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QUALIFYING LASER-INTEGRATED MACHINE TOOLS WITH MULTIPLE WORKSPACE FOR MACHINING PRECISION

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Abstract: *Production of complex components requires different production sequences. Especially in the mold and die production, heat treatment, hardening or deposition welding are required. Additional processing systems can be combined in one machine in order to reduce logistical effort in the production of such components. Machine concepts offering these options pose new challenges for the maintenance of machining accuracy. The presented research examines different aspects concerning operation accuracy of a machining centre with two workspaces and an integrated industrial robot. Potential loss of accuracy is analyzed and experimental results of the most important influences are discussed. Interactions between the workspaces, basically resulting from simultaneous processing, are focused.*

Key words: *integrated machine tools, laser integration, machining precision, thermal impact, mechanical interactions, and qualification.*

1. INTRODUCTION

The Cluster of Excellence "Integrative Production Technology for High-Wage Countries" of RWTH Aachen University focuses on the polylemma of production. As illustrated in Fig. 1 the polylemma is spanned between the dimensions scale and scope in one axis as well as between the dimensions plan and value in the other axis. Descriptions of each dimension and the corresponding dilemma are listed at the lower part of Fig. 1. Main target of the Cluster is the resolution of the polylemma of production by merging the contradicting corners. In this way manufacturers necessity to focus on a single strategy can be reduced.

"Productivity vs. flexibility" is one of the main conflicts that split production methods. Customized production on the one hand requires flexibility and small batches; on the other hand the increase of productivity is essential for low cost per piece in mass production [1, 2]. Consequently modern production systems have to meet both, the requirements of flexible production and economical efficiency.

Figure 2 illustrates the need of high-wage countries to use their ledge of innovation from the point of view of industry´s competitiveness. To ensure competitiveness in high wage countries it is necessary to ensure a certain ledge in the utilization of technology and to remain it by being more innovative compared to low wage countries. From the point of view of cost per piece the actual state is plotted in the lower part of Fig. 2. As illustrated the curve of total costs in a high wage country compared to those of low-wage countries are higher, basically due to higher unit labour costs. Costs for technical resources are similar all over the world. Consequently the optimum costs per piece are reached in a high-wage country at a higher intensity of technology usage compared to the optimum of low-wage countries [3].

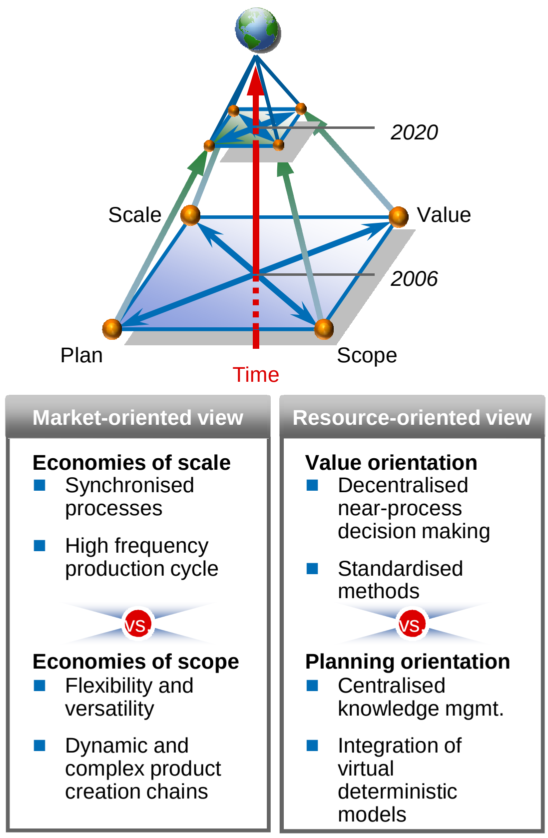

Fig. 1. Resolution of the Polylemma of Production.

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Focusing future production systems in high wage countries it is essential to be more flexible on the one hand but remain cost efficient in terms of part costs on the other hand.

For being more flexible one approach is to enable production systems to execute further production steps if required for certain lots [4]. That for in the past more and more machine tools were equipped with additional technologies. Those hybrid concepts can be divided in three categories: integrated applications or combinations of different physical mechanisms, integrated machines performing different processes on the same workpiece and integrated combinations of production steps [5]. But, by integrating additional technologies, the cost per piece rise also being caused by higher machine hour rates and idle times of some components.

Within the Cluster of Excellence the research question was consequently defined to be: How can multi-technology platforms be designed taking into account the complex machine/ process interdependencies and how can the complexity be handled in order to shorten innovation cycles, time to market or to reduce costs per unit?

In the next chapters different kinds of integrated production systems are categorized, a demonstration machine is introduced, possible interactions are classified and those appearing at the demonstrator machine are qualified metrological.

