Jens Peter Wulfsberg
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Production at the leading edge of technology

Proceedings of the 9th Congress of the German Academic Association for Production Technology (WGP), September 30th - October 2nd, Hamburg 2019

WGP
Wissenschaftliche
Gesellschaft für
Produktionstechnik

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Preface

In 2019, the annual congress of the German Academic Association for Production Technology (WGP) will be held in Hamburg from September 30th to October 2nd under the slogan "Production at its limits – keeping the lead, securing the future". The WGP is hosting its annual congress for the 9th time in a row, inviting to the Helmut Schmidt University in Hamburg.

On behalf of the WGP, the three organizing institutes, the Institute of Production Engineering of the Helmut Schmidt University, the Institute for Production Management and Technology of the Technical University of Hamburg and the Institute for Forming Technology and Machines of the Leibniz University of Hanover are looking forward to exciting discussions with experts from industry and research.

Production research permanently shifts the boundaries of what is feasible. Under the slogan "Production at its limits", the contributions show production processes that advance into new areas in terms of methodology, use of resources or interdisciplinary.

But where does the search for new borders lead to? Which borders do we still have to cross, which ones do we prefer not to cross?

The focus of the congress is on production processes in border areas related to extreme velocity, size, accuracy, methodology, use of resources and interdisciplinarity. Challenges from the fields of cutting machines and processes, forming machines and processes, automated assembly and robotics, management sciences and interdisciplinary projects will be addressed.

The conference transcript summarizes the contributions from production science and industrial research. They provide the readership with an overview of current trends in production research and give an insight into ongoing research by the German Academic Association for Production Technology.

We wish all participants an interesting and inspiring WGP annual congress and look forward to welcoming you to Hamburg.

September 2019

Prof. J. P. Wulfsberg | Prof. W. Hintze | Prof. B.-A. Behrens

Vorwort

Der Jahreskongress der Wissenschaftlichen Gesellschaft für Produktionstechnik (WGP) im Jahr 2019 steht unter dem Motto „Produktion im Grenzbereich - Vorsprung halten, Zukunft sichern!“ und findet vom 30. September bis 2. Oktober in Hamburg statt. Die WGP richtet ihren Jahreskongress bereits zum 9. Mal in Folge aus und lädt hierfür an die Helmut-Schmidt-Universität nach Hamburg ein.

Die drei organisierenden Institute, das Laboratorium Fertigungstechnik der Helmut-Schmidt-Universität, das Institut für Produktionsmanagement und -technik der Technischen Universität Hamburg und das Institut für Umformtechnik und Umformmaschinen der Leibniz Universität Hannover freuen sich im Namen der WGP auf spannende Diskussionen mit Fachleuten aus Industrie und Forschung.

Die Produktionsforschung verschiebt permanent die Grenzen des Machbaren. Die Beiträge zeigen unter dem Motto „Produktion im Grenzbereich“ Produktionsprozesse auf, die in neue Bereiche hinsichtlich Methodik, Ressourceneinsatz oder Interdisziplinarität vorstoßen.

Doch wohin führt die Suche nach den neuen Grenzen? Welche Grenzen müssen wir noch überschreiten, welche wollen wir lieber nicht überschreiten?

Im Fokus des Kongresses stehen Produktionsprozesse in Grenzbereichen bezogen auf beispielsweise extreme Geschwindigkeit, Größe, Genauigkeit, Methodik, Ressourceneinsatz, Interdisziplinarität. Angesprochen werden Herausforderungen aus den Bereichen der spanenden Werkzeugmaschinen und Fertigungsverfahren, der umformenden Werkzeugmaschinen und Fertigungsverfahren, der automatisierten Montage und Robotik, der Betriebswissenschaften sowie interdisziplinären Projekten.

Der Tagungsband fasst die Beiträge aus der Produktionswissenschaft und Industrieforschung zusammen. Sie liefern der Leserschaft einen Überblick über aktuelle Trends in der Produktionsforschung und geben einen Einblick in laufende Forschungen der Wissenschaftlichen Gesellschaft für Produktionstechnik.

Wir wünschen allen Teilnehmenden einen interessanten und inspirierenden WGP-Jahreskongress und freuen uns, Sie in Hamburg begrüßen zu dürfen.

September 2019

Prof. J. P. Wulfsberg   Prof. W. Hintze   Prof. B.-A. Behrens

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I. Forming Machine Tools and Manufacturing Processes

Overcoming Limits - Die Forging of Cast Preforms

Grenzen überwinden - Gesenkschmieden gegossener Vorformen

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Abstract. Casting and forging are among the technologies with the highest material and energy requirements. Many efforts have been made to minimise the expenditures involved, but in most cases they have been limited to the individual application case. While the combination of casting and forming processes has been described and applied extensively for aluminium components, this approach has been far less investigated and advanced for steel components.

The latest developments in the software with a direct interface between casting and forming simulation enabled the creation of a continuous simulation from the casting to the finished forged part. The match between the simulation and the real component was verified on the basis of manufactured sample parts.

Currently ongoing investigations focus on the formation of the microstructure in the component. At the same time, the process chain casting - forging is being developed and evaluated for a further component.

This approach overcomes existing limits and opens up new possibilities for component design by linking simulations of casting and forging technologies into an integrated continuous process chain simulation.

