230-1 and ISO 230-2, geometric tests and tests for checking the accuracy and repeatability of positioning of numerically controlled axes for general purpose, normal accuracy, bridge-type milling machines with a fixed bridge (portal type). This document also specifies the applicable tolerances corresponding to the above-mentioned tests.

This document is applicable to machines with moving tables and fixed double columns. It does not include single-column (open sided) machines and those with fixed tables and moving columns.

This document deals only with the verification of the accuracy of the machine. It does not apply to the testing of the machine operation (vibration, abnormal noise, stick-slip motion of components, etc.) nor to machine characteristics (such as speeds, feeds, etc.), which should generally be checked before testing the accuracy.

This document provides the terminology used for the principal components of the machine and the designation of the axes with reference to ISO 841.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 230-1:2012, *Test code for machine tools — Part 1: Geometric accuracy of machines operating under no-load or quasi-static conditions*

ISO 230-2:2014, *Test code for machine tools — Part 2: Determination of accuracy and repeatability of positioning of numerically controlled axes*

ISO 230-7:2015, *Test code for machine tools — Part 7: Geometric accuracy of axes of rotation*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 230-1:2012, ISO 230-2:2014, ISO 230-7:2015 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

3.1
milling operation
machining operation to generate surfaces of various geometries in which the principal cutting motion is the rotation of a cutting tool with multiple cutting edges against the non-rotating workpiece and where the cutting energy is brought by the cutting tool rotation

Note 1 to entry: Milling operations mostly involve face milling or end milling. The tools are mounted either in the boring spindle taper or, as for face milling cutters, on the tool-holding spindle nose.

[SOURCE: ISO 3070-2:2016, 3.2]

3.2
boring operation
operation which consists of machining the diameters of cylindrical, conical, blind or through holes, to the required size

3.3
drilling and tapping operations
operations which consist of drilling and tapping blind or through holes

3.4
fixed bridge-type (portal-type) milling machine
double-column machine with one or more vertical spindle heads mounted on the cross-rail, above a table which has a longitudinal traverse (X-axis) only

Note 1 to entry: Additional horizontal spindle heads may be mounted on the columns. The horizontal spindle axes can have a tilting capability.

4 Classification and description of fixed bridge-type milling machines

4.1 Classification

These machine tools are classified into two types depending upon their construction:

- bridge-type milling machines with cross-rail movable along Z-(W-) axis and a bridge or tie-piece between the columns;
- bridge-type milling machines with a fixed height cross-rail which can replace the bridge or tie-piece.

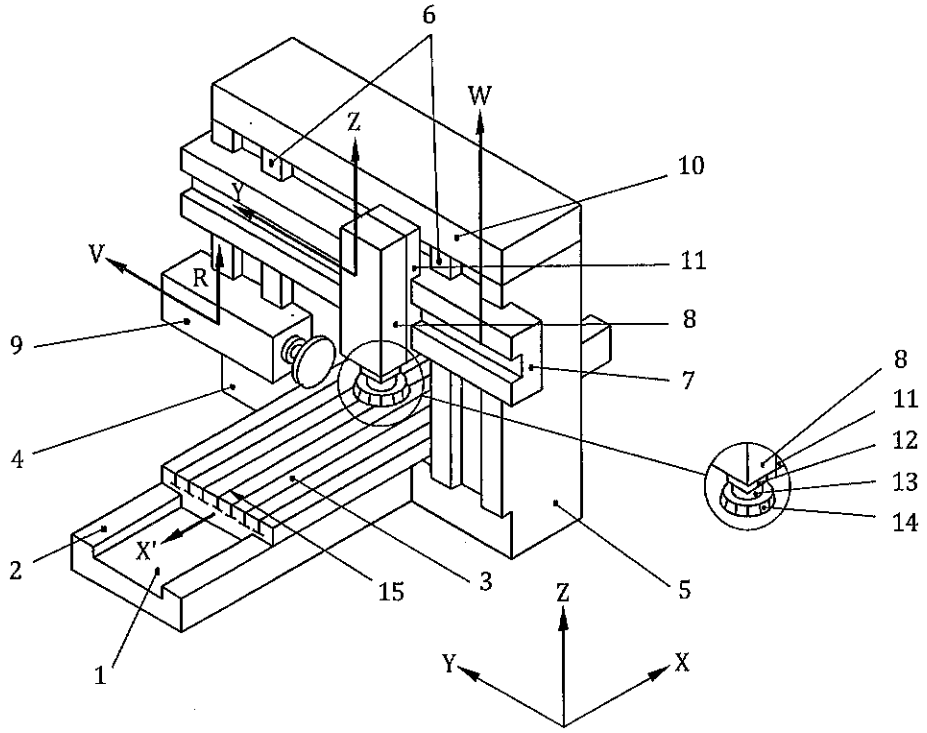
4.2 Descriptions of principal components

4.2.1 General

The principal components of these machine tools are described below. The number indicated in brackets corresponds to the relevant key in Figure 1.

4.2.2 Bed and table

The bed (1) is the fixed base of the machine which may be constructed of several parts. It supports the table (3) which moves parallel to the major axis of the bed.



Key	English	French
1	bed	banc
2	bed slideways	glissière du banc
3	table	table
4	left-hand column	montant gauche
5	right-hand column	montant droit
6	slideways of right-hand and left-hand columns	glissières des montants droit et gauche
7	cross-rail (movable or fixed)	traverse (mobile ou fixe)
8	vertical spindle head	chariot porte-outils vertical
9	horizontal spindle head	tête de broche horizontale
10	tie-piece	entretoise
11	vertical spindle head saddle	chariot porte-outils vertical
12	quill (ram)	fourreau (coulant)
13	tool-holding spindle	broche porte-outil
14	tool (milling cutter)	outil (fraise)
15	reference T-slot	rainure de référence
R	vertical motion of the horizontal spindle head (R-axis)	mouvement vertical de la tête de broche horizontale (axe R)
V	horizontal motion of the horizontal spindle head(V-axis)	mouvement horizontal de la tête de broche horizontale (axe V)
W	movable cross-rail vertical motion (W-axis)	mouvement vertical de la traverse mobile (axe W)

X'	X'-axis	axe X
Y	Y-axis	axe Y
Z	Z-axis	axe Z

Figure 1 — Fixed bridge- (portal-) type milling machine with variable height cross-rail

4.2.3 Column, cross-rail and bridge or tie-piece

The columns (4) and (5) provide the vertical frame of the machine and are fixed on either side of the bed.

The columns may be fitted with vertical slideways to accommodate horizontal spindle head (9) with other horizontal spindle axis.

The tie-piece (10) is a fixed piece connecting both columns at or near the top.

The cross-rail (7) has its major axis parallel to the table plane and is fitted with slideways on which one or more vertical spindle heads (8) can move.

The variable height cross-rail, where available, can be moved up and down the vertical slideways (6) on the columns.

In the case of machines with a fixed-height cross-rail, the latter is also fastened to the columns and can replace the tie-piece.

4.2.4 Spindle head(s)

These heads include the spindle and drive mechanism and the means for their mounting on the cross-rail or column. In some cases, the tool-holding spindle (13) may be mounted in a ram or quill (12) with a feed speed motion for drilling, tapping or boring operations.

4.2.5 Cutting motion

Cutting motion is provided by the spindles and drive mechanisms of the spindle heads.

4.2.6 Feed motion

The following feed speed motions can be provided with a constant or variable feed speed:

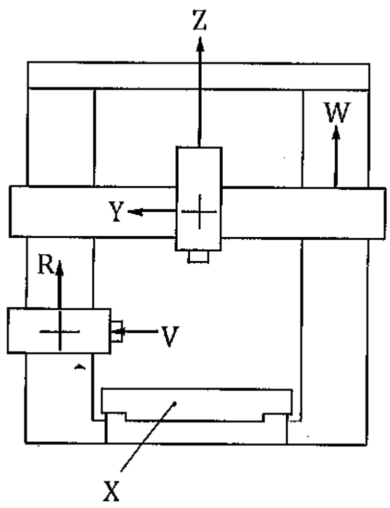
- horizontal motion of the table;
- horizontal motion of the spindle heads on the cross-rail or vertical movement of the horizontal heads;
- vertical motion of spindle rams or quills (if any).

NOTE 1 In general, rapid traverse is available in addition to feed speed motion.

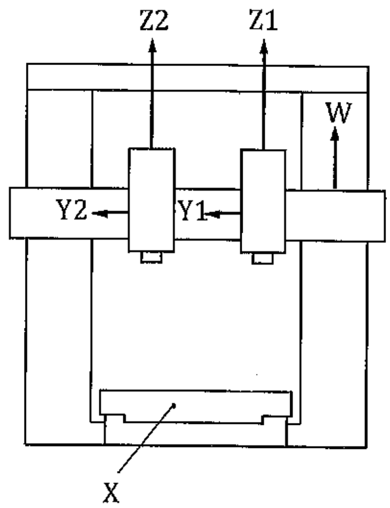
NOTE 2 The vertical movement of the cross-rail (if any) is usually a positioning motion.