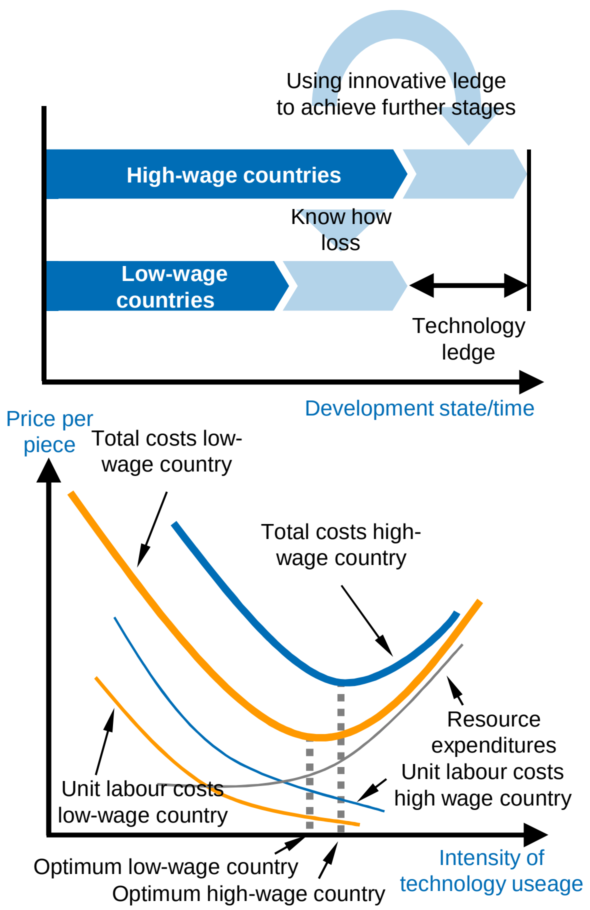

Fig. 2. Technological and innovative edge for safeguarding the industry's competitiveness.

2. TECHNOLOGY INTEGRATION INTO MASCHINE TOOLS

Focusing on production technology the term "hybrid" can be related with products, manufacturing processes and production systems. Typical examples for hybrid products are hybrid semi-finished sheet metals, fiber-reinforced cast components or plastics with integrated conductor tracks. They all consist of different materials that are usually not combined and mainly have completely different properties.

Concerning manufacturing processes the following definition resulted from discussions within CIRP [6]: “Hybrid manufacturing processes are based on the simultaneous and controlled interaction of process mechanisms and/or energy sources/tools having a significant effect on the process performance” That means a conventional manufacturing method is supported by a second process in order to reduce the manufacturing cost of a product, to achieve a higher quality or to overcome other existing limits. A typical process is laser assisted turning, being used for materials that cannot be machine in common lathes.

Production systems are called hybrid whenever an additional dissimilar process step can be applied within the same machine tool. At least two different technologies must be applied [7]. In contrast to hybrid processes, hybrid production systems are also called hybrid if the processes are applied sequentially at the same workpiece.

Another basic difference can be found in the economical motivation. Most hybrid processes are driven by the idea to machine materials that cannot be machined with convectional technologies or to enlarge the economic benefit by increasing the productivity of the processes [8 and 9]. Hybrid production systems basically provide additional production steps that are normally applied by machine tools next in line.
Economic benefits can result shortening the overall time of production or from increasing the quality by manufacturing without re-clamping. As illustrated in several studies [10], the main disadvantage of most hybrid production systems is the investments in combination with the losses of relative productivity. In most applications, one proces unit is used, whereas the others are idle [11].

Besides the reduction of overall production time, advantages of integrated machine tools are typically a higher flexibility, especially regarding small batch sizes. Form the point of view of manufactures arguments like:

- High degree of automation.
- Complete machining in a single clamping.
- Continuous process data chain.
- Option of integrated workpiece qualification.
- High processing flexibility.
- Reduction of efforts for transport and setup need to be taken into account when discussing the integration of technologies into machine tools [2].

Figure 3 gives a short overview over different hybrid machine tools being developed in industry and at research institutes the last years.

One of the first machine tools combining completely different technologies is the TruMatic 6000 from TRUMPF Werkzeugmaschinen GmbH+Co. KG. In order

Fig. 3. Development of Technology Integrated Machine Tools.

to be able to fulfil the requirements of mass production on the one hand and to provide the flexibility for individualized production on the other hand a conventional punching machine is equipped with an additional laser for laser cutting. Using this hybrid design it is possible to produce standard parts in large lots very cost efficient by punching and to be flexible for smaller lots by laser cutting.

In order to overcome limitations of turning processes and corresponding process chains the RNC 400 Laser-Turn was developed in cooperation between the machine tool manufacturer A. Monforts GmbH & Co. KG and the Fraunhofer IPT. Such machine concepts allow laser assisted turning operation, but in some versions of the machine also laser deposition welding. Deposition welding and laser hardening can be used for the production of shafts with integrated bearing seat or for example for highly wear resistant valve seats. Laser assisted turning basically offers economical advantages in terms of higher removal rates and reduced tool wear [2, 12, 13 and 14].

The third example for hybrid machine tools are the model series GS and GX of Alzmetall Werkzeugmaschinenfabrik und Gießerei Friedrich GmbH & Co. KG as presented in Fig. 3. By integrating the machining process drilling, turning, milling and grinding as well as measurement devices, the machining centres GS offer the option of complete machining in one clamping. Machines of the GX series are equipped with laser hardening, laser re-melting, laser alloying, laser dispersing and laser deposition welding enabling complete thermal five axis machine of highly wear resistant components [15].