Keywords: cast preforms, die forging, continuous process chain simulation

Abstract. Während für Aluminiumbauteile die Kombination von Ur- und Umformprozess bereits näher beschrieben und umgesetzt wurde, ist für Bauteile aus Stahl eine solche Vorgehensweise bisher kaum untersucht worden.

Die neusten Entwicklungen von Schnittstellen zwischen Gieß- und Schmiedesimulation im Softwarebereich erlauben den Aufbau einer durchgängigen Simulation vom Abguss bis zum Schmiedeteil, welche am Beispiel einer Schaltgabel nachvollzogen wurde. Die Verifizierung der Simulationsergebnisse erfolgte anhand eines real gefertigten Bauteiles.

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Die derzeit laufenden Untersuchungen konzentrieren sich auf die Abbildung der Mikrostruktur im Bauteil sowie den Aufbau der Prozesskette Gießen - Schmieden für ein weiteres Bauteil.

Keywords: Gussvorformen, Gesenkschmieden, kontinuierliche Prozessketten-simulationen

1 Motivation

In the search for new production concepts for complex steel components, the combination of casting and forging is once again moving into the focus of investigations. As early as the middle of the last century, the first attempts were made to combine the casting and forming processes [1]. These investigations and current ones have in common the goal for minimising the material use. A further positive aspect of combining these two processes is the possibility of eliminating defects such as cavities or pores resulting from the casting process with the subsequent forging operation. In most cases, these investigations are limited to the manufacture of semi-finished products [2-5]. In this product stage, casting defects are easier to eliminate, as it can generally be assumed that the forming directions are frequently changing.

Forged components made from cast preforms are generally not subject to these high levels of deformation but are optimally formed in one step and in one direction. Components produced in this way can combine the advantages of these two manufacturing processes, a high degree of flexibility with regard to geometry and areas of higher strength as a result of forming. Werke et al. [6, 7] describe the advantages of components produced by combined manufacturing. Applying the combination of casting and forging processes, components can be produced which can have different properties in different component areas and which overcome the boundaries between casting and forming.

2 Approach and Preliminary Studies

2.1 Demonstration Part

The feasibility of the process combination casting - forging was established as result of a benchmark for shift fork manufacturing routes in preliminary studies. Compared to a complete forging chain, there is a significant reduction in the number of process steps in such a combined process chain, which led to considerations as to how such a production process could be simulated and implemented.

Fig. 1. The demonstration part selected for simulation and manufacturing

Alternative manufacturing routes included, for instance, multiple forming stages coupled with bending and joining operations, or a complex joining process consisting of joining operations of separate component elements. The manufacture of a cast preform appeared to be a promising approach not only with regard to the utilisation of material but also with regard to the required component properties.

2.2 Software for Simulation

The initial task in developing the process chain for the component shown in Figure 1 was to develop the forging process and the corresponding forging dies for pre- and final forming. Using the FORGE® simulation software, a two-stage forging process was designed and optimized with regard to material flow and die filling. The result of the forging simulation is used as the base for the design of a casting model for sand casting (Fig. 2), which was developed in cooperation with the Gießerei-Institut, TU Freiberg. Figure 3 shows the derived model for the production of the casting moulds.

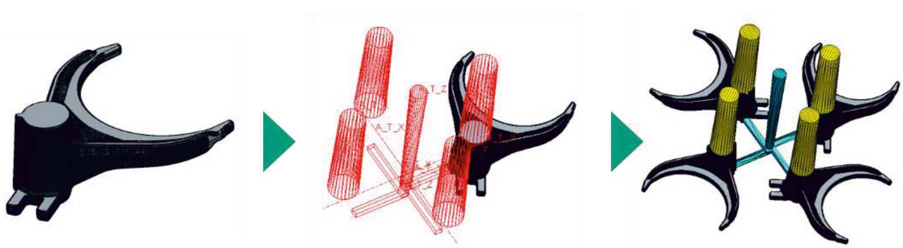

Fig. 2. Modified model for casting simulation (left: forging part, centre: the new injection system, right: cast model)

Fig. 3. Derived model for mould making (left: upper part, right: lower part)

No casting optimisation of the component was carried out, since the focus of the investigation lay on simulation and verification of the process combination.

The next challenge was the selection of a suitable material. Historically, not only the casting and forging technologies have developed independently of each other, but the materials available have also been adapted to the respective application and the associated technologies [8]. The 42CrMo4 steel grade data from the data base JMatPro was used for initial tests.

The quality of the components produced by a combination of casting and forging is considerably dependent on the casting process. New materials with improved casting properties for similar applications were developed at Gesenkschmiede Schneider GmbH Aalen [9, 10]. Due to the limited availability of suitable materials, it is necessary to determine the relevant material properties as a basis for a combined simulation of the two methods. Krüger et al. [11] describe a possible procedure for such a case.

MAGMASOFT® is the most commonly used simulation software for casting processes in Germany. For the purpose of this project, it is necessary to transfer the simulation results from the casting to the subsequent forming simulation. MAGMASOFT® transfer and interface possibilities are limited at the current state. Therefore, the THERCAST® system, which has so far not been well-known in Germany, was used, as this system allowed a direct transfer of results to the forming simulation software FORGE®. Both THERCAST® and FORGE® were provided by the French manufacturer Transvalor S.A. This company has developed an interface for data transfer without loss of model parameters.

