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Automatic re-contouring of repair-welded tool moulds

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Abstract

The process of repairing damaged tool moulds is conducted manually in the industry. This results in long process times as well as a high dependence of the repair result on the experience of the worker. After a visual inspection, the detected damages are removed by metal cutting and the missing material is filled by a build-up welding process. Afterwards, the target geometry is restored via machining re-contouring process. Because of the individual tool mould surface and welded seam, each repair case requires an individual machining strategy as well as toolpaths and process control parameters to ensure high surface quality and shape accuracy. This paper introduces an innovative design for re-contouring of repair-welded tool moulds, which takes into consideration the individual mould surface, repair welding and material properties. For that purpose, the actual geometry of the tool mould is measured directly in the CNC machine using an optical profile line sensor. Based on the measurement, the re-contouring process is planned automatically by means of a computer aided manufacturing (CAM) software. A material removal simulation with cutting force prognosis is carried out to adapt the process parameters individually with regard to repair time and surface quality. To set up the force and surface simulation model with high model quality, re-contouring experiments are carried out on welded seams made of 1.2343 (AISI H11) as well as on Toolox 44 and 1.2343 workpieces for comparison.

Keywords: Material removal, Mold (Mould), Planning, Simulation, Automation, In-process measurement, Sensor

1. Introduction and state of the art

For the reduction of CO_2 emissions and the implementation of electric mobility, it is necessary to use lightweight technologies to reduce the weight of vehicle and aircraft components [1]. Injection moulding and die-casting are highly economical key technologies for the production of complex thin-walled components from plastics or light metal materials in large quantities [2]. Tool moulds have a significant influence on the economic efficiency of the production process. Roughly 5-15% of the production costs can be allocated to the tool mould [3,4].

During the injection and die-casting process, tool moulds are subject to high thermal, mechanical and chemical stresses [5]. In particular, the combination of high pressures and high flow velocities, a cyclically dynamic temperature profile due to rapid heating and cooling as well as the chemical reaction during mould filling considerably reduce the lifetime of the mould [3]. As a result of the load spectrum, shape damage such as stress cracks, thermal fatigue cracks, erosion, adhesion (sticking), break-outs and dents occur [5-7].

Mould repair is an economical alternative to manufacturing new tool moulds, especially for large and complex moulds [8]. The repair process is a highly challenging process, usually carried out manually by a skilled worker [9,10]. This includes damage detection based on a visual inspection, removal of the damaged areas, filling of the mould by deposition welding as well as restoration of the target geometry by machining, the so-called re-contouring process (see Fig. 1) [10-14].

To restore the target surface, excess material from the deposition welding process is currently being removed by hand grinding, milling or eroding [14,15]. For simple surfaces,

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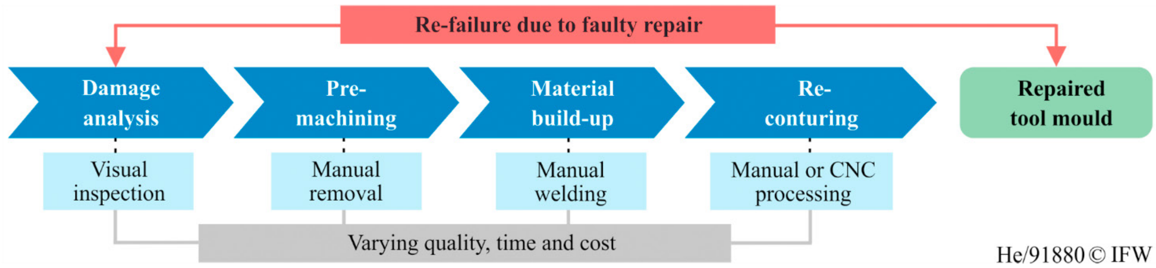

Figure 1: Process chain of typical tool mould regeneration in industry

the toolpaths are programmed directly on the CNC machine by a worker. In the case of complex freeform surfaces, NC programs for new production – unchanged or slightly modified – are used. The NC programs are usually not adapted to the individual damage and weld seam, which can result in long process times, insufficient surface quality and shape inaccuracies. In the case of abrupt intervention of the milling tool into the hard weld seam, tool breakage or machine damage can occur.