More or less the reasons for combining processes in the way the examples illustrate are similar in each case. Additional technologies are integrated in order to provide additional process steps for more flexibility in the same clamping. From the technical point of view all concepts succeeded in providing the expected advantages. Focusing the economical view the utilization of integrated technologies must be taken into account as well. That means it must be taken into account how expensive each production resource is and in which extend it is used. Whenever production resources are used sequentially some of them have idle times that increase the machine hour rate and therefore the production cost per piece.

A consequent further evolution of this approach to solve the dilemma between technical requirements and economical boundaries is the development of integrated machine tool concepts that offer the possibility to use different technologies simultaneously. That means production resources for different processes can be used for value creation parallel to each other [11]. In this way their overall degree of utilization rises tremendously compared to integrated machine tools that do not offer this option [10].

One solution to have multiple tools or processing units in operation is limited to comparative huge workpieces and to certain limitations of axis configurations. That means there must be enough space for processing in terms of large workpieces in huge workspaces. Further the workpiece should be static on the table. Else the workpiece movement must be compensated by the second manipulator.

Another machine tool design providing the option for simultaneous processing is illustrated in Fig. 4. The platform for hybrid metal processing was designed and built within the first phase of the Cluster of Excellence "Integrative Production Technology for High-Wage Countries" of RWTH Aachen University.

In cooperation with the machine tool manufacturer CHIRON-WERKE GmbH & Co. KG a common milling machine was selected to be the base for the integration of additional laser processes. With a bed length of 2000 mm the base machine provides enough space for two equal workspaces and an additional manipulator in the middle. A processing unit for laser deposition welding and laser hardening (d) as well as another processing unit for laser texturing and laser deburring (b left one) were integrated. They can be picked up by the robot (f housing) or by the spindle (a) from their magazine (b) in the middle between both swivel tables (c) in the workspaces. Both laser processing units are equipped with media supplies (e) being able to enter both workspaces.

Such a design allows simultaneous processing of two workpieces – one in each workspace. It is possible to get the flexibility for small batch sizes and technological advantages without losing economic efficiency caused by disproportional ratio of idle times like hybrid machine tools with non simultaneous processing normally show. Produced use cases and demonstrator scenarios showed

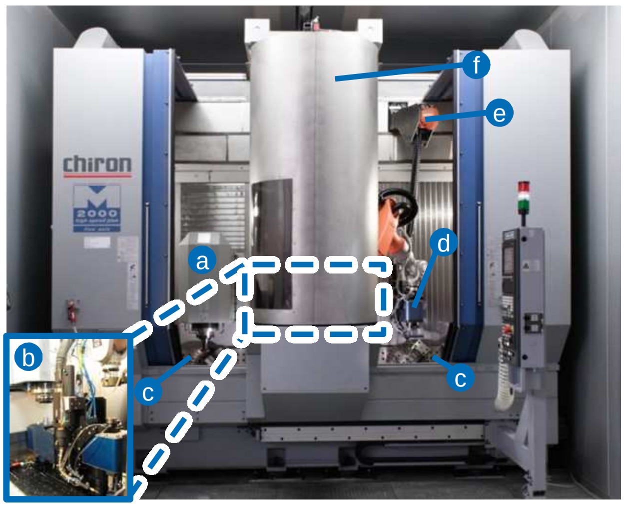

Fig. 4. Configuration of the Hybrid Machine Tool for Metal Processing.

that the utilization of processing units highly depends on boundary conditions like the combination and length of processes but can easily be driven above common levels.

In how far technical limitations can border these achievements and how machine tools like that one can be qualified is derived in general and exemplarily illustrated in the next chapters. In particular this includes demonstrating possible mutual influences of integrated machine tools in form of cause-and-effect diagrams and identifying possibilities of the metrological examination and qualification of the main impact factors on the trade off between processing quality and efficiency.

3. IDENTIFICATION AND CLASSIFICATION OF INTERACTION PRINCIPLES

Machining processes have to meet requested specifications in terms of quality and productivity. Normally these objectives are opposed. A higher quality can easier be achieved when running the process at lower levels of productivity – the other way around high output rates decrease the quality being achievable.

Regarding integrated machine tools additional boundaries and mechanisms of interactions might occur. For example optical systems, being highly sensitive to mechanical impacts or to contaminations cannot provide best quality in a common machine tool environment.

Besides process specific impacts resulting from technological parameters like cutting rate, cutting material, feed rate, and tool types influences may result from the machine tool or from configuration of process chains.

This paper focuses on the impacts resulting from the machine setup and in somehow resulting from different setups of process chains.

In order to reduce or eliminate a potential decrease of machining precision it is essential to understand the mechanisms that are responsible. Depending on the configuration of a specific integrated machine tool different effects, shown in Fig. 6 might occur. While listing the cause-and-effect diagram the focus is on laser integrated machine tools and their specialties in terms of resulting interactions due to the integration. In addition to the impacts that affect machining precision in common machine tools like milling, drilling or turning the effects caused by the contactless machining of the laser units as well as potential synergetic effects inducted by the different technologies have to be taken into account.
Focusing on laser integrated machine tools causes for the displacement can be subdivided into three main categories as shown in Fig. 6.