3 Investigation Results

The main focus of the described work was the realisation of a combined simulation of a casting process and a forging process. Therefore, a detailed evaluation of the individual processes was not carried out at this point. A distinction was not made between solidification and gas porosity, as is the case with non-ferrous metals in particular. Moreover, the influence of friction conditions in the forging dies was not considered either. The term risk of porosity is used in the context of component defects resulting from the solidification of the casting material.

Studies are currently underway to evaluate and compare the microstructures in the component, taking into account the respective manufacturing process. Special attention is given to the estimation of the size up to which internal and external defects can be closed and whether this is a compaction or a fusion of the grain boundaries.

3.1 First Simulation - Casting

The casting simulation was set up as a sand casting process according to the conditions of actual implementation for real components with a casting time of 12 seconds at a casting temperature of 1650°C. To shorten the calculation time, the symmetrical model was modified and only a quarter was calculated. The cooling time in the sand mould was assumed to be 10 hours.

The blowholes and porosity of the model generated in this way were essentially evaluated according to three criteria:

- Porosity_Transfer_of Parameters_(Niyama)
- Porosity_Transfer_of Parameters_(Shrinkage) and
- Porosity_Transfer_of Parameters_(Yamanaka).

A distinction of several parameters is necessary to describe the porosity in order to consider both thermal (Niyama) and mechanical (Yamanaka) aspects. In addition, the parameters refer to either the elements (shrinkage) or the nodes (Niyama) of the mesh in the simulation model.

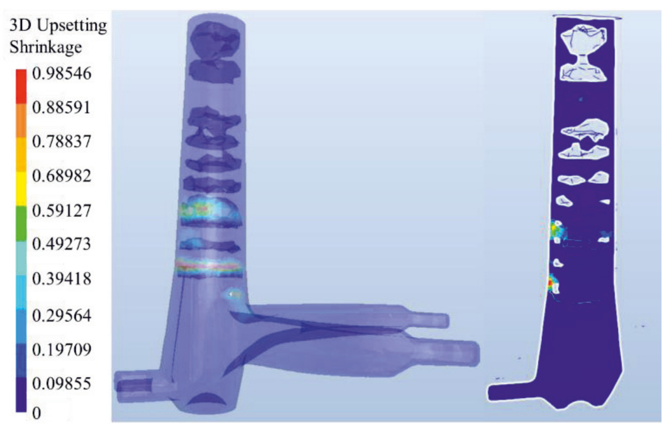

Fig. 4. Distribution of cavities on the casting (left: transparent, right: in cross-section)

The shrinkage parameter is used in the two process steps to represent internal defects. Due to the solidification of the liquid metal, shrinkage occurs in individual component areas. The expected distribution of blowholes is shown in Figure 4.

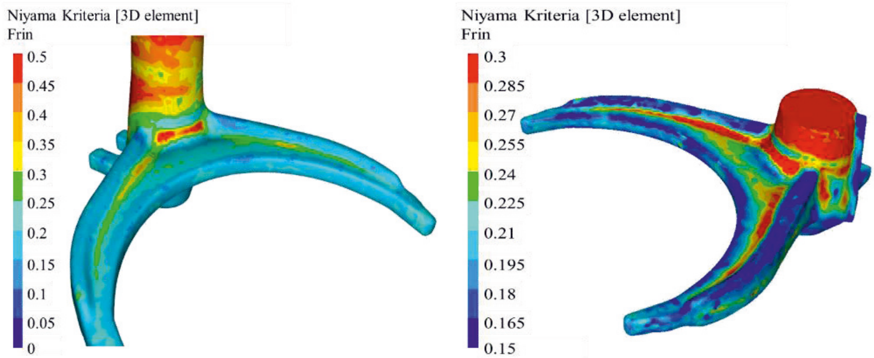

Fig. 5. Distribution of porosity on the casting (left: after casting simulation, right: in preparation of forging simulation)

The Niyama parameter is used to evaluate the surface porosity and indicates the areas with increased tendency to form pores. The expected distribution of porosity (Niyama criteria) is shown in Figure 5.

3.2 Second Simulation - Forging

In order to transfer the results of the casting simulation to the forging simulation, the feeder system of the casting model was removed with a trim operation. A similar approach is used in actual component manufacture, where critical areas with porosities or blowholes are placed in such a way that they are removed during subsequent machining. Starting from the model of the casting simulation after cooling down, the forging model is initiated with a heating phase in a first step. A comparison of the thermal expansion during heating and the shrinkage during cooling in the previous process shows a very close conformity.

Due to the near-net-shape cast preform, the forging simulation uses only the final die cavity of the initially developed tool. For the design of a continuous process simulation it is sufficient to define the tools as rigid. The current focus of the investigation does not lie on the optimised technology for manufacturing a component, but on the possibility of linking different simulation models with each other without loss of information in order to be able to realise new manufacturing paths.