Experimental investigations show an increase in feed and cutting forces during machining of hard weld seams (55-59 HRC) compared to the base material (19 HRC) [16]. Nguyen Trong investigated the influence of the hardnesses on the surface roughness (Ra) in dry machining of 40CrMnMo7 with the result that the roughness decreases linearly with increasing hardness [17]. Albersmann presented first approaches to computer-aided mould rework by using a forging mould as an example. The welded contour is recorded by a tactile measuring method, the NC paths for the milling process are generated from the measured data and the air cutting time is optimised by changing the feed speed [18]. Klocke et al. developed the Controlled Metal Build Up (CMB) process for the repair of tool moulds. In this process, laser welding is combined with 3-axis high-speed plan milling [19]. In the OptoRep research project, an automated repair station was investigated in which an optical measuring method and a laser deposition unit were integrated into a vertical CNC machine. The focus of the project was on machine integration of optical metrology and laser welding technology as well as NC path generation for the welding process [10].

Based on the state of the art, it becomes obvious that current mould regeneration is a very manual and time-consuming process, which requires a high level of process knowledge, experience and skill. The determination of optimal toolpaths and process parameters for the machining of individual repair-welded tool mould surfaces does not exist sufficiently in research and industry. This paper presents an innovative concept for an automatic re-contouring of repair-welded tool moulds, which addresses this research gap and aims the reduction of repair time, improvement of mould surface quality and prevention of human errors.

2. Conceptual design of an automated re-contouring process

Figure 2 shows an innovative process flow for automated re-contouring of welded mould surfaces. The weld seam detection is carried out with an optical laser line profile sensor, which is integrated into a CNC machine. The downstream process planning consists of a control loop including definition of processing strategy, path planning and material removal simulation for optimising cutting parameters and milling toolpaths. The area highlighted in blue shows the developed assistance system, which performs all planning and model generating tasks. It includes the sensor path planning, model generation, manufacturing strategy and path planning as well as the material removal simulation. The grey marked area highlights the processing steps, the optical scanning and the re-contouring process, which are done in the CNC machine.

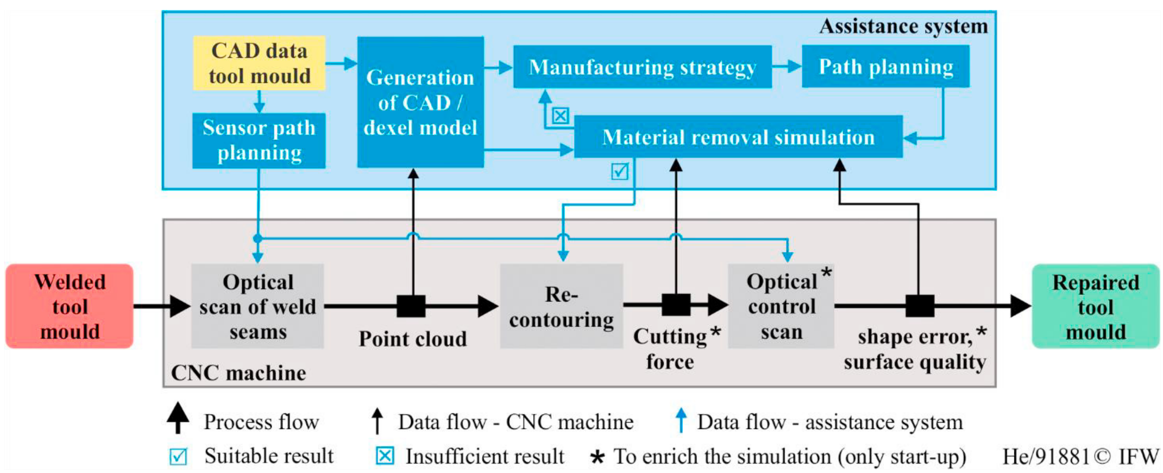

Figure 2: Innovative process flow for re-contouring of welded tool moulds

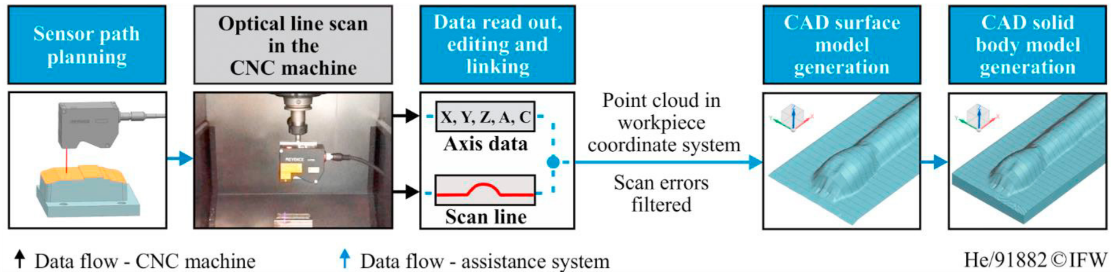

Figure 3: Process sequence for scanning and CAD generating of the welded mould surfaces