- static-mechanical displacement;
- dynamic-mechanical displacement;
- thermal displacement.

The category static-mechanical displacement lists all causes that influence the position of a certain reference even statically. That means any impact is mentions that appears without movement and is caused by additional integration specific weights. Considering an additional process unit it´s weight must be taken into account, but also further components that became necessary to handle that unit. That might be an additional manipulator that is mounted on an additional platform and can be posed in different positions.

Effects being listed in the category dynamic-mechanical displacement are basically inertia forces resulting from any movement or utilization of integrated components. That might be the acceleration and the motion masses among defined path in combination with dynamic transmission behaviours.

Regarding thermally caused displacements the process power, the initial system temperature and the mechanisms of energy transportation must be mentioned first. The exact position of processing units and manipulators in relation to the heat source, point of machining and the time of exposition to heat might also be important factors affecting the exact thermally caused displacement.

The fragmentation in Fig. 6 is consistent for all laser integrated machine tools. Breaking down the three categories in elementary causation, leads up to a more specific differentiation whose impact is heavily dependent on the particular configuration of the integrated machine tool.

The integration of a laser processing unit in a machine tool always influences the machine setup. Additional media has to be transferred to the processing unit as well as the guidance of the actual laser unit has to be realized. Therefore the magnitude of static mechanical influences depends among other characteristics on the rigidity of the manipulator, the weight of the laser processing unit and the passive forces being applied by supply systems.

The structure of the machine tool and its components apart from the way the process is performed, sequential or parallel, are responsible for the degree of impact of the static-mechanical caused displacement.

Laser integrated machine tools that perform the machining processes sequential are rather insensitive for specific mechanical effects than for thermal effects. The duration of dynamic mechanical effects compared to thermal effects is not sustainable and thus does not affect

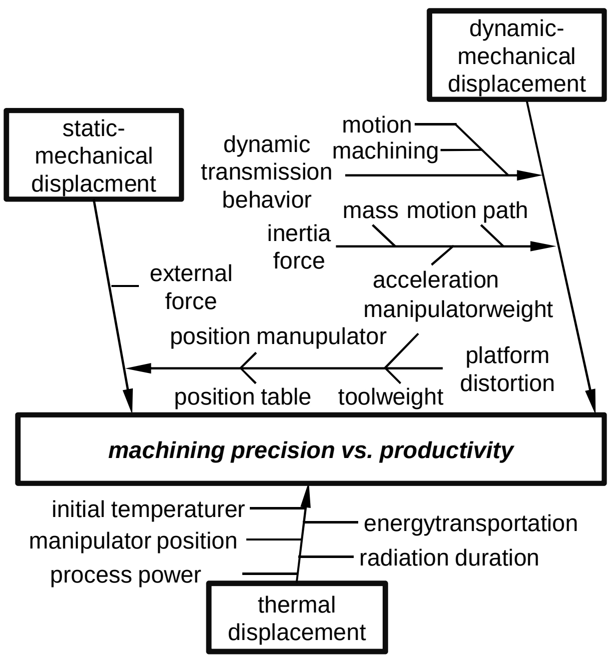

Fig. 6. Priciples of interaction.

the sequential machining process. Heat energy, introduced by the laser is inert and it´s decay needs much more time than the decay of dynamic vibrations. Consequently sequentially following processes might be affected by thermally caused displacement.

Inspecting laser integrated machine tools that can apply multiple processes simultaneously dynamic mechanical effects are becoming more interesting. E.g. laser processing units might be affected by vibrations resulting from mechanical processes being carried out simultaneously. The abstract identification and classification of interaction principles is generally valid for laser integrated machine tools, independent from the specific laser technology.

As derived in previous chapters machine tools can be equipped with multiple workspaces. By realizing such a design the combinations of potential mechanisms of interactions rises disproportional. Figure 7 illustrates possible principles of interactions of machining in two working spaces. In the process level input values of the machining process cause undesired thermal and mechanical effects beside the desired process results. Thermal and mechanical transmission behaviour transfers these effects to thermal and mechanical distortions and deviations of the machine structure and components in the machine level. Regarding the process level these distortions influence the machining process and thus the process result. Special feature of the exemplary integrated machine tool is the existence of a second working space, which allows time parallel processing. Following this machine structure, the thermal and mechanical effects in the process level are not only affecting the workspace they ordinate from, but also the second workspace. Especially thermal impacts are becoming a history based dimension that depends on their duration in each workspace and must be considered according to the process chains in both workspaces.

4. MECHANICAL EVALUATION OF A DEMONSTRATOR MASCHINE

After identifying and classifying interaction principles, possible interactions will be exemplary investigated focusing on the demonstrator machine. The demonstrator machine is the integrated machine tool for hybrid metal processing described in the prior chapters. Characterizing the integrated machine tool is, besides the features of the base machine, the existence of two equal workspaces, a centre-installed robot to handle a laser processing unit for being able to access both workspaces and a second laser processing unit which can be picked up by the machine spindle. Following the categorization of displacement causes shown in Fig. 6 the static-mechanical and dynamic-mechanical distortion will be analyzed.