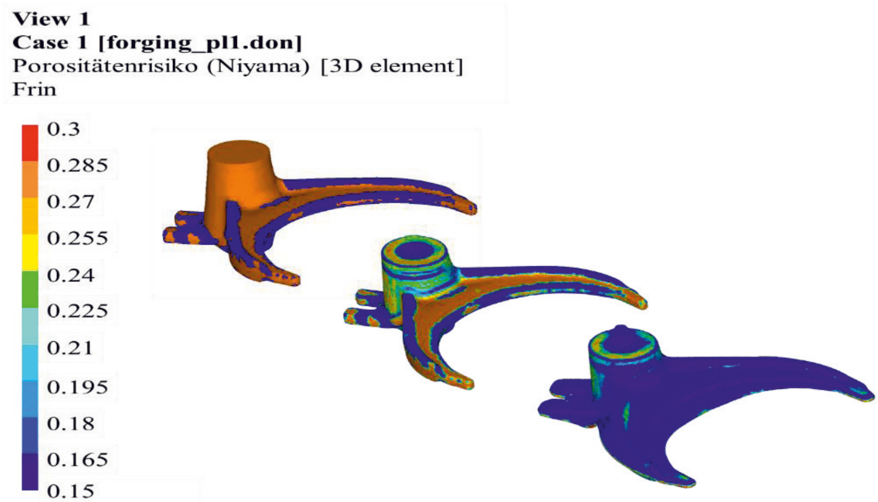

Fig. 6. Risk of porosity (orange - high; blue - small; left: after casting simulation, centre: during forging simulation, right: after forging simulation)

Conventional forming models and simulations do not contain any parameters regarding the porosity distribution. Porosity parameters were taken from the casting simulation and assigned to the component as user variables. This procedure enables the evaluation of porosities in the forming simulation, thus allowing for a statement on the extent to which the forming process affects the properties of the cast model.

Figure 6 shows the changes of the porosity distribution from casting to forming. A large number of surface pores are present on the surface of the casting, which are obviously closed during subsequent forging. The improvement of the surface shown in the simulation has also been demonstrated on real components, Figure 7.

Fig. 7. Porosity on the casting (left) and after forging (right)

External defects and porosities of the corresponding production stages can be compared by marking the components. The evaluation of sections and microstructures is only possible by comparison on different parts.

In local areas with a high effective strain of forming, blowholes up to a size of 5 mm, as shown in Figure 4, were almost closed during the forming simulation.

In comparison, the real cast part exhibits shrinkage cavities and segregation zones, especially in the large cross-section of the section plane 1. The forged part is free of cavities. The formation of folds, oxide inclusions or slags must be investigated in more detail. Figure 8 shows the sections of investigation.

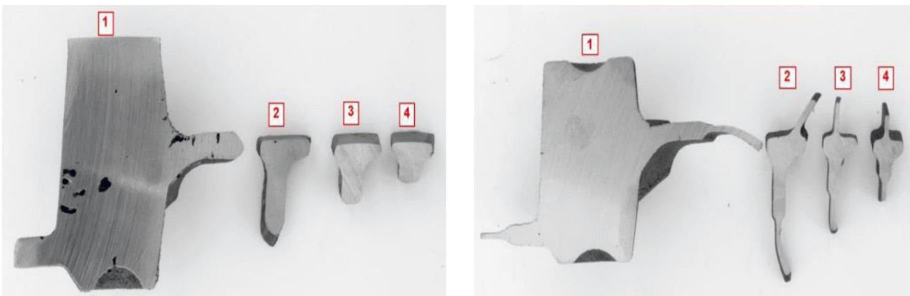

Fig. 8. Representation of the section planes for metallographic investigations (left: cast part, right: forged part)

4 Conclusion and Outlook

A simulation was set up for a steel component with a complex geometry that combines the casting and forging process steps. The development of the software enables a transfer of the simulation data from one process to another without loss of information. Therefore, it is no longer necessary to treat the simulation of each process separately for the production of steel components. For useful results, however, it is essential that each process is individually well understood and implemented in the simulation.

Results of the simulation regarding the distribution of porosities or the formation of blowholes were basically confirmed on actually manufactured components. First examinations of the component microstructure show the expected mixed structure as a result of forming of the cast microstructure. More specific results on the relationship between the degree of deformation and the change in microstructure cannot be made at the current state of investigation.

The use of the casting - forging process combination for this component led to a reduction of approx. 20% regarding burr formation. Since almost no optimization of the individual processes was carried out during the study, further increase in the savings potential can be assumed.

Currently running experiments are intended to analyse possible forging defects. In particular, the closing of larger pores or surface defects must be viewed critically in order to avoid the formation of wrinkles or the forging in of scale.

Future investigations are planned to include an enhanced coupling of the combined casting and forging simulation with a prediction of the expected microstructure. In order to make the presented process simulation available to a broader circle of users, a comparison is intended with the MAGMASOFT® - Simufact.forming® software systems which are widely used in Germany. Currently another lightweight complex component is being investigated to show the potential of the presented approach. Initial results indicate that there will be significant material savings for this component as well.

The combination of primary and secondary forming technologies combines the design freedom of casting with the strength-enhancing properties of forming technology in a single process chain. The presented materials and the associated developed manufacturing technology provide the end user with completely new tools with which it is possible to develop components in a new manner. Thus, a highly inhomogeneous property level can be defined and also implemented in terms of production technology. This process chain opens up completely new possibilities for lightweight construction and makes a considerable contribution to the conservation of resources along the entire processing route.