4.3 Designation of axes

See Figures 2 to 4.



a) One vertical spindle head placed on the cross-rail, and one horizontal spindle head placed on the left-hand column



b) Two vertical spindle heads on the cross-rail

Figure 2 —Portal type machine tools with two spindle heads

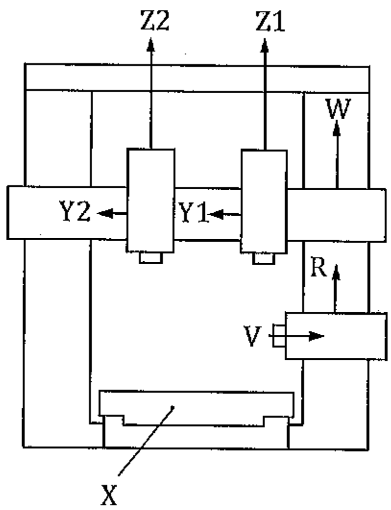


Figure 3 — Portal type machine tool with three spindle heads

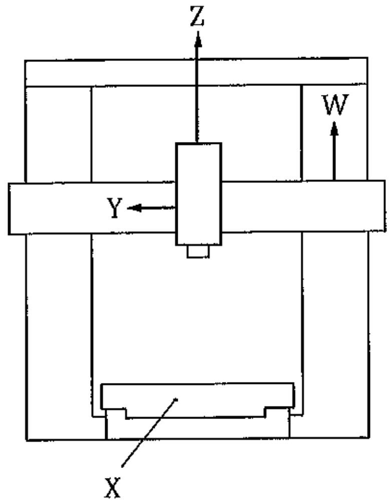


Figure 4 — Portal type machine tool with one spindle head on the cross-rail

5 Preliminary remarks

5.1 Measuring units

In this document, all linear dimensions, deviations, errors and corresponding tolerances are expressed in millimetres; angular dimensions are expressed in degrees, and angular errors and the corresponding tolerances are primarily expressed in ratios (e.g., 0,010/1 000), but in some cases, microradians (µrad) or arcseconds (") are used for clarification purposes. The following formula (1) should be used for the conversion of the units of angular errors or tolerances:

$$0{,}010/1\,000 = 10\ \mu\text{rad} \approx 2'' \quad (1)$$

5.2 Reference to ISO 230-1, ISO 230-2 and ISO 230-7

To apply this document, reference shall be made to ISO 230-1 and ISO 230-7 when required, especially for the installation of the machine before testing, warming up of the spindle(s) and other moving components, description of measuring methods and recommended accuracy of testing equipment.

In the "Observations" box of the tests described in the following clauses, the instructions are preceded by a reference to the corresponding clause in ISO 230-1, ISO 230-2 or ISO 230-7 in cases where the test concerned is in compliance with the specifications of one of those parts of ISO 230 series.

5.3 Machine levelling

Prior to conducting tests on a machine tool, the machine tool should be levelled according to the recommendations of the manufacturer/supplier (see ISO 230-1:2012, 6.1).

5.4 Temperature conditions

The temperature conditions throughout the tests shall be specified by agreement between the manufacturer/supplier and user.

5.5 Testing sequence

The sequence in which the tests are presented in this document in no way defines the practical order of testing. In order to make the mounting of instruments or gauging easier, tests may be performed in any order.

5.6 Tests to be performed

When testing a machine, it is not always necessary nor possible to carry out all the tests described in this document. When the tests are required for acceptance purposes, it is up to the user to choose, in agreement with the manufacturer/supplier, those tests relating to the components and/or the properties of the machine which are of interest. ISO 230-1:2012, Annex A provides valuable information about selection of primary and secondary axes and associated tests. These tests are to be clearly stated when ordering a machine. Simple reference to this document for the acceptance tests, without specifying the tests to be carried out, and without agreement on the relevant expenses, cannot be considered as binding for any contracting party.

5.7 Measuring instruments

The measuring instruments indicated in the tests described in the following clauses are examples only. Other instruments measuring the same quantities and having the same, or a smaller, measurement uncertainty can be used. Reference shall be made to ISO 230-1:2012, Clause 5, which indicates the relationship between measurement uncertainties and the tolerances.

When a "dial gauge" is referred to, it can mean not only dial test indicators (DTI), but any type of linear displacement sensor such as analog or digital dial gauges, linear variable differential transformer (LVDTs), linear scale displacement gauges, or non-contact sensors, when applicable to the test concerned.

Similarly, when a "straightedge" is referred to, it can mean any type of straightness reference artefact, such as a granite or ceramic or steel or cast-iron straightedge, one arm of a square, one generating line on a cylindrical square, any straight path on a reference cube, or a special, dedicated artefact manufactured to fit in the T-slots or other references.

In the same way, when a "square" is mentioned, it can mean any type of squareness reference artefact, such as a granite or ceramic or steel or cast-iron square, a cylindrical square, a reference cube, or, again, a special, dedicated artefact.

When a "precision level" is referred to, it can mean any type of level such as bubble tube, digital and analogue electronic levels.

Valuable information on measuring instruments is available in ISO/TR 230-11.

5.8 Software compensation

When built-in software facilities are available for compensating geometric, positioning, contouring and thermal deviations, their use during these tests should be based on agreement between manufacturer/supplier and user, with due consideration to the machine tool intended use, e.g., if the intended use of the machine tool is with or without software compensation for geometric errors. When the software compensation is used, this shall be stated in the test report. It shall be noted that when software compensation is used, some machine tool axes cannot be locked for test purposes.

Valuable information on numerical compensation of geometric errors can be gathered in ISO/TR 16907.

5.9 Minimum tolerance

By mutual agreement, manufacturer/supplier and user can establish the tolerance for a measuring length different from that given in the tests described in the following clauses. However, it should be considered that the recommended minimum value of tolerance is 0,005 mm, unless otherwise specified.

In specifying the minimum tolerance, measurement uncertainty associated with the test and the recommended instrument, shall be taken into account, see 6.7.

5.10 Positioning tests

Positioning tests for numerically controlled machines shall refer to ISO 230-2. Tolerances in this document are given only for some parameters. The presentation of the test results shall be in compliance with ISO 230-2.

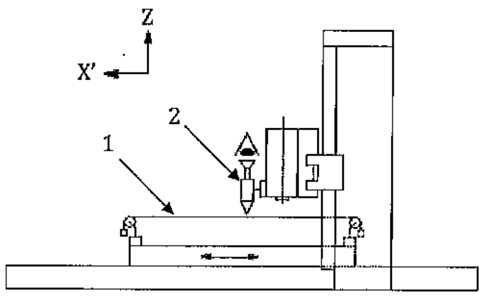
6

6 Geometric tests for axes of linear motion

Object — **G1**

Checking of the straightness of motion of the table (X'-axis) in the horizontal XY plane, $E_{YX'}$.

Diagram



Key

1 microscope   2 taut wire

Tolerance

	For a measuring length up to:			
	2 500	5 000	7 500	10 000
For a) and b):	0,025	0,050	0,075	0,100

Local tolerance: 0,010 for any measuring length of 1 000

For measuring lengths over 10 000, the tolerance shall be agreed between manufacturer/supplier and user.

Measurement results: For a measuring length of:

Measuring instruments

Microscope and taut wire or other straightness measurement optical instruments

Observations and references to ISO 230-1:2012, 8.2.2.1, 8.2.2.2, 8.2.2.3 and 8.2.2.4

The microscope shall be fixed on the spindle, if it can be locked, or on the spindle head.

When optical instruments are used, it should be considered that, their measurement uncertainty for long measurement length can be higher than the measurement uncertainty of microscope and taut wire.

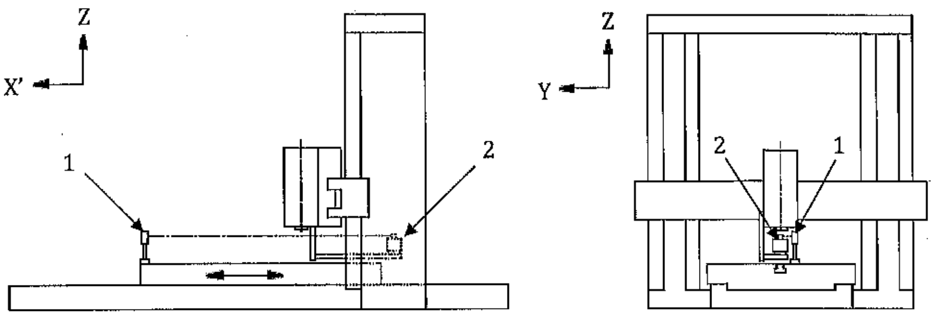
Measurements shall be carried out on at least six positions along the travel, with equally spaced steps not exceeding 500. Traverse the table in the X-axis direction and note the readings.

Measurements shall be with Y- and Z-axis at their mid travel positions or otherwise, measurement location shall be reported.

Object	**G2**

Checking of the straightness of motion of representative points of the table (X'-axis) in the vertical ZX plane, $E_{ZX'}$;

Diagram



Key

1 target 2 laser scanning device

Tolerance

	For a measuring length up to:			
	2 500	5 000	7 500	10 000
For a) and b):	0,050	0,100	0,150	0,200

Local tolerance: 0,020 for any measuring length of 1 000

For measuring lengths over 10 000, the tolerance shall be agreed between manufacturer/supplier and user.

Measurement results: For a measuring length of:

Measuring instruments

Laser scanning device or straightness measurement optical instruments excluding microscope and taut wire

Observations and references to ISO 230-1:2012, 8.2.2.1, 8.2.2.2, 8.2.2.3 and 8.2.2.4

Taut wire is not recommended because of the sag of the wire.

The laser scanning device can be mounted on the spindle head so that the optical plane is parallel to the X'-axis motion, or the lack of parallelism shall be considered in the measurement.

The target can be mounted on a representative point on the table.

Measurements shall be carried out on at least six positions along the travel, with equally spaced steps not exceeding 500. Traverse the table in the X-axis direction and note the readings.

Measurements shall be with Y- and Z-axis at their mid travel positions or otherwise, measurement location shall be reported.

The rigid body model is typically not applicable to the motion of the table.

The target shall be placed at the two ends of the table and possibly in the middle of the table.

The target located at one end of the table explores the characteristics of half of the bed.

The target located in the middle of the table reveals different deviations from the ones located at both ends of the table.

See Annex B for information on possible methods to be applied to minimize the effect of non-rigid body behaviour of the table motion on measurement uncertainty.