First static based influences on the spindle and rotating swivel table are taken into account. While investigating this machine tool pervious tests and numerical simulations in the design phase showed that the platform distortion due to the position of the spindle, the weight of the laser processing unit and the pose of the rotating swivel table can be neglected considering the accuracy demands. Appearing forces during a milling process are more crucial than the listed effects. Concerning the robot external forces, in this particular case they are resulting from the media supply. Considering the fact that machining precision depends on the characteristics of single components makes clear why all these influence have no effect on static-mechanical displacement of the spindle and the table. Both have to meet more restrictive requirements as components of the base machine tool.

Differing from the spindle and table combination is the requirement for the robot and rotating swivel table combination. As already mentioned the table shows almost no distortion so that the deviation of the process point of the robot and rotation swivel table is mainly

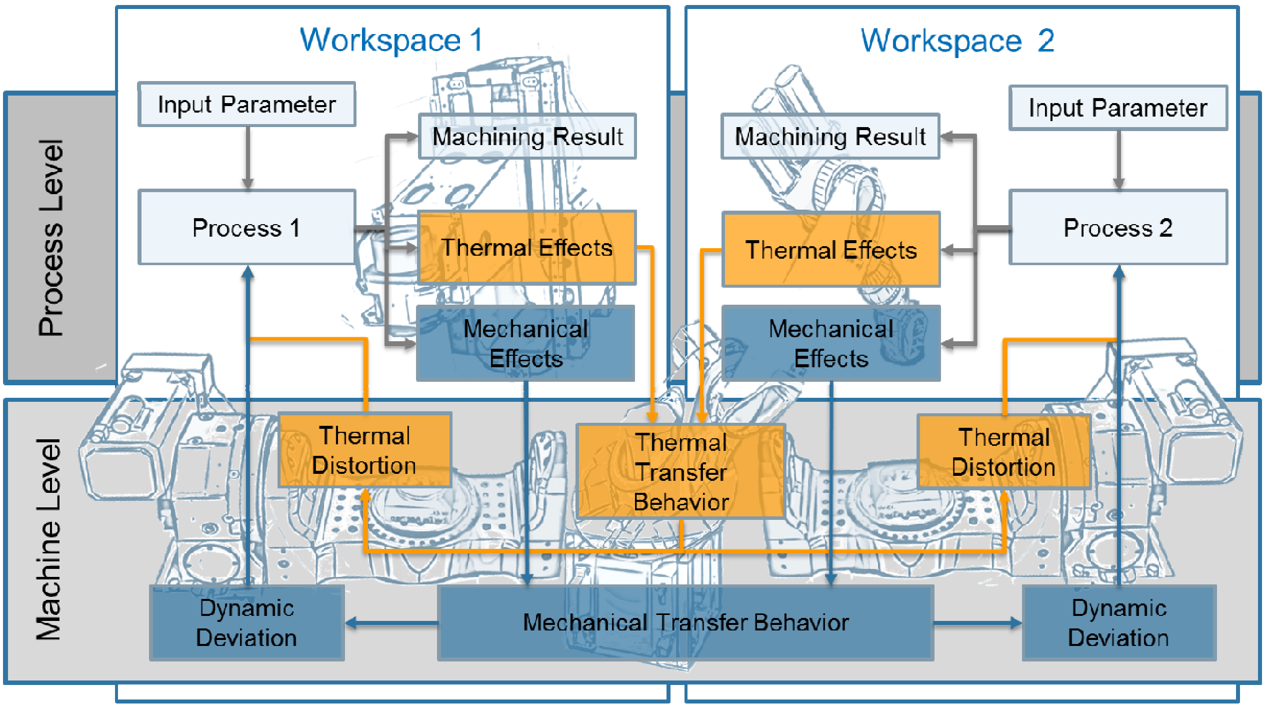

Fig. 5. Cross linked transfer of deviations between the workspaces.

affected by the robot´s deviations. No distortion occurs but the possibility always has to be taken into account when designing an integrated machine tool.

The requirements on the robot in general are rather low regarding the maximum load and the evolving sensitivity to external forces. Chances of displacement due to influences arising from the integration are high. In particular external forces that affect the positioning ability of the robot derive from the weight of the laser unit, the weight compensation and the installed media supply. Experiments showed different derivation of the robot directed laser processing unit depending on the actual and pervious movement of the laser processing unit. Especially the media supply affects the position precision of the robot.

In the second instance the dynamic-mechanical displacement of both manipulators and the corresponding rotating swivel table combinations are examined.

Consistent to the structure of Fig. 6 the effects of the passive forces consisting of accelerations, masses and different motion paths are investigated. Therefore the special influences of the media supply and the weight compensation as well as the acceleration and speed of the manipulators are in the centre of interest. Similarly to the reasons of disregarding, some effects on the spindle in the first instance would not be considered here. Again the sensitivity of the robot to external forces pushes its behaviour into the focus. The results of experiments show a clear dependency of the robot´s precision on the media supply again.