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Manufacturing of optical surfaces by burnishing of PMX170CrVMo18-3-1

Herstellung optischer Oberflächen durch das Glattdrücken von PMX170CrVMo18-3-1

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Abstract. Manufacturing of workpieces with a surface roughness of Rt ≤ 0.5 µm by milling is time-consuming and cost-intensive. The burnishing technology with spherical tools made of single crystalline diamond (SCD) is an appropriate process to improve the surface roughness with a high level of efficiency. Furthermore, the burnishing tools can be used after the milling process in the same machine tool and optical surfaces can be machined economically. In the presented investigations the ELMAX steel PMX170CrVMo18-3-1 was burnished after the milling process and the hardness H as well as the surface roughness were investigated. Thereby, minimal values of the surface roughness with Rt = 0.34 µm and Ra = 0.06 µm, depending on the initial surface roughness, were determined and a maximum increase of the hardness H by 5 % could be reached.

Keywords: Burnishing, Milling, Surface Roughness, Hardness.

Abstract. Die Herstellung von Werkstücken mit einer maximalen Rautiefe von Rt ≤ 0,5 µm durch das Fräsen ist zeit- und kostenintensiv. Ein zur Reduzierung der Oberflächenrauheit geeignetes Verfahren ist das Glattdrücken mit spherischen Werkzeugen aus monokristallinem Diamant (MKD). Dabei können die für das Glattdrücken eingesetzten Werkzeuge direkt nach dem Fräsprozess in die Werkzeugmaschine eingespannt und optische Oberflächen wirtschaftlich hergestellt werden. In den dargestellten Untersuchungen wurde der ELMAX-Stahl vom Typ PMX170CrVMo18-3-1 nach dem Fräsprozess mit dem Glattdrückprozess nachbearbeitet und die Härte H sowie die Oberflächenrauheitskennwerte untersucht. Dabei konnten eine maximale Rautiefe von Rt = 0,34 µm und ein arithmetischer Mittenrauwert von Ra = 0,06 µm in Abhängigkeit der Ausgangsoberflächenrauheit ermittelt sowie ein maximaler Anstieg der Härte H um 5 % erzielt werden.

Keywords: Glattdrücken, Fräsen, Oberflächenrauheit, Härte.

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1 Introduction

For the manufacturing of technical surfaces by milling, the surface roughness is decisively determined by the cutting tool, the machine tool, the milling technology as well as the material properties of the workpiece. By using micro-milling tools an improved surface quality can be achieved. However, this is time consuming and costly. For the post-machining and improvement of the surfaces different technologies like machine hammer peening (MHP), burnishing or rolling can be used [1, 2, 3, 4]. Within the burnishing or rolling process a ball or roller is pushed into the workpiece surface and a plastic deformation of the surface and subsurface takes place. The surface roughness can be reduced and the residual stress conditions can be improved [4, 5, 6]. Thereby, the burnishing or rolling tools are mostly mechanically or hydraulically controlled. However, the use of super-hard cutting materials in the form of fixed spherical and aspherical single crystalline diamond (SCD) offers a promising approach [7]. At the state of the art the burnishing technology with diamond spheres is mainly used on turning machine tools [7, 8, 9]. However, it shows great potential for the finishing process on milling machine tools for die and mould manufacturing or deep drawing tools with required optical surfaces.

In order to extend the knowledge for the post-processing of milled components made of high-strength steels for the die and mould fabrication, specific investigations for the post-processing of the shaped steel ELMAX PMX170CrVMo18-3-1 were carried out. Thereby, the surface roughness and hardness H of the burnished components were investigated. In particular, the influence of the process parameters stepover a_{St}, feed velocity v_f as well as burnishing force F_{BN} on the surface roughness and the hardness H of the burnished surfaces were examined.

2 Burnishing

The used burnishing tools consist of a shank for clamping into the spindle, a spring element, a cylindrical case and a burnishing head, shown in Fig. 1. The burnishing head is made of SCD. The advantages of diamond materials for the burnishing process are in particular the high hardness H, the high resistance to abrasive wear as well as the low friction coefficient μ [1]. With the penetration depth a_p the burnishing head is pressed on the surface of the workpieces. The spring length L_S changes and results in a burnishing force F_{BN}, which increases uniformly with the penetration depth a_p. During the process a constant penetration depth a_p is set. Further process parameters are the feed velocity v_f and the stepover a_{St} [10]. The process can be improved by adding a lubricant. The theoretical surface roughness R_{th} for burnishing is mainly dependent on the stepover a_{St} due to the geometrical conditions. However, the initial surface roughness of the workpiece significantly influences the selection of the process parameters for the burnishing process.

The burnishing with super-hard materials offers the potential to significantly reduce the surface roughness, to increase the hardness H of the machined surfaces as well as to improve the residual stress σ_r of the workpiece [10]. Furthermore, it can be shown that the burnishing process influences the boundary zones in the material and mechanical and plastic deformations take place [7, 11, 12].