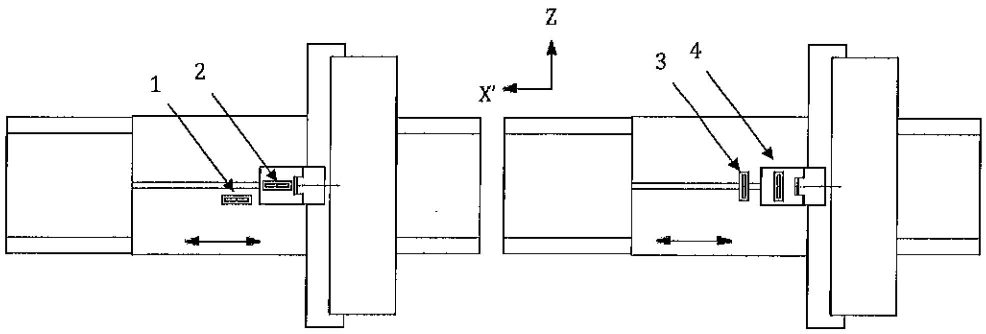
Object — **G3**

Checking of the angular errors of the table motion (X'-axis):

a) in the vertical ZX plane ($E_{BX''}$: pitch);

b) in the vertical YZ plane ($E_{AX''}$: roll);

Diagram



Key a) b)

1 measuring level for pitch

2 reference level for pitch

3 measuring level for roll

4 reference level for roll

Tolerance

For measuring length up to:

	2 500	5 000	7 500	10 000
For a):	0,030/1 000	0,040/1 000	0,050/1 000	0,060/1 000
For b):	0,020/1 000	0,020/1 000	0,020/1 000	0,020/1 000

Local tolerance for a) and b): 0,020/1 000 for any measuring length of 1 000

For measuring lengths over 10 000, the tolerance shall be agreed between manufacturer/supplier and user.

Measurement results

For a measuring length of:

a)

b)

Measuring instruments

For a): precision level or optical instruments;

for b): precision level;

Observations and references to ISO 230-1:2012, 8.4.2.1, 8.4.2.2 and 8.4.2.3

The measuring level or the instrument shall be placed on the table:

If the X'-axis motion causes angular deviation of both the table and spindle head, differential measurements of the two angular motions shall be taken.

For a) and b), measurements shall be carried out on at least six positions along the travel, with equally spaced steps not exceeding 500.

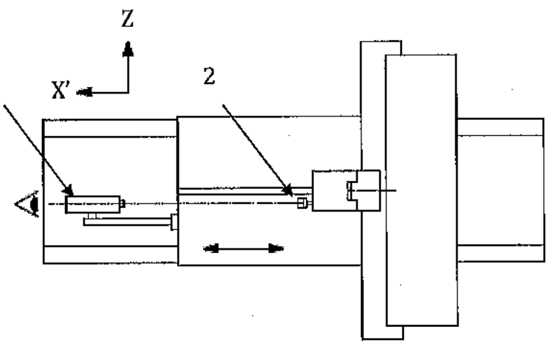
For a) and b), the angular error to be reported is the difference between the maximum and the minimum readings. Measurement location shall be reported.

For tests a) and b), the instrument shall be placed at the two ends and possibly in the middle of the table. The instrument located at one end of the table explores the characteristics of half of the bed.

The instrument located in the middle of the table reveals different deviations from the ones located at both ends of the table.

Object	G4
Checking of the angular errors of the table motion (X'-axis) in the horizontal XY plane ($E_{CX''}$: yaw);	

Diagram



Key

1 autocollimator 2 mirror

Tolerance

For measuring length up to:

2 500	5 000	7 500	10 000
0,030/1 000	0,040/1 000	0,050/1 000	0,060/1 000

Local tolerance: 0,020/1 000 for any measuring length of 1 000

For measuring lengths over 10 000, the tolerance shall be agreed between manufacturer/supplier and user.

Measurement results For a measuring length of:

Measuring instruments

Autocollimator or other optical angular measurement instrument

Observations and references to ISO 230-1:2012, 8.4.2.1, 8.4.2.2 and 8.4.2.3

The autocollimator shall be placed on the table:

Measurements shall be carried out on at least six positions along the travel, with equally spaced steps not exceeding 500.

The angular error to be reported is the difference between the maximum and the minimum readings. Measurement location shall be reported.

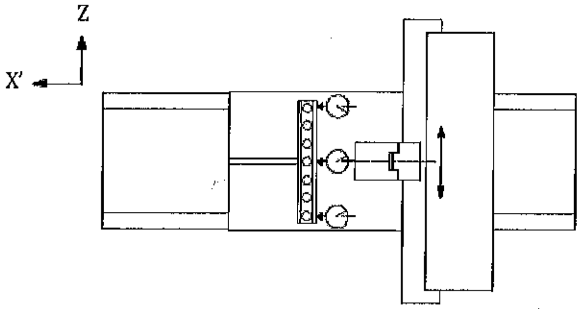
Object — **G5**

Checking of the straightness of the horizontal motion of the spindle head on the cross-rail (Y-axis):

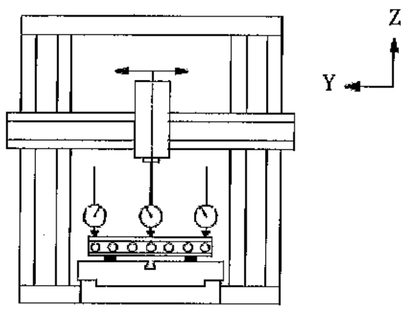
a) in the horizontal XY plane, E_{XY};

b) in the vertical YZ plane, E_{ZY}.

Diagram



a)



b)

Tolerance

For measuring length up to:

	1 000	2 000	3 000	4 000
For a) and b):	0,010	0,020	0,030	0,040

Local tolerance for a) and b): 0,015 for any measuring length of 800

For measuring lengths over 4 000, the tolerance shall be agreed between manufacturer/supplier and user.

Measurement results — ***For a measuring length of*:**

a)

b)

Measuring instruments

Dial gauge, straightedge and gauge blocks or optical instruments.

Observations and references to ISO 230-1:2012, 8.2.2.1, 8.2.2.3, 8.2.2.4 and 8.2.2.5

Fix the movable cross-rail in mid travel and move the table in mid travel.

Set a straightedge on the table, with the reference surface approximately parallel to the Y-axis: in the horizontal plane for a) and in the vertical plane for b).

If the spindle can be locked, the dial gauge may be mounted on it. If the spindle cannot be locked, the dial gauge shall be mounted on the ram.

Traverse the spindle head in the Y-direction through the measuring length and record the readings. The measuring length is normally the length between the two columns (not the full length of cross-rail). In other cases, this shall be agreed upon between the supplier/manufacturer and user.

Measurements shall be carried out on at least six positions along the travel, with equally spaced steps not exceeding 400.

Object — **G6**

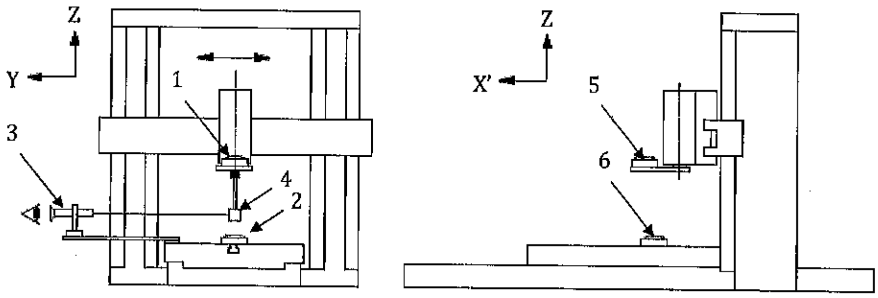
Checking of the angular errors of the horizontal motion of the spindle head (Y-axis):

a) in the vertical YZ plane (E_{AY}: pitch);

b) in the vertical ZX plane (E_{BY}: roll);

c) in the horizontal XY plane (E_{CY}: yaw).

Diagram



a) and c) — b)

Key

1 measuring level for pitch
2 reference level for pitch
3 autocollimator for yaw/pitch
4 mirror for yaw/pitch
5 measuring level for roll
6 reference level for roll

Tolerance

For measuring length up to:

	2 000	3 000	4 000	5 000
For a), b) and c):	0,040/1 000	0,050/1 000	0,060/1 000	0,060/1 000

For a), b) and c), local tolerance: 0,015/1 000 for any measuring length of 800

For measuring lengths over 5 000, the tolerance shall be agreed between manufacturer/supplier and user.

Measurement results — For a measuring length of:

a) b) c)

Measuring instruments

For a): Precision level or optical instruments;

for b): Precision level;

for c): Autocollimator or other optical instruments.

Observations and references to ISO 230-1:2012, 8.4.2.1, 8.4.2.2 and 8.4.2.3

The level or mirror or retro-reflector shall be placed on the movable component:

for a), (E_{AY}: pitch): the level shall be placed in the Y-axis direction;

for b), (E_{BY}: roll): the level shall be placed in the X-axis direction;

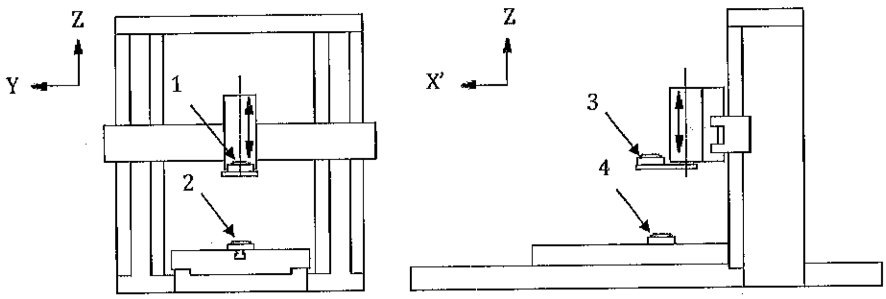
for c): (E_{CY}: yaw): set autocollimator horizontally in the Y-axis direction.

Measurements shall be carried out on at least six positions along the travel, with equally spaced steps not exceeding 400.

For a), b) and c), the angular error to be reported is the difference between the maximum and the minimum readings.

Object	**G7**
Checking of the angular errors of the spindle head vertical motion (Z-axis): a) in the vertical YZ plane, E_{AZ}; b) in the vertical ZX plane, E_{BZ}.	