In the next step the transmission behaviour of the components regarding their machining precision is examined. Figure 7 shows the experiment set-up being used to investigate the characteristic of transmitting mechanical impacts between the workspaces. In this case the interactions during simultaneous machining in both workspaces are of major interest. The excitation takes place between the machine spindle and the rotating swivel table. In the illustrated set-up a hydraulic exciter is clamped on the table in the left workspace and excites the spindle.

To measure the reaction of the components acceleration sensors are installed at desired spots at the machine structure and the robot being located in the other workspace.

The experimental results of the excitation of the robot and spindle are shown in Fig. 8. The graphs in the upper diagram represent the response of the spindle (dashed line) and the robot (solid line) to the excitation of the

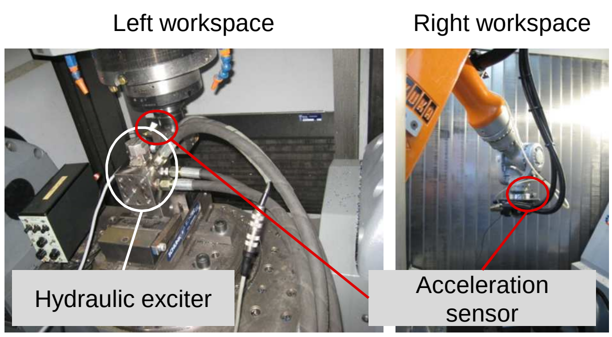

Fig. 7. Experiment set-up for the investigation of mechanical interactions.

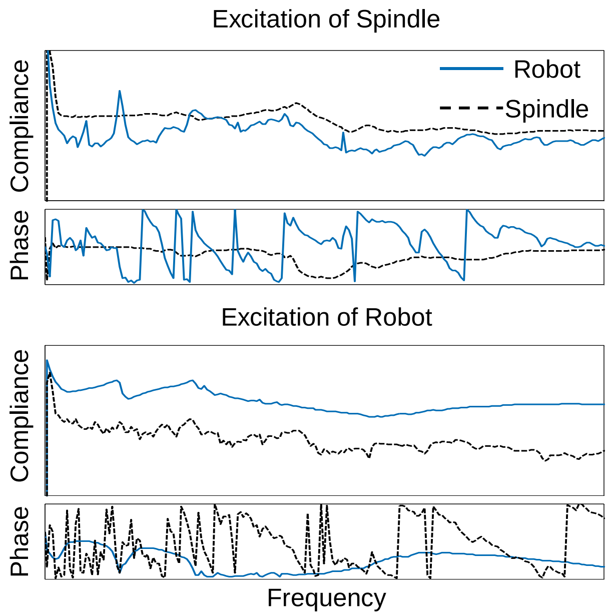

Fig. 8. Mechanical experiment results.

spindle by a hydraulic exciter. In this case the robots compliance is lower than the one of the spindle except for the resonance frequency. Meanwhile the diagram at the bottom illustrates the response of the spindle and robot due to the excitation of the robot with an impact hammer.

As expected the compliance of the robot responding to the direct excitation of the robot is much higher than the indirect response of the spindle.

Comparing the response of the spindle to the excitation of the spindle and robot shows a lower compliance for the indirect execution. Examining the response of the robot in the same way indicates a much higher compliance of the robot on direct excitation than indirect by the spindle as well as the same resonance area as in the first set-up.

After analyzing of the dynamic mechanical effects by their transfer behaviour the path accuracy the laser processing unit being guided by the robot need to be evaluated in practical applications. Therefore a defined metal ring is clamped on the swivel table and the laser processing unit is positioned above it, in order to mark relative movement on the surface of the workpiece with the laser beam. To generate a reference for the evaluation independent from any dynamic-mechanical effects the workpiece is clamped coaxial to the rotational axis of the table and the laser processing unit is positioned 25 mm off the centre. By rotating the table the activated laser beam marks an almost perfect ring with a diameter of 50 mm ring. In further tests the workpieces are clamped eccentric in order to force the robot to carry out compensation movement as shown in Fig. 9.

The adjustment is a circle with a shifted centre point. Besides the test setup the laser marks as well as the tracked path of the processing unit are shown in Fig. 9. The deviation in principle is consistent with previous results gathered during tests with the isolated robot prior to its installation into the machine tool. Slight deviance in the amplitude of the deviations can be explained by the impacts of the media supply and weight compensa-

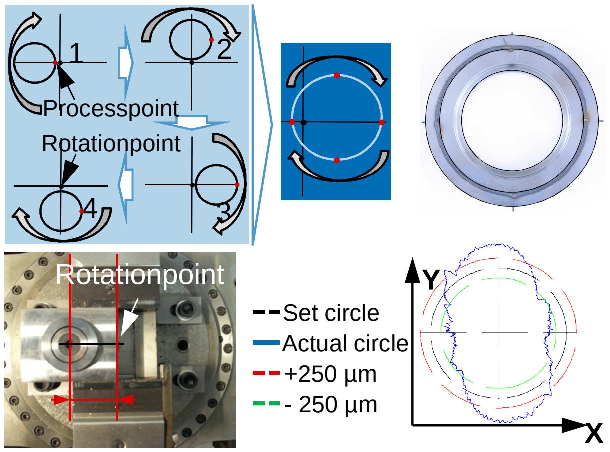

Fig. 9. Test setup and results for robot assisted laser welding.

tion. Other deviations of prior results potentially are caused by the changes of the robot´s control caused by integration into the machine tool control. This has to be verified by further experiments.