VARGA ET AL. [8] investigated the burnishing process on a turning machine tool with cylindrical workpieces made of C45. The effects of the burnishing forces F_{BN}, the feed f, the penetration depth a_p as well as lubricants with different viscosities on the geometry were examined. As a result, it could be concluded that a lower burnishing force F_{BN} tends to lead to increased shape accuracy a_c. KORZYNSKI [9] developed a model to describe the surface formation of the workpiece during burnishing with a spherical diamond burnishing tool as a function of the workpiece material properties, the resultant surface roughness and the geometric contact conditions for the rotatory workpiece movement. For the machining of ground 42CrMo4 steel, an optimum burnishing force of $110\ N \leq F_{BN} \leq 150\ N$ could be identified and was experimentally verified. In addition, a strong influence of the initial surface roughness could be shown. LABANOWSKI and OSSOWSKA [7] investigated the burnishing technology for UNS S32550 duplex steel finishing. Thereby, a burnishing tool made of diamond with a ball diameter $d_B = 2$ mm was used. The workpiece was burnished with three different burnishing forces F_{BN} and a surface roughness of $Ra \geq 0.06\ \mu m$ was determined. This corresponds to a reduction of the surface roughness Ra of approximately 86 %. In particular, burnishing forces of $F_{BN} = 70$ N and $F_{BN} = 120$ N were proved to be suitable.

3 Experimental Setup

For the following investigations burnishing tools from the company BAUBLIES AG, Renningen-Malmsheim, Germany, were used. The structure of these tools is presented in Fig. 1. The burnishing head consist of a sphere with a diameter of $d_S = 3$ mm made of single crystalline diamond. For the experiments a hardened ELMAX steel of the type PMX170CrVMo18-3-1 was used. The hardness H of the powder metallurgically produced steel was $H = 923\ HV_{0.1}$. The material is typically used for the manufacturing of long-running, low-maintenance moulds. The milling of the workpieces and subsequent finishing with the burnishing tools were carried out on a 5-axis high precision machine tool PFM4024-5D from the company PRIMACON GMBH, Peissenberg, Germany. The burnishing forces F_{BN} were measured with a 3-component dynamometer of the type MiniDyn 9256C2 from the company KISTLER INSTRUMENTE AG, Winterthur, Switzerland. For heat dissipation and reduction of friction between the workpiece and the burnishing tool a constant lubricant supply with the high-performance cutting oil Swisscut 6122S, MOTOREX-BUCHER GROUP AG, Langenthal, Switzerland, was used.

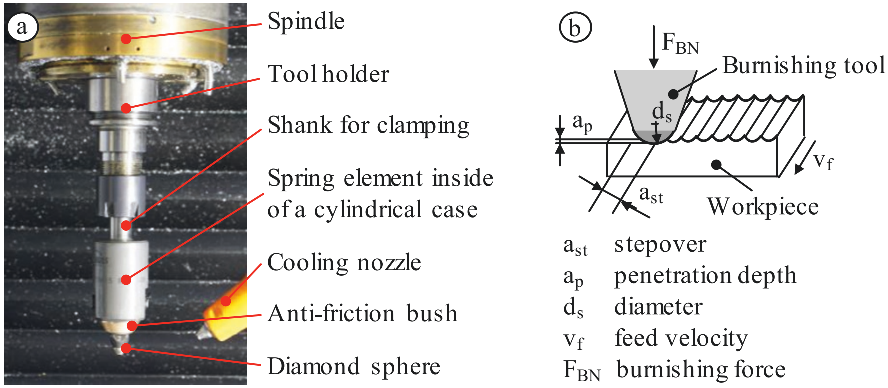

Fig. 1. Burnishing tool, a) clamped into the high-precision machine tool PFM 4024-5D, b) kinematic scheme of the burnishing process and parameters.

The workpieces had a thickness of t = 25 mm, a length of l_w = 60 mm and a width of w_w = 50 mm. The orientation of the burnishing tool was perpendicular to the workpiece surface. In the investigations flat fields with a width of w = 6 mm and a length of l = 6 mm were machined. Thereby, the influence of the stepover was varied with a_{st} = 4 µm and a_{st} = 90 µm. Furthermore, the feed velocity was varied in four steps in the range of 100 mm/min $\leq v_f \leq$ 4,000 mm/min. In preliminary tests, the spring characteristic curves were determined around the penetration depth a_p and the resultant burnishing forces F_{BN} were measured. For a penetration depth of a_p = 13 µm a burnishing force of F_{BN} = 40 N was determined and for a penetration depth of a_p = 1,300 µm a burnishing force of F_{BN} = 90 N was determined. Both penetration depths a_p were used within the experiments to investigate the influence of the burnishing forces F_{BN}. The parameters are given in Table 1.

Table 1. Process parameters for the burnish investigations.

Parameter	Value
Penetration depth a_p	13 µm; 1,300 µm
Burnishing force F_{BN}	40 N; 90 N
Stepover a_{st}	4 µm; 90 µm
Feed velocity v_f	100 mm/min; 1,000 mm/min; 2,000 mm/min; 4,000 mm/min

After the burnishing processes the surface roughness was analysed accordingly to DIN EN ISO 4288 [13] with a tactile surface roughness measurement device Hommel etamic nanoscan 855 from JENOPTIK AG, Jena, Germany. The measuring distance was determined with ln = 4.00 mm and three measurements were taken for each field. Furthermore, the hardness H of the burnished surfaces was measured with a LEITZ MINILOAD 2 from ERNST LEITZ WETZLAR GMBH, Wetzlar, Germany.