Diagram



a) b)

Key

1 measuring level for E_{AZ}

2 reference level for E_{AZ}

3 measuring level for E_{BZ}

4 reference level for E_{BZ}

Tolerance

For measuring length up to:

	1 000	2 000	3 000	4 000
For a) and b):	0,020/1 000	0,030/1 000	0,040/1 000	0,050/1 000

Local tolerance for a) and b): 0,015/1 000 for any measuring length of 600

For measuring lengths over 4 000, the tolerance shall be agreed between manufacturer/supplier and user.

Measurement results

For a measuring length of:

a)

b)

Measuring instruments

Precision level or optical instruments.

Observations and references to ISO 230-1:2012

The level or mirror or retro-reflector shall be placed on the movable component:

for a), (E_{AZ}): the level shall be placed in the Y-axis direction;

for b), (E_{BZ}): the level shall be placed in the X-axis direction.

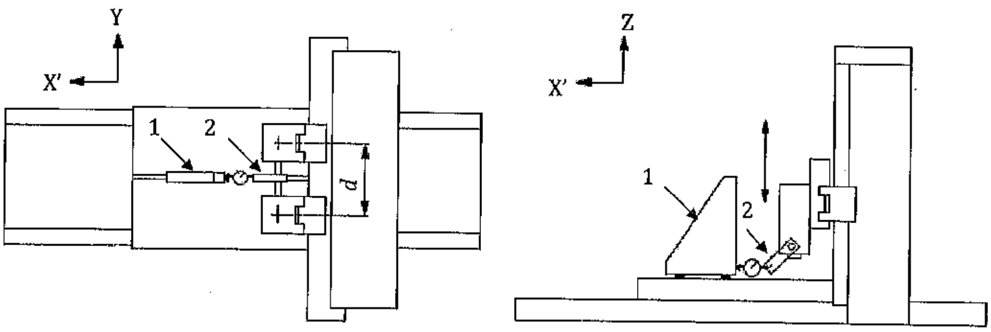
Measurements shall be carried out on at least six positions along the travel, with equally spaced steps not exceeding 300.

For a) and b), the angular error to be reported is the difference between the maximum and the minimum readings.

Object **G8**

Checking of the angular error of the spindle head vertical motion (Z-axis) in the horizontal XY plane, E_{CZ} (roll).

Diagram



Key

1 square   2 special arm   *d* travelled distance along Y-axis

Tolerance

For measuring length up to:

1 000	2 000	3 000	4 000
0,020/1 000	0,030/1 000	0,040/1 000	0,050/1 000

Local tolerance: 0,015/1 000 for any measuring length of 600

For measuring lengths over 4 000, the tolerance shall be agreed between manufacturer/supplier and user.

Measurement results   For a measuring length of:

Measuring instruments

Square, dial gauge mounted on special arm or taut wire and microscope or sweeping laser.

Observations and references to ISO 230-1:2012, 8.4.2.4

Measure the E_{XZ} straightness deviation of the Z-axis by an instrument mounted on a special arm with a horizontal offset $d/2$ from the spindle axis, alternatively: (i) by a dial gauge against a square set up as in G7 a) and in G11 a), as depicted in Diagram, (ii) by a microscope targeting a vertical taut wire or (iii) by a target of a sweeping laser generating an optical YZ plane. Note the readings and the relevant measuring positions on the spindle head travel (Z-axis).

Position or turn the special arm (carrying the instrument) to the opposite side of the spindle head, and move the Y-axis of *d* in order to repeat the same readings against the same reference; the possible roll of the Y-axis motion shall be measured and taken into account.

For (iii) no Y-axis movement is required.

The instrument shall be reset, the new measurements shall be taken at the same heights of the previous ones, and the results shall be noted.

Measurements shall be carried out on at least six positions along the travel, with equally spaced steps not exceeding 300.

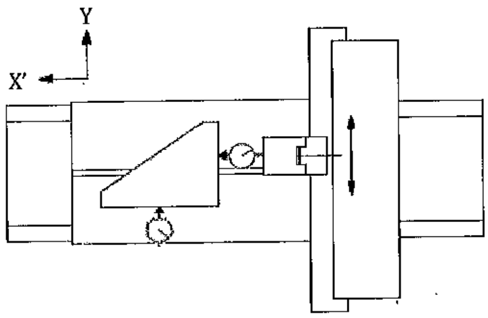
For each measurement position, calculate the algebraic difference between the two readings, and then calculate the difference between maximum and minimum divided by the distance *d* for obtaining the angular deviation.

NOTE: this setup is also applicable for test G14.

Object	**G9**

Checking of the squareness of the spindle head horizontal motion on cross-rail (Y-axis) to the table motion (X'-axis), $E_{C(0X')Y}$.

Diagram



Tolerance

0,040/1 000

Measurement results

Measuring instruments

Square and dial gauge or optical instruments.

Observations and references to ISO 230-1:2012, 10.3.2.2

Place the table in mid travel.

Fix the dial gauge on the spindle head.

Set a square on the table and align one side parallel to the table motion (X'-axis), or the lack of parallelism shall be considered in the measurement.

Place the dial gauge stylus against the other arm of the square measuring in the X-direction. Position the Y-axis close to one end of the square surface and zero the dial gauge.

Move the Y-axis to measure close to the other end of the square surface and note the reading.

The squareness error, $E_{C(0X')Y}$, to be reported is the ratio between the reading and the travelled distance along the Y-axis.

For large machines, the measurement should be repeated at the two extreme table positions.

Object **G10**

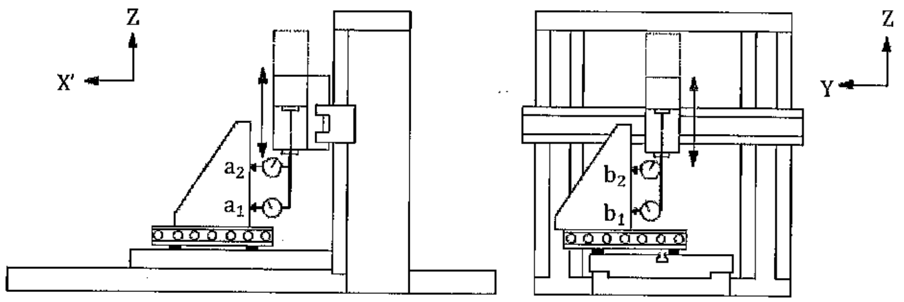
Checking of the squareness of the spindle head vertical motion (Z-axis) to:

a) the X'-axis motion, $E_{B(0X')Z}$;

b) the Y-axis motion, $E_{A(0Y)Z}$.

This test is also applicable to additional vertical spindle heads on the cross-rail.

Diagram



Key

a_1, a_2, b_1 and b_2 measurement positions

Tolerance

For a) and b): 0,050/1 000

Measurement results

a) b)

Measuring instruments

Square, straightedge, adjustable blocks and dial gauge or optical instruments.

Observations and references to ISO 230-1:2012, 10.3.2.2

Place table, movable cross-rail and spindle head at mid travel.

For a): set a straightedge parallel to the X'-axis motion using adjustable blocks or the lack of parallelism shall be considered in the measurement and then place a square on it. Fix a dial gauge on the spindle head. Lock movable cross-rail on columns, where possible.

Apply the stylus of the dial gauge to the square in position a_1, measuring in the X-direction and zero the dial gauge. Move the Z-axis to position a_2 and record the dial gauge reading. The squareness error, $E_{B(0X')Z}$, to be reported is the ratio between the reading in a_2 and the travelled distance along the Z-axis.

For b): set the straightedge parallel to the Y-axis motion using adjustable blocks or the lack of parallelism shall be considered in the measurement and then place the square on it.

Apply the stylus of the dial gauge to the square in position b_1, measuring in the Y-direction and zero the dial gauge. Move the Z-axis to position b_2 and record the dial gauge reading. The squareness error, $E_{A(0Y)Z}$, to be reported is the ratio between the reading in b_2 and the travelled distance along the Z-axis.

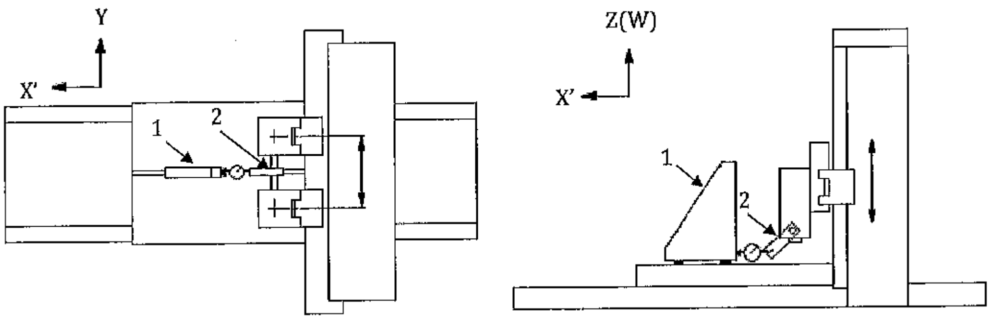
For large machines, checking of the squareness error of Z- to X'-axis, $E_{B(0X')Z}$, should be repeated at the two extreme table positions.

NOTE: This test setup is also applicable to tests G7, G12 and G15. The use of the straightedge is optional.

Object | **G13**

Checking of the angular error of the movable cross-rail in its W-axis motion in the horizontal XY plane, E_{CW}.

Diagram



Key

1 square   2 special arm   *d* travelled distance along Y-axis

Tolerance

For measuring length up to:

2 000	3 000	4 000	5 000
0,030/1 000	0,040/1 000	0,050/1 000	0,060/1 000

Local tolerance: 0,015/1 000 for any measuring length of 1 000

For measuring lengths over 5 000, the tolerance shall be agreed between manufacturer/supplier and user.

Measurement results   For a measuring length of:

Measuring instruments

Square, dial gauge mounted on special arm, or taut wire and microscope, or sweeping laser.