At the beginning of the novel re-contouring process, the welded mould is fixed and set up on the CNC machine table. After that, the welded surfaces are scanned by an optical line sensor and an adapted sensor path planning. Based on the scan data, the as-is CAD-model and a dexel simulation model are generated. According to the target and actual data, a production strategy and path planning individually adapted to the repair case will be created. With the support of an interconnected material removal simulation, which includes a force and surface model, the process control parameters are adjusted until the required manufacturing result is obtained. Once the optimisation loop is successfully completed, the re-contouring process begins. Process forces are measured during machining and the line sensor is applied a second time to monitor the final surface. The recorded data is used to improve the simulation model. Once a good level of simulation maturity is reached, the force and surface measurement is no longer required.

To investigate the concept, the assistance system is integrated into the simulation software IFW CutS [20]. The CAD modelling and path planning is carried out via the interface NXOpen (Siemens NX). A DMG HSC 55 CNC machine with an intermediate-connected Beckhoff IPC and an optical sensor from Keyence is used.

2.1 Individual optical scanning and modelling

For an exact re-contouring process, an accurate measurement of the individually repair-welded mould surface is necessary. In view of the repair time, the scan process has to be performed fast. Figure 3 shows the technical process sequence for scanning and CAD generation of the welded mould surfaces, which complies both requirements.

At process start, the measuring paths are generated by sensor path planning and transferred to the CNC machine as NC code. A calibrated optical line sensor (Option A: in tool holder, Option B: fixed to the spindle slide) oriented to the workpiece reference origin moves through the mould surfaces in accordance with the defined measuring strategy. During the measuring process, the machine axis data and the scan line of the optical sensor are continuously read out, interference signals filtered and the data linked together in a point cloud. With this method, no time-consuming fitting of actual and target surfaces is necessary. In addition, complicated 5-axis scanning strategies are realisable. With the linked data, a surface model in the first step and second a solid body model are created by the assistance system in the CAD system.

2.2 Adapted toolpath planning for manufacturing

For an individual design of the machining strategy, the surface and weld seam properties have to be detected. To enable this, an algorithm is developed and implemented in the assistance system. First, the algorithm analyses the geometric characteristics of the scanned weld seam such as width, height, position and orientation in the reference coordinate system. In the next step, the algorithm identifies the mould surfaces from the CAD target model and analyses the geometric properties such as curvature, angle, start and end points as well as position and orientation. By comparing the properties and positions of the weld seam and surfaces, it is detected which surfaces were welded. According to the surface properties and seam geometry, a 3-axis, 3+2-axis or 5-axis maching strategy is applied. In addition, an adapted milling tool is defined and the tool diameter corresponding to the maximum weld seam width is selected (see Fig. 4).

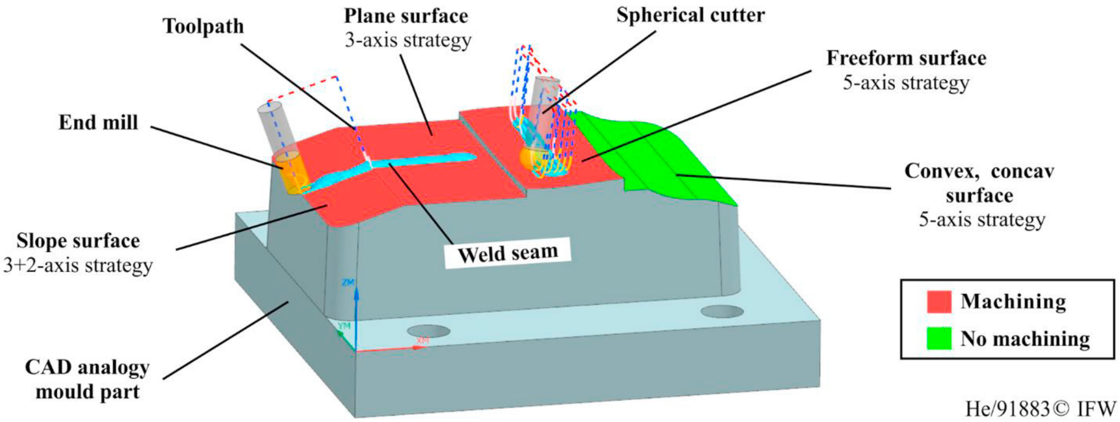

Figure 4: Representation of the algorithm on the basis of a tool mould analogy part