4 Results and Discussion

4.1 Surface Roughness

The results of the surface roughness measurements are given in Fig. 2. The red line marks the determined surface roughness of the workpiece after the milling process with Rt = 4.05 µm ± 0.29 µm, Ra = 0.67 µm ± 0.05 µm and Rz = 3.55 µm ± 0.31 µm. In all cases the surface roughness could be significantly reduced by the burnishing process. In the comparison between the stepover a_{st} and the burnishing force F_{BN}, resulting from the change of the penetration depth a_p, best results were achieved with the low stepover of a_{st} = 4 µm and the burnishing force of F_{BN} = 40 N. The surface roughness could be reduced from Rt = 4.05 µm to Rt = 0.93 µm by 77 %. A similar improvement could be observed with a stepover of a_{st} = 4 µm and a burnishing force of F_{BN} = 90 N.

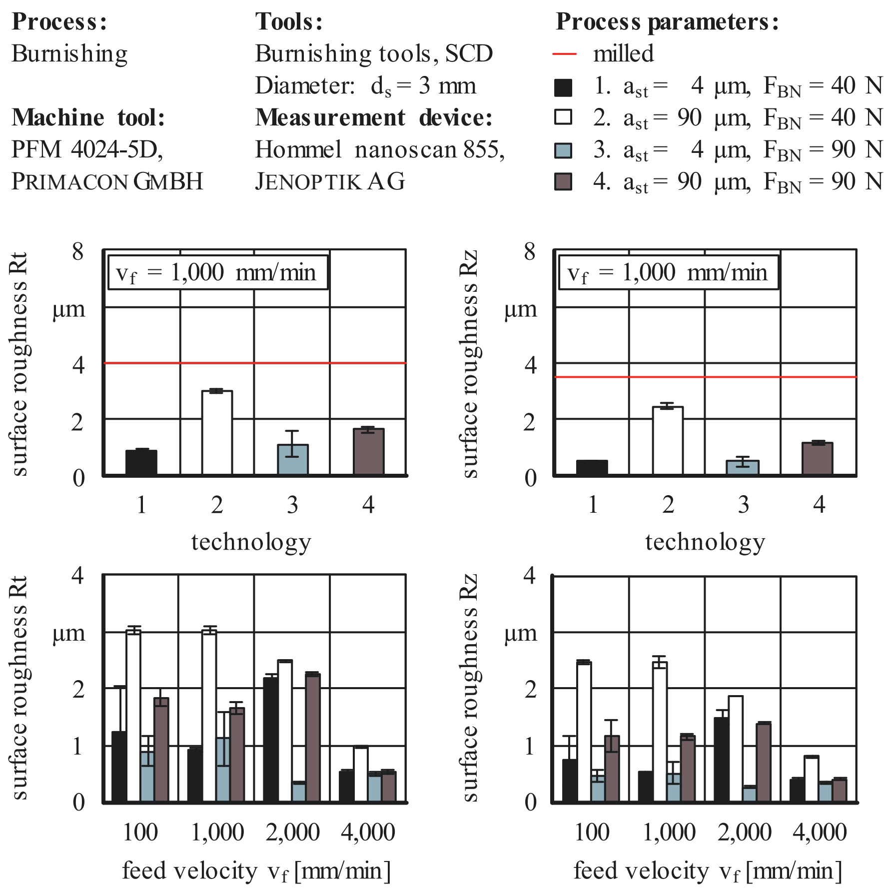

Fig. 2. Surface roughness Rt and Rz of the burnished surfaces in dependence of the process parameters.

With increasing feed velocity v_f the increased burnishing force F_{BN} leads to an additional improvement of the surface roughness. The lowest surface roughness was achieved with a stepover of $a_{st} = 4$ µm, a burnishing force of $F_{BN} = 90$ N and a feed velocity of $v_f = 2{,}000$ mm/min. Thereby, a surface roughness of Rt = 0.34 µm, Ra = 0.06 µm and Rz = 0.27 µm was determined. The results correspond to an improved surface roughness of 92 % for the surface roughness Rt, of 91 % for the surface roughness Ra and of 93 % for the surface roughness Rz.

Fig. 3 shows microscope images of four surfaces, which were machined with different stepover a_{st} and penetration depth a_p at a feed velocity of $v_f = 2{,}000$ mm/min. It can be shown that the lower stepover a_{st} in combination with the higher burnishing force F_{BN} leads to a better surface quality. The rough peaks resulting from the milling process are pressed into the workpiece surface by the diamond sphere, whereby a homogenous surface can be achieved.