Observations and references to ISO 230-1:2012, 8.4.2.4

Measure the E_{XW} straightness deviation of the W-axis by an instrument mounted on a special arm with a horizontal offset $d/2$ from the spindle axis, alternatively: (i) by a dial gauge against a square set up as in G7 a) and in G11 a), as depicted in Diagram, (ii) by a microscope targeting a vertical taut wire or (iii) by a target of a sweeping laser generating an optical YZ plane. Note the readings and the relevant measuring positions on the cross-rail travel (W-axis).

If used, the taut wire shall be tightened between the table and another fixed part independent from the bridge.

Position or turn the special arm (carrying the instrument) to the opposite side of the spindle head and move the Y-axis of *d* in order to repeat the same readings against the same reference; the possible roll of the Y-axis motion shall be measured and taken into account.

For (iii) no Y-axis movement is required.

The instrument shall be reset and the new measurements shall be taken at the same heights of the previous ones, and the results shall be noted.

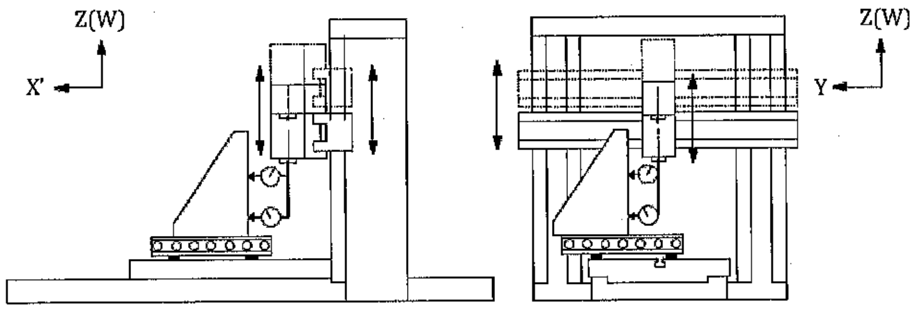
Measurements shall be carried out on at least six positions along the travel, with equally spaced steps not exceeding 500. If the cross-rail is only movable when being positioned in fixed steps, measurements positions shall be selected accordingly.

For each measurement position calculate the algebraic difference between the two readings, and then calculate the difference between maximum and minimum divided by the distance *d* for obtaining the angular error.

NOTE: This test setup is also applicable to test G9.

Object	**G14**
Checking of the parallelism of the movable cross-rail vertical motion (W-axis) to the Z-axis motion: a) in the vertical ZX plane, $E_{B(0Z)W}$; b) in the vertical YZ plane $E_{A(0Z)W}$.	

Diagram



a) b)

Tolerance

For a) and b): 0,030/1 000

Measurement results

a) b)

Measuring instruments

Square, straightedge on adjustable blocks and dial gauge.

Observations and references to ISO 230-1:2012, 10.1.2.2

This test uses the same test setup as G7, G11 and G12.

For a): execute the straightness measurement E_{XZ} described in G7 a) and record the computed slope then, without altering the square alignment, execute the straightness measurement E_{XW} described in G12 a) and record the computed slope.

The parallelism error, $E_{B(0Z)W}$, to be reported, is the difference of the slopes obtained in G7 a) and in G12 a).

For b): execute the straightness measurement E_{YZ} described in G7 b) and record the computed slope then, without altering the square alignment, execute the straightness measurement E_{YW} described in G12 b) and record the computed slope.

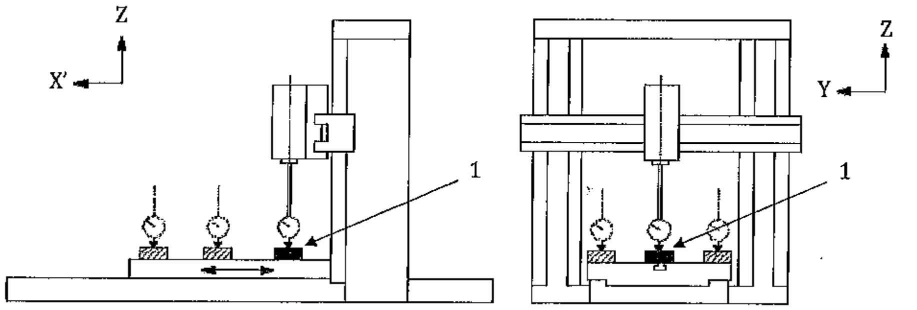
The parallelism error, $E_{A(0Z)W}$, to be reported, is the difference of the slopes obtained in G7 b) and in G12 b).

7 Geometric tests for the table

Object | **G15**

Checking of the parallelism of the table surface to the motion of the table (X'-axis).

Diagram



a) b)

Key

1 gauge block

Tolerance

	For lengths of the longest side of the table up to:			
	2 500	5 000	7 500	10 000
Parallelism tolerance	0,050	0,750	0,150	0,200

For table lengths over 10 000, the tolerance shall be agreed upon between manufacturer/supplier and user.

The above tolerances are specified assuming that finish-machining of the table is not carried out in situ after assembly. If the table is finished in situ, the tolerances shall be agreed upon between the manufacturer/supplier and user.

Measurement results For a measurement distance of: Over a table length of:

Measuring instruments

Dial gauge and gauge block.

Observations and references to ISO 230-1:2012, 12.3.2.5.2

Attach a dial gauge to the tool-holding spindle or to the head near the spindle. The dial gauge stylus shall be touching the table surface directly or touching a gauge block located on the table surface.

The spindle head is at mid travel.

Move the table in the X-direction and record the dial gauge readings.

Measurements shall be carried out at a number of positions equally spaced at steps not exceeding 1/10 of the longest side of the table (see Diagram a)).

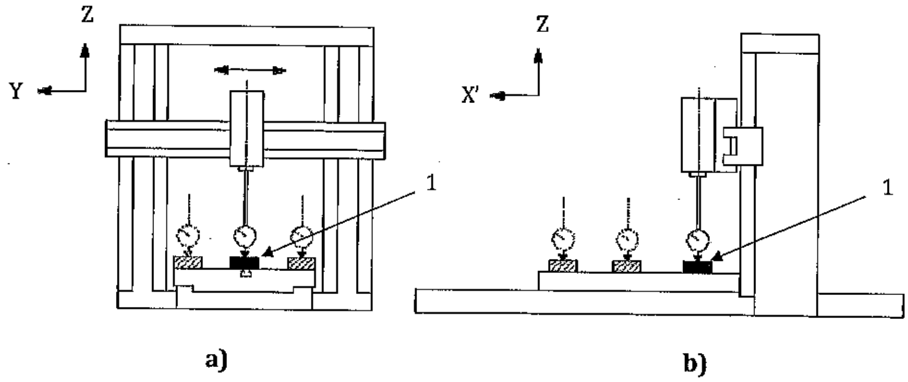
Repeat the test in two other Y-axis positions of the spindle head, symmetrical to the previous position, and record the maximum difference of the readings in the same way (see Diagram b)).

The parallelism error to be reported is the largest of the maximum differences recorded at each Y-axis position.

Object | **G16**

Checking of the parallelism of the table surface to the motion of the spindle head (Y-axis).

Diagram



Key

1 gauge block

Tolerance

	For lengths of the shortest side of the table up to:			
	3 000	4 000	5 000	6 000
Parallelism tolerance	0,030	0,050	0,070	0,090

For table with shortest side lengths over 6 000, the tolerance shall be agreed upon between manufacturer/supplier and user.

The above tolerances are specified assuming that finish-machining of the table is not carried out in situ after assembly. If the table is finished in situ, the tolerances shall be agreed upon between the manufacturer/supplier and user.

Measurement results For a measurement distance of: Over a table width of:

Measuring instruments

Dial gauge and gauge block.

Observations and references to ISO 230-1:2012, 12.3.2.5.2

Attach a dial gauge to the tool-holding spindle or to the head near the spindle. The dial gauge stylus shall be touching the table surface directly or touching a gauge block located on the table surface.

The table is at mid travel.

Move the spindle head in the Y-direction and record the dial gauge readings.

Measurements shall be carried out at a number of positions equally spaced at steps not exceeding 1/5 of the shortest side of the table (see Diagram a)).

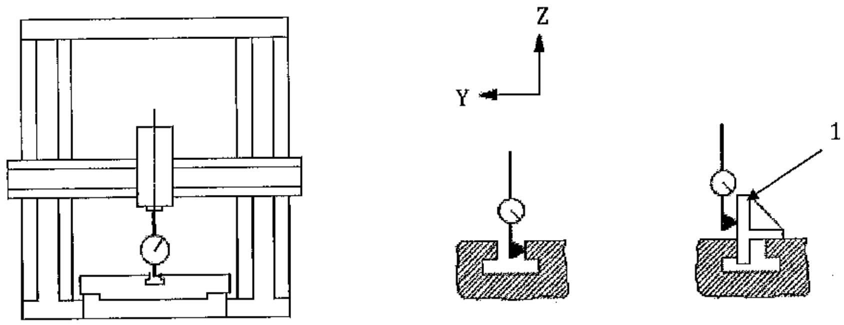
Repeat the test in the two extreme positions of the table and record the maximum differences of the reading in the same way (see Diagram b)).

The parallelism error to be reported is the largest of the maximum differences recorded at each position of the table.

Object — **G17**

Checking of the parallelism of the median or reference T-slot (where present) to the motion of the table (X'-axis).

Diagram



Key

1 cross-square

Tolerance

For length of the longest side of the table up to:

	2 500	5 000	7 500	10 000
Parallelism tolerance	0,075	0,100	0,125	0,150

For table lengths over 10 000, the tolerance shall be agreed upon between manufacturer/supplier and user.

Measurement results For a measurement distance of: Over a table length of:

Measuring instruments

Dial gauge and cross-square.

Observations and references to ISO 230-1:2012, 12.3.2.5.2

Attach a dial gauge to the tool-holding spindle or to the head near the spindle.