The mechanically caused displacements of the machining point are affected to a certain degree by effects that are based on the integration of technology in a machine tool. The requirements regarding machining precision that have to be met by the demonstrator machine are reached [16]. The machining precision mainly depends on the accuracy reached by each single component.

5. THERMAL EVALUATION OF A DEMONSTRATOR MASCHINE

Completing the analysis of interactions the thermally caused losses of accuracy are examined. Thermal effects can affect both workspaces during simultaneous and sequential machining because of comparatively long decay time. Taking the tool centre point into focus the following scenario makes clear how the utilization of laser processing unit might affect the machining precision in long term.

The laser machining unit performs in one workspace inserting heat into the workpiece and into the machine structure causing distortions of all components being influenced directly. The heat energy reaches the second workspace with less impact but still causes distortion there. Using the full potential of the machine set-up, the manipulators permanently switch between both workspaces. Warm and more or less deformed manipulators might enter relatively cold workspace or the other way around. Machining precision cannot be ensured especially regarding the spindle a few degrees easily lead to high losses of accuracy.

Figure 10 illustrates the experimental set-up to investigate the thermal interaction between workspaces. The laser processing unit is placed by the robot into the left working space performing an interval laser machining process with 1.8 kW laser power. The displacement of the laser machining unit is detected by a laser tracker with an accuracy of 10 µm. The spindle is placed above the centre of the right rotating swivel table. Using path sensors and dummy tool deviations of the position of the spindle can be monitored.

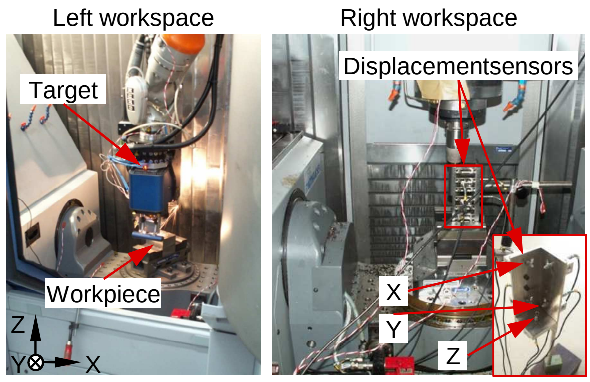

Fig. 10. Experiment set-up for the investigation of thermal interactions.

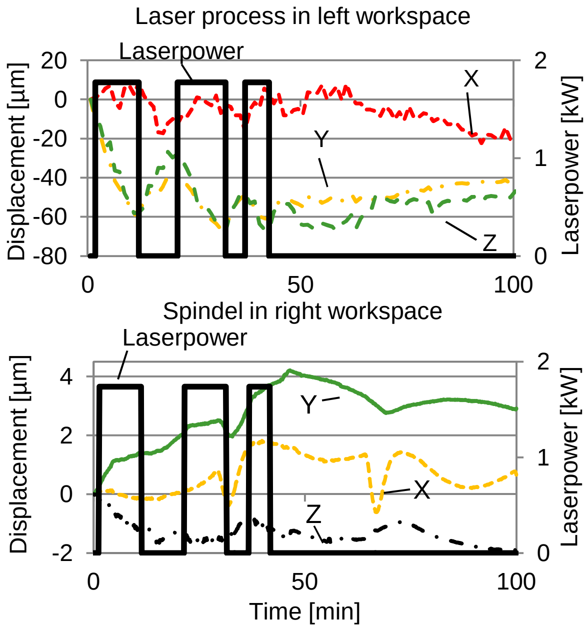

Fig. 11. Experiment set-up for mechanical interactions.

The deviations detected in this experiment are illustrated in Fig. 11. The upper diagram shows the behaviour of the robot in the three axis directions. Especially in the *Y* and *Z* direction the correlation of deviation and heat injection can be investigated.

The displacement of the laser machining unit grows in negative axis direction depending on the utilization of the laser processing unit. The reaction of the spindle in the right workspace is more indirect than the one of the robot in the direct heated workspace. Displacement in *X* and *Y* direction grows up during the interval of heat generation and starts to lessen some time after the ending of injection. The repeating negative local peaks at about 40 minutes and 70 minutes are generated by the coolant of the spindle.

Carrying on the explanation of interactions in laser integrated machine tools displacements due to specific problems arising from the integration are detected. The influence of laser integration of in terms of thermal elastic deformation affects the machining precision. The actual loss of machining precision due to all effects in both workspaces and the alternation of manipulator positions have to be analyzed in further experiments as well as simulations of the thermal elastic behaviour of laser integrated machine tools.