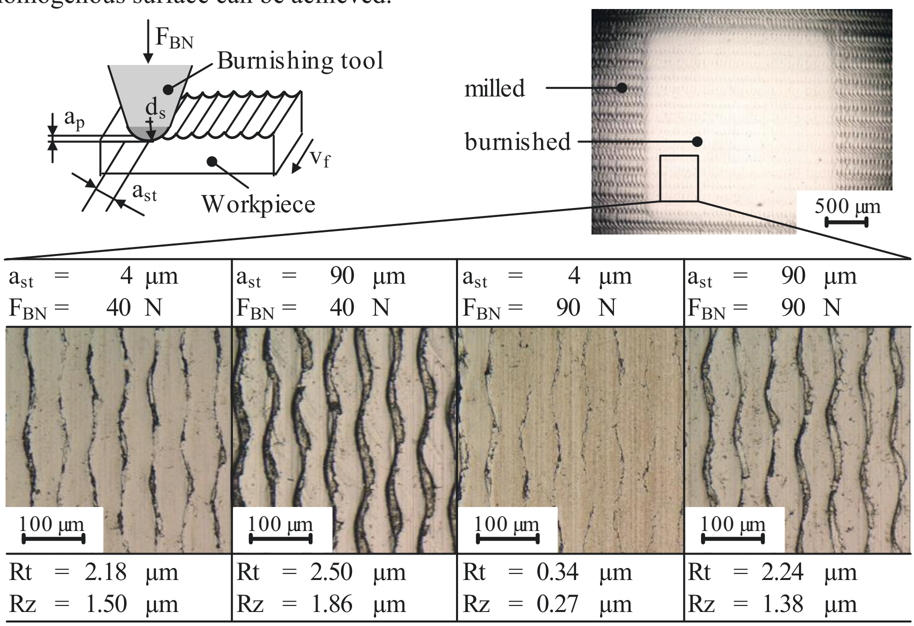

Fig. 3. Microscope images of the burnished surfaces machined with different process parameters at a feed velocity of $v_f = 2{,}000$ mm/min.

4.2 Hardness

In consequence of the burnishing forces F_{BN} and the pressure p of the diamond sphere on the workpiece surface changes of the material structure in the peripheral zone can be occur. Therefore, the hardness H of the burnished surfaces was measured and the results are given in Fig. 4. For the investigated set of parameters the results show no significant change of the hardness H through the burnishing process. Accordingly, most of the values are in the range of the standard deviation. With increased stepover a_{st} and higher burnishing force F_{BN} the hardness H can be increased, whereby the burnishing force F_{BN} shows the greater influence.

With increased feed velocity v_f an increasing hardness H can be determined. In general, the highest hardness H was determined with a stepover of $a_{st} = 90$ µm, a burnishing force of $F_{BN} = 90$ N and a feed velocity of $v_f = 4{,}000$ mm/min with H = 971 $HV_{0.1}$. In comparison to the measured hardness H after the milling process with H = 923 $HV_{0.1}$ the hardness H could be increased by 5 %. It can be assumed that the burnishing force F_{BN} is not high enough for the manipulation of the stress state of the surface and therefore only slight influence on the peripheral zone can be determined.

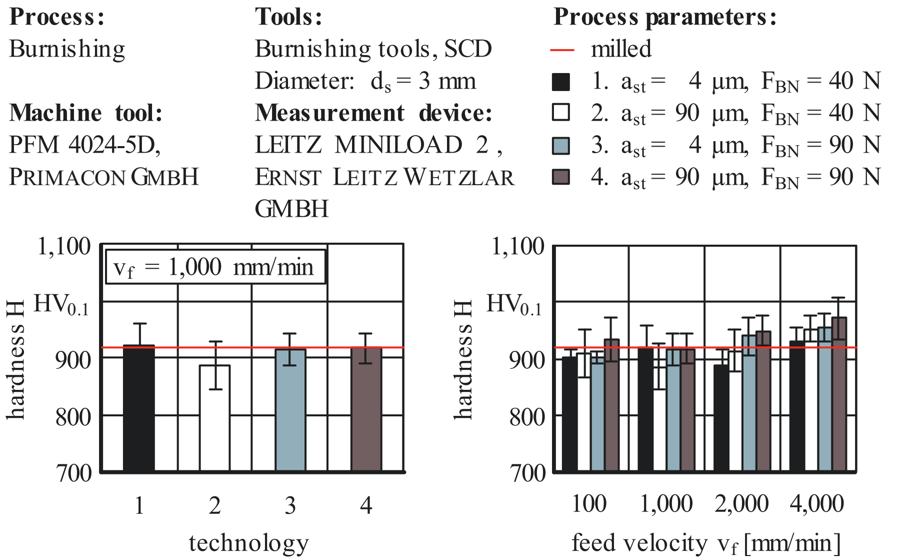

Fig. 4. Hardness H of the burnished surfaces in dependence of the process parameters.

5 Summary and Outlook

The burnishing process with fixed spheres made of single crystalline diamond is a promising technology for the finishing of milled workpieces and the production of optical surfaces. In particular, the use in machine tools used for the milling processes promises an economic alternative to other technologies like the polishing processes or the ultra-precision machining. Within the presented investigations, burnishing heads with single crystalline diamond spheres with a diameter of $d_S = 3$ mm were used for the burnishing of the ELMAX steel PMX170CrVMo18-3-1. The effect of the process parameters stepover a_{St}, feed velocity v_f as well as the burnishing force F_{BN} were examined for the surface roughness and the hardness H.

The results show that an improvement of the surface roughness Rt up to 92 % could be achieved with a stepover of $a_{st} = 4$ µm, a burnishing force of $F_{BN} = 90$ N and a feed velocity of $v_f = 2{,}000$ mm/min. The surface roughness could be reduced from Rt = 4.05 µm, Ra = 0.67 µm and Rz = 3.55 µm down to Rt = 0.34 µm, Ra = 0.06 µm and Rz = 0.27 µm. With increased feed velocity of $v_f = 4{,}000$ mm/min an improvement of the surface roughness values with simultaneous increase of the surface hardness H