Place the gauge stylus in contact with the measuring face of the reference T-slot or use a cross-square.

Move the table and record the dial gauge readings.

Measurements shall be carried out at a number of positions equally spaced at steps not exceeding 1/10 of the longest side of the table.

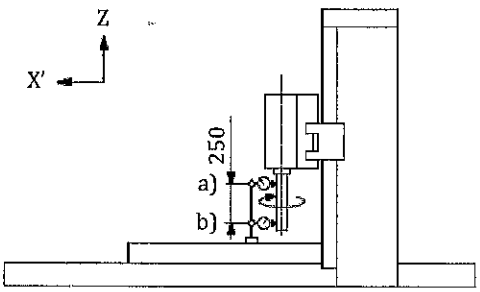
Traverse the X-axis from one measurement position to the following without contact between the stylus and the reference surface. At each measurement position either move down the Z-axis to bring the dial gauge into contact with the reference surface or insert the cross-square between the stylus and the table surface.

The parallelism error to be reported is the difference between the maximum and the minimum readings.

8 Geometric tests for the vertical spindle head

Object	G18
Checking of the run-out of internal taper of the tool-holding spindle: a) close to the spindle nose; b) at a distance of 250 mm from position a). Carry out these tests for each tool-holding spindle of the machine.	

Diagram



Key

a) and b) measurement positions

Tolerance

	$D \leq 125$	$125 < D \leq 200$	$D > 200$
For a):	0,010	0,015	0,020
For b):	0,020	0,025	0,030

where *D* is the diameter of the spindle-nose face (See G20 Diagram).

Measurement results

a) b)

Measuring instruments

Dial gauge and test mandrel.

Observations and references to ISO 230-1:2012,12.5.2

Attach a dial gauge to a fixed part of the machine and insert the test mandrel in the spindle.

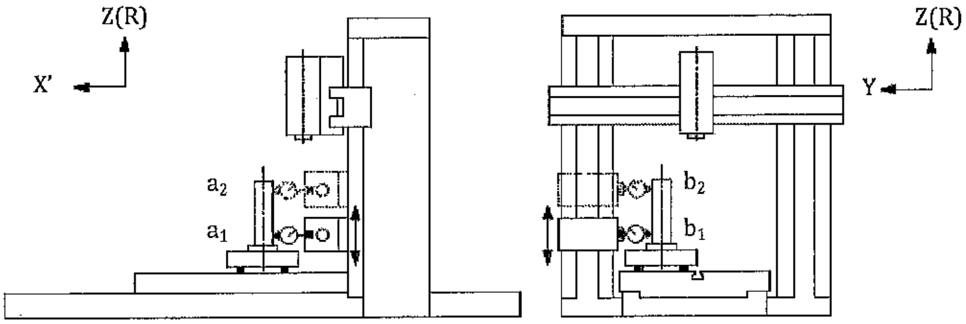
For a): Place the dial gauge stylus as close as possible to the spindle nose, rotate the spindle and record the reading.

Repeat the same operation at position b) at a distance of 250 from position a).

See also test AR1 in Annex A.

For b): place a straightedge at the centre of the table parallel to the Y-axis in the vertical plane or the lack of parallelism shall be considered in the measurement. Attach the special arm with dial gauge to the tool-holding spindle and adjust the stylus of the dial gauge to touch the straightedge, and record the reading. Then rotate the spindle by 180° and record the new reading. The squareness error, $E_{A(0Y)(C)}$, to be reported is the difference between the two readings over the distance between the two measurement points. This test can be performed without straightedge. Mount the dial gauge on special arm and touch a gauge block placed on a specific point of the table. Set the dial gauge to zero and mark the point. Rotate the arm by 180° and move the X-axis for a) and the Y-axis for b) to touch the marked point and read the dial gauge. The difference between the two readings divided by the distance of movement of the axis is the error to be reported. Straightness error motions and pitch error motions of moving axis E_{ZX} and E_{BX} for a) and E_{ZY} and E_{AY} for b), influence the test results.

9 Geometric tests for the horizontal spindle head

Object	**G21**
Checking of the squareness of the vertical motion of the horizontal spindle head (R-axis) on a column to: a) the X-axis motion, $E_{B(0X')R}$; b) the Y-axis motion, $E_{A(0Y)R}$.	
Diagram 	
a)	**b)**
Key	
a_1, a_2, b_1 and b_2 measurement positions	
Tolerance For a) and b): 0,050/1 000	
Measurement results a)	b)
Measuring instruments Cylindrical square, surface plate, adjustable blocks and dial gauge or optical instruments.	
Observations and references to ISO 230-1:2012, 10.3.2.2 Place movable cross-rail and vertical spindle head at mid travel.	

Fix the dial gauge to the side spindle head. If the spindle can be locked, the dial gauge may be mounted on it. If the spindle cannot be locked, the dial gauge shall be placed on a fixed part of the side spindle head.

Place a cylindrical square, or a regular square, on a surface plate oriented parallel to the reference plane defined by the X'-axis motion of the table and the Y-axis motion of the vertical spindle head, or the lack of parallelism shall be considered in the measurement; then orient the dial gauge stylus in the X-axis direction to touch at point a_1 on the cylindrical square and zero the dial gauge. Move side spindle head to point a_2 and record the dial gauge reading.

Rotate the cylindrical square by 180° and repeat the checking in the same order.

The squareness error, $E_{B(0X')R}$, to be reported is the average value of the recorded dial gauge readings divided by the distance between points $a_1$and a_2 for a) and between points $b_1$and b_2 for b).

Then carry out checking in the Y-axis direction at points b_1 and b_2 for the determination of the squareness error, $E_{A(0Y)R}$.

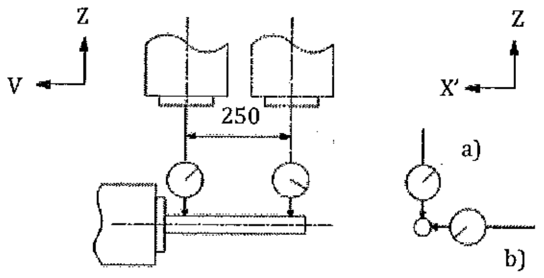
Object | **G22**

Checking of the parallelism of the horizontal spindle head spindle axis, (B), to the Y-axis motion:

a) in the vertical YZ plane, $E_{A(0Y)(B)}$;

b) in the horizontal XY plane, $E_{C(0Y)(B)}$.

Diagram



Tolerance

For a) and b): 0,060/1 000 (0,015/250)

Measurement results

a) b)

Measuring instruments

Test mandrel and dial gauge or optical instruments.

Observations and references to ISO 230-1:2012, 10.1.4

Attach the dial gauge to the vertical spindle head and adjust its stylus to touch the test mandrel mounted on the horizontal tool-holding spindle, for a) vertically and for b) horizontally, as near as possible to the spindle nose.

Horizontal spindle head is locked in low-position. Movable cross-rail is locked in mid travel, where possible.

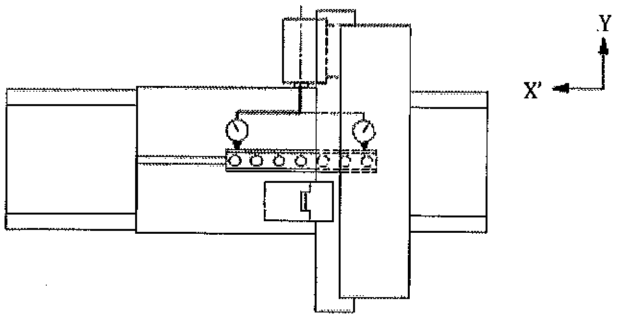
Move the vertical spindle head (Y-axis) for the measuring length and record the readings.

Record the maximum difference of dial gauge readings, then rotate the spindle axis, (B), by 180° and record again the maximum difference of dial gauge readings. The measurement results to be reported are the averages of the maximum readings recorded with spindle axis, (B), at 0° and at 180° respectively.

Object | **G23**

Checking of the squareness of the axis of rotation of the horizontal tool-holding spindle, (B), to the motion of the table (X'-axis), $E_{C(0X')(B)}$.

Diagram



Tolerance

0,060/1 000 (0,030/500)

Measurement results

Measuring instruments

Straightedge, dial gauge mounted on special arm.

Observations and references to ISO 230-1:2012, 10.3.3

Place a straightedge at the centre of the table parallel to the X'-axis motion in the horizontal plane or the lack of parallelism shall be considered in the measurement.

The table is locked at mid travel, where possible.

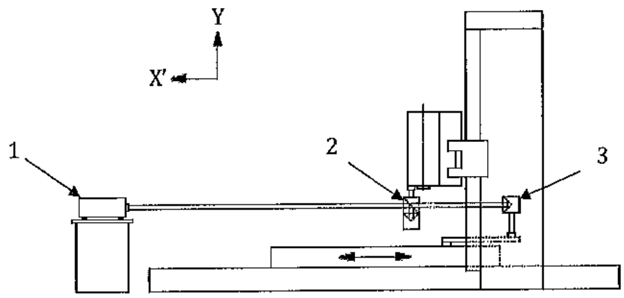
Attach the special arm with dial gauge to the horizontal tool-holding spindle and adjust the stylus of the dial gauge to touch the straightedge and record the reading. Then rotate the spindle by 180° and record the new reading.

The squareness error, $E_{C(0X')(B)}$, to be reported is the ratio of the difference between the two readings over the distance between the two measurement points.

10 Accuracy and repeatability of positioning of linear axes

Object	**P1**
Checking of the accuracy and repeatability of the X-axis motion of the table, $E_{XX'}$.	