6. SUMMERY AND CONCLUSION

The motivation for the development of integrated machine tools is the combination of economic benefits from mass production with the flexibility of individual production. By building up and using laser integrated machine tools advantages of both dimensions of dilemma between scale and scope can be reached. In particular, it was shown that multiple workspaces can increase productivity and the resource-specific degree of utilization significantly. Besides these advantages additional workspaces also result in a variety of other undesired interactions and thus potential loss of productivity or accuracy. Within this paper different factors were divided into two major fields - mechanical and thermal influences. This grouping can be applied to all laser integrated machine tools but especially to the demonstrator machine that was build up in the first phase of the Cluster of Excellence.

The demonstrator machine is unique and offers the possibility to investigate and to qualify influences and principles of interaction independently from each other.

In particular it was shown that the mechanical transmission behaviour affects the achievable machining accuracy of various processing resources. Furthermore, the laser-induced warm-up behaviour and the associated thermally induced loss of precision were determined.

The resulting data base can be used in further steps, especially to develop and align thermal simulation and prediction models. Using such matched models the behaviour of the machine structure becomes predictable and can be compensated by appropriate compensation cycles in future. Furthermore, the experience to simulate the effects of laser processes to machine tool structures can in particular support to the development of future production systems.

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REFERENCES

[1] F. Piller, *Mass Customization – Ein wettbewerbs-strategisches Konzept im Informationszeitalter*(Mass Customization – a competitive strategic concept in the information age), Gabler, Wiesbaden, 2006.

[2] K. Arntz et al., *Hybride Produktionstechnik – Kurzfristiger Trend oder langfristiger Mehrwert?* (Hybrid production technology – short-term trend or long-term benefit?), Aachener Werkzeugmaschinen Kolloquium 2011, Brecher, Klocke, Schmitt, Schuh, pp. 317–344, Aachen, Mai 2011, Shaker Verlag, Aachen.

[3] C. Brecher, *Integrative Production Technology for High-Wage Countries*, Springer, Berlin, 2011.

[4] G. Schuh, J. Kreysa; S. Orilski, *”Hybride Produktion” – Wie 1+1=3 – Effekte in der Produktion maximiert werden können* (Hybrid production – how 1+1 = 3 – effects in production can be maximized), ZWF, Vol. 104, 2009, pp. 385–391.

[5] F. Klocke et al., *Scannerbased Laser Cladding*, LANE 2012, Proceedings of the Laser Assisted Net Shape Engineering, pp. 346–353, 2012.

[6] B. Lauwers, *Surface Integrity in Hybrid Machining Processes*, 1st CIRP Conference on Surface Integrity (CSI), 2011, pp. 241–251.

[7] C. Brecher, T. Breitbach, D. Do-Khac, S. Bäumler, W. Lohse, *Efficient utilization of production resources in the use phase of multi-technology platforms*, Production Engineering Research and Development, (Published online), 2013, pp. 1–10.

[8] B. Lauwers, F. Klocke, A. Klink, *Advanced manufacturing through the implementation of hybrid and media assisted processes*, Int. Chemnitz Manufacturing Colloquium, R. Neugebauer, pp. 205–220, Chemnitz, September 2010, Wissenschaftliche Scripten, Chemnitz.

[9] A. Zaboklicki, *Laserunterstütztes Drehen von dichtgesinterter Siliziumnitrid-Keramik* (Laser supported turning of dense-sintered silicon nitride ceramic), Dissertation RWTH Aachen University, Aachen, 1998.

[10] F. Klocke, S. Tönissen, H. Wegner, A. Roderburg, *Modelling economic efficiency of multi-technology platform*, Production Engineering Research and Development, Vol. 5, No. 3, 2011, pp. 293–300.

[11] C. Brecher, T. Breitbach, D. Do-Khac, *Strategies and Boundaries for cost efficient Multi Technology Machine Tools*, 15th International Conference on Machine Design and Production, UMTIK-2012 Vol. 1, June 19–22, 2012, Pamukkale, Denizli, Turkey, 2012, pp. 251-266.

[12] M. Weck, *Werkzeugmaschinen – Maschinenarten und Anwendungsbereiche* (Machine tools – machine types and applications), Springer, Berlin, 2005.

[13] A. Monforts, Werkzeugmaschinen GmbH & Co. KG: Firmenhomepage available at: `http://www.monforts-werkzeugmaschinen.de/index.php?id=41&L=`, accessed: 2013-05-27.

[14] B. Kuttkat, *Dreh-Fräs-Zentrum mit Lasersystem verkürzt Fertigung komplexer Werkstücke* (Machining center with laser system reduces manufacturing of complex workpieces). Kombimaschine. available at: `http://www.maschinenmarkt.vogel.de/themenkanaele/prodproduk/spanendefertigung/maschinen/articles/90649/` accessed: 2013-05-27.

[15] Alzmetall Werkzeugmaschinenfabrik und Gießerei Friedrich GmbH & Co. KG.. available at: `http://www.alzmetall.de/alzmetall/index.php?id=gs 14005` accessed: 2013-05-27.

[16] C. Brecher, A. Karlberger, *Steuerungskonzept für ein hybrides Bearbeitungszentrum* (Control architecture for a hybrid machining centre), *Hybride Technologien in der Produktion* (Hybrid technologies in production), Krüger, Uhlmann, pp. 78–93, Düsseldorf, Sept 2010, VDI-Verlag, Düsseldorf.