Diagram



Key

1 laser head 2 interferometer 3 retro-reflector

Tolerance		Measured length			**Measurement results**
For axes up to 2 000		≤ 500	≤ 1 000	≤ 2 000	
Bi-directional positioning accuracy of X-axis [a]	$E_{XX',A}$	0,020	0,025	0,032	
Unidirectional positioning repeatability of X-axis [a]	$E_{XX',R\uparrow}$; $E_{XX',R\downarrow}$	0,008	0,010	0,013	
Bi-directional positioning repeatability of X-axis	$E_{XX',R}$	0,011	0,014	0,017	
Mean reversal value of X-axis	$E_{XX',\bar{B}}$	0,010	0,013	0,016	
Bi-directional systematic positioning error of X-axis [a]	$E_{XX',E}$	0,016	0,020	0,025	
Mean bi-directional positioning error of X-axis [a]	$E_{XX',M}$	0,010	0,013	0,016	
For axes exceeding 2 000					
Bi-directional systematic positioning error of X-axis [a]	$E_{XX',E}$	0,025 + 0,005 for each additional 1 000			
Mean bi-directional positioning error of X-axis [a]	$E_{XX',M}$	0,016 + 0,003 for each additional 1 000			

[a] Possible basis for machine acceptance.

Measuring instruments

Laser measurement equipment or linear scale.

Observations and references to ISO 230-1:2012, 3.4.3; ISO 230-2:2014, 3, 5.3.2 and 5.3.3

Relative measurement between the tool position and work-piece position is desired. When a linear scale is used, it shall be set on the table parallel to the X'-axis, the scale reader being on the tool position. When laser equipment is used, the reflector shall be set on the vertical spindle head and the interferometer on the table.

For axes exceeding 2 000, one or more segments of 2 000 with 5 runs forward and backward each. Tolerances for axis lengths ≤ 2 000 shall be applied.

For axes up to 4 000 one measurement over one 2 000 segment is recommended; for axes over 4 000 and up to 8 000 two 2 000 segments are recommended, and so forth.

Test segments shall be equally spaced along the full axis length, with any excess length equally divided at the beginning, in between, and at the end of the test segments.

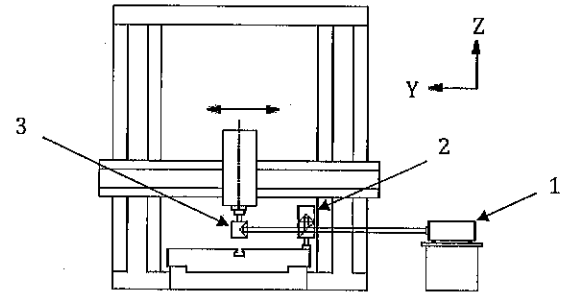
Other number of 2 000 mm segments, other lengths of segments, as well as the positions of the segments within the working area can be subject to agreement between manufacturer/supplier and user. Additionally, one test over the total travel of the axis (once forward and once backward) shall be performed.

Concerning the test conditions, test program and presentation of results, ISO 230-2:2014, Clauses 3, 4 and 7 and subclause 8.2.4 shall be referred to. The starting point of measurement shall be stated.

Object — **P2**

Checking of the accuracy and repeatability of the Y-axis motion of the vertical spindle head, E_{YY}.

Diagram



Key

1 laser head 2 interferometer 3 retro-reflector

Tolerance		Measured length			**Measurement results**
For axes up to 2 000		≤ 500	≤ 1 000	≤ 2 000	
Bi-directional positioning accuracy of Y-axis [a]	$E_{YY,A}$	0,020	0,025	0,032	
Unidirectional positioning repeatability of Y-axis [a]	$E_{YY,R\uparrow}$; $E_{YY,R\downarrow}$	0,008	0,010	0,013	
Bi-directional positioning repeatability of Y-axis	$E_{YY,R}$	0,011	0,014	0,017	
Mean reversal value of Y-axis	$E_{YY,\bar{B}}$	0,010	0,013	0,016	
Bi-directional systematic positioning error of Y-axis [a]	$E_{YY,E}$	0,016	0,020	0,025	
Mean bi-directional positioning error of Y-axis a	$E_{YY,M}$	0,010	0,013	0,016	
For axes exceeding 2 000					
Bi-directional systematic positioning error of Y-axis [a]	$E_{YY,E}$	0,025 + 0,005 for each additional 1 000			
Mean bi-directional positioning error of Y-axis [a]	$E_{YY,M}$	0,016 + 0,003 for each additional 1 000			

[a] Possible basis for machine acceptance.

Measuring instruments

Laser measurement equipment or linear scale.

Observations and references to ISO 230-1:2012, 3.4.3; ISO 230-2:2014, 3, 5.3.2 and 5.3.3

Relative measurement between the tool position and work-piece position is desired. When a linear scale is used, it shall be set on the table parallel to the Y-axis, the scale reader being on the tool position. When laser equipment is used, the reflector shall be set on the vertical spindle head and the interferometer on the table.

For axes exceeding 2 000, one or more segments of 2 000 with 5 runs forward and backward each. Tolerances for axis lengths ≤ 2 000 shall be applied.

For axes up to 4 000 one measurement over one 2 000 segment is recommended; for axes over 4 000 and up to 8 000 two 2 000 segments are recommended, and so forth.

Test segments shall be equally spaced along the full axis length, with any excess length equally divided at the beginning, in between, and at the end of the test segments.

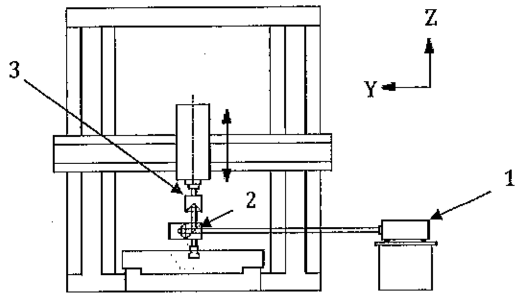
Other number of 2 000 mm segments, other lengths of segments, as well as the positions of the segments within the working area can be subject to agreement between manufacturer/supplier and user. Additionally, one test over the total travel of the axis (once forward and once backward) shall be performed.

Concerning the test conditions, test program and presentation of results, ISO 230-2:2014, Clauses 3, 4 and 7 and subclause 8.2.4 shall be referred to. The starting point of measurement shall be stated.

Object — **P3**

Checking of the accuracy and repeatability of the Z-axis motion of the vertical spindle head ram or quill, E_{ZZ}.

Diagram



Key

1 laser head 2 interferometer 3 retro-reflector

Tolerance		Measured length			**Measurement results**
For axes up to 2 000		≤ 500	≤ 1 000	≤ 2 000	
Bi-directional positioning accuracy of Z-axis [a]	$E_{ZZ,A}$	0,020	0,025	0,032	
Unidirectional positioning repeatability of Z-axis [a]	$E_{ZZ,R\uparrow}$; $E_{ZZ,R\downarrow}$	0,008	0,010	0,013	
Bi-directional positioning repeatability of Z-axis	$E_{ZZ,R}$	0,011	0,014	0,017	
Mean reversal value of Z-axis	$E_{ZZ,\bar{B}}$	0,010	0,013	0,016	
Bi-directional systematic positioning error of Z-axis [a]	$E_{ZZ,E}$	0,016	0,020	0,025	
Mean bi-directional positioning error of Z-axis [a]	$E_{ZZ,M}$	0,010	0,013	0,016	
For axes exceeding 2 000					
Bi-directional systematic positioning error of Z-axis [a]	$E_{ZZ,E}$	0,025 + 0,005 for each additional 1 000			
Mean bi-directional positioning error of Z-axis [a]	$E_{ZZ,M}$	0,016 + 0,003 for each additional 1 000			

[a] Possible basis for machine acceptance.

Measuring instruments

Laser measurement equipment or linear scale.

Observations and references to ISO 230-1:2012, 3.4.3; ISO 230-2:2014, 3, 5.3.2 and 5.3.3

Relative measurement between the tool position and work-piece position is desired. When a linear scale is used, it shall be set on the table parallel to the Z-axis, the scale reader being on the tool position. When laser equipment is used, the reflector shall be set on the vertical spindle head and the interferometer on the table.

For axes exceeding 2 000, one or more segments of 2 000 with 5 runs forward and backward each. Tolerances for axis lengths ≤ 2 000 shall be applied.

For axes up to 4 000 one measurement over one 2 000 segment is recommended; for axes over 4 000 and up to 8 000 two 2 000 segments are recommended, and so forth.

Test segments shall be equally spaced along the full axis length, with any excess length equally divided at the beginning, in between, and at the end of the test segments.

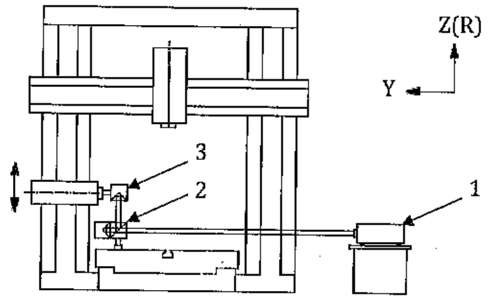
Other number of 2 000 mm segments, other lengths of segments, as well as the positions of the segments within the working area can be subject to agreement between manufacturer/supplier and user. Additionally, one test over the total travel of the axis (once forward and once backward) shall be performed.

Concerning the test conditions, test program and presentation of results, ISO 230-2:2014, Clauses 3, 4 and 7 and subclause 8.2.4 shall be referred to. The starting point of measurement shall be stated.

Object — **P4**

Checking of the accuracy and repeatability of the vertical R-axis motion of the horizontal spindle head, E_{ZR}.

Diagram



Key

1 laser head 2 interferometer 3 retro-reflector

Tolerance For axes up to 2 000		Measured length ≤ 500	Measured length ≤ 1 000	Measured length ≤ 2 000	Measurement results
Bi-directional positioning accuracy of R-axis [a]	$E_{ZR,A}$	0,020	0,025	0,032	
Unidirectional positioning repeatability of R-axis [a]	$E_{ZR,R\uparrow}$; $E_{ZR,R\downarrow}$	0,008	0,010	0,013	
Bi-directional positioning repeatability of R-axis	$E_{ZR,R}$	0,011	0,014	0,017	
Mean reversal value of R-axis	$E_{ZR,\bar{B}}$	0,010	0,013	0,016	
Bi-directional systematic positioning error of R-axis [a]	$E_{ZR,E}$	0,016	0,020	0,025	
Mean bi-directional positioning error of R-axis [a]	$E_{ZR,M}$	0,010	0,013	0,016	
For axes exceeding 2 000					
Bi-directional systematic positioning error of R-axis [a]	$E_{ZR,E}$	0,025 + 0,005 for each additional 1 000			
Mean bi-directional positioning error of R-axis [a]	$E_{ZR,M}$	0,016 + 0,003 for each additional 1 000			

[a] Possible basis for machine acceptance.

Measuring instruments

Laser measurement equipment or linear scale.

Observations and references to ISO 230-1:2012, 3.4.3; ISO 230-2:2014, 3, 5.3.2 and 5.3.3

Relative measurement between the tool position and work-piece position is desired. When a linear scale is used, it shall be set on the table parallel to the Z-axis, the scale reader being on the tool position. When laser equipment is used, the reflector shall be set on the horizontal spindle head and the interferometer on the table.

For axes exceeding 2 000, one or more segments of 2 000 with 5 runs forward and backward each. Tolerances for axis lengths ≤ 2 000 shall be applied.

For axes up to 4 000 one measurement over one 2 000 segment is recommended; for axes over 4 000 and up to 8 000 two 2 000 segments are recommended, and so forth.

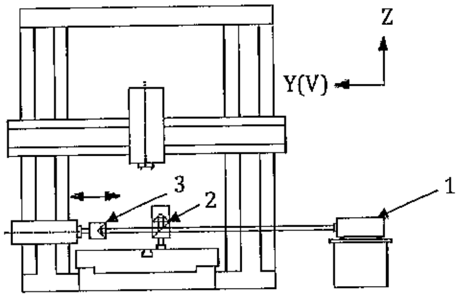
Test segments shall be equally spaced along the full axis length, with any excess length equally divided at the beginning, in between, and at the end of the test segments.

Other number of 2 000 mm segments, other lengths of segments, as well as the positions of the segments within the working area can be subject to agreement between manufacturer/supplier and user. Additionally, one test over the total travel of the axis (once forward and once backward) shall be performed.

Concerning the test conditions, test program and presentation of results, ISO 230-2:2014, Clauses 3, 4 and 7 and subclause 8.2.4 shall be referred to. The starting point of measurement shall be stated.

Object	P5
Checking of the accuracy and repeatability of the horizontal V-axis motion of the horizontal spindle head or quill, E_{YV}.	

Diagram



Key

1 laser head 2 interferometer   3 retro-reflector

Tolerance For axes up to 1 000		Measured length		**Measurement results**
		≤ 500	≤ 1 000	
Bi-directional positioning accuracy of V-axis [a]	$E_{YV,A}$	0,020	0,025	
Unidirectional positioning repeatability of V-axis [a]	$E_{YV,R\uparrow}$; $E_{YV,R\downarrow}$	0,008	0,010	
Bi-directional positioning repeatability of V-axis	$E_{YV,R}$	0,011	0,014	
Mean reversal value of V-axis	$E_{YV,\bar{B}}$	0,010	0,013	
Bi-directional systematic positioning error of V-axis [a]	$E_{YV,E}$	0,016	0,020	
Mean bi-directional positioning error of V-axis [a]	$E_{YV,M}$	0,010	0,013	

[a] Possible basis for machine acceptance.

Measuring instruments

Laser measurement equipment or linear scale.

Observations and references to ISO 230-1:2012, 3.4.3; ISO 230-2:2014, 3, 5.3.2 and 5.3.3

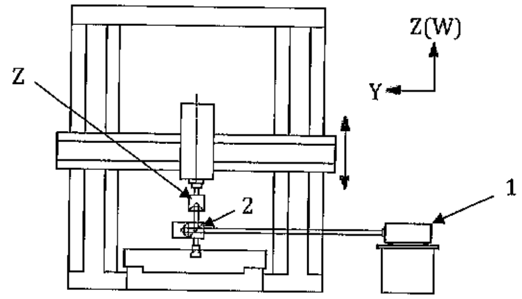
Relative measurement between the tool position and work-piece position is desired. When a linear scale is used, it shall be set on the table parallel to the Y-axis, the scale reader being on the tool position. When laser equipment is used, the reflector shall be set on the horizontal spindle head and the interferometer on the table.

Concerning the test conditions, test program and presentation of results, ISO 230-2:2006, Clauses 3, 4 and 7 and subclause 8.2.4 shall be referred to.

Object — **P6**

Checking of the accuracy and repeatability of the W-axis motion of the cross-rail when numerically controlled, E_{ZW}.

Diagram



Key

1 laser head 2 interferometer 3 retro-reflector

Tolerance

For axes up to 2 000		Measured length			Measurement results
		≤ 500	≤ 1 000	≤ 2 000	
Bi-directional positioning accuracy of W-axis [a]	$E_{ZW,A}$	0,020	0,025	0,032	
Unidirectional positioning repeatability of W-axis [a]	$E_{ZW,R\uparrow}$;$E_{ZW,R\downarrow}$	0,008	0,010	0,013	
Bi-directional positioning repeatability of W-axis	$E_{ZW,R}$	0,011	0,014	0,017	
Mean reversal value of W-axis	$E_{ZW,\bar{B}}$	0,010	0,013	0,016	
Bi-directional systematic positioning error of W-axis [a]	$E_{ZW,E}$	0,016	0,020	0,025	
Mean bi-directional positioning error of W-axis [a]	$E_{ZW,M}$	0,010	0,013	0,016	
For axes exceeding 2 000					
Bi-directional systematic positioning error of W-axis [a]	$E_{ZW,E}$	0,025 + 0,005 for each additional 1 000			
Mean bi-directional positioning error of W-axis [a]	$E_{ZW,M}$	0,016 + 0,003 for each additional 1 000			

[a] Possible basis for machine acceptance.

Measuring instruments

Laser measurement equipment or linear scale.

Observations and references to ISO 230-1:2012, 3.4.3; ISO 230-2:2014, 3, 5.3.2 and 5.3.3

Relative measurement between the tool position and work-piece position is desired. When a linear scale is used, it shall be set on the table parallel to the Z-axis, the scale reader being on the tool position. When laser equipment is used, the reflector shall be set on the vertical spindle head and the interferometer on the table.

For axes exceeding 2 000, one or more segments of 2 000 with 5 runs forward and backward each. Tolerances for axis lengths ≤ 2 000 shall be applied.

For axes up to 4 000 one measurement over one 2 000 segment is recommended; for axes over 4 000 and up to 8 000 two 2 000 segments are recommended, and so forth.

Test segments shall be equally spaced along the full axis length, with any excess length equally divided at the beginning, in between, and at the end of the test segments.

Other number of 2 000 mm segments, other lengths of segments, as well as the positions of the segments within the working area can be subject to agreement between manufacturer/supplier and user. Additionally, one test over the total travel of the axis (once forward and once backward) shall be performed.

Concerning the test conditions, test program and presentation of results, ISO 230-2:2014, Clauses 3, 4 and 7 and subclause 8.2.4 shall be referred to. The starting point of measurement shall be stated.

The difference between the readings of target 1 and target 2 allows for appropriate differential measurements. Stability is monitored by the readings of optional target 3.

In Figure B.2, for graphical reasons, target 1 is represented as not being aligned with the centre of rotation of the laser scanning device head but, to improve measurement execution efficiency, it is suggested to locate target 1 to be in alignment.

In the setup depicted in Figure B.2, the distances between the laser scanning device and the various targets (especially for optional target 3) are larger than the distances required with the setup depicted in Figure B.1, so measurement uncertainty is expected to increase as it is highly influenced by any air turbulences, e.g., caused by changing surface temperatures along the laser path.

Annex C
(informative)

Terms in other languages

See Table C.1.

Table C.1 — Terms in other than official ISO languages for Figure 1

Key	German	Italian	Japanese	Persian
1	Bett	banco		
2	Führungsbahn, Bett	guida del banco		
3	Tisch	tavola		
4	Ständer, links	montante sinistro		
5	Ständer, rechts	montante destro		
6	Führungsbahn, Ständer rechts und links	guide dei montanti		
7	Querbalken (beweglich, fest)	traversa mobile (o fissa)		
8	Spindelstock, senkrecht	testa porta-utensili verticale		
9	Spindelstock, waagerecht	testa porta-utensili orizzontale		
10	Traverse	traversa fissa		
11	Unterschlitten	slitta orizzontale		
12	Traghülse (Pinole)	cannotto		
13		mandrino porta-utensile		
14	Werkzeug (Fräser)	utensile (fresa)		
15	Richtnut	scanalatura di riferimento		
R	vertikale Bewegung des horizontalen Fräskopfes (R-Achse)	movimento verticale della testa di fresatura orizzontale (asse R)		
V	horizontale Bewegung des horizontalen Fräskopfes (V-Achse)	movimento orizzontale della testa di fresatura orizzontale (asse V)		
W	bewegliche Traverse, vertikale Bewegung (W-Achse)	movimento verticale della traversa mobile (asse W)		
X'	X-Achse	asse X		
Y	Y-Achse	asse Y		
Z	Z-Achse	asse Z		

Bibliography

[1] ISO/TR 230-11, *Test code for machine tools — Part 11: Measuring instruments suitable for machine tool geometry tests*

[2] ISO 841:2001, *Industrial automation systems and integration — Numerical control of machines — Coordinate system and motion nomenclature*

[3] ISO 10791-7:2019, *Test conditions for machining centres — Part 7: Accuracy of finished test pieces*

[4] ISO 13041-2:2019, *Test conditions for numerically controlled turning machines and turning centres — Part 2: Geometric tests for machines with a vertical workholding spindle*

[5] ISO/TR 16907:2015, *Machine tools — Numerical compensation of geometric errors*

[6] Knapp, W., Bringmann, B.; Straightness Measurement for Long Movements. Nanotechnology and Precision Engineering, (2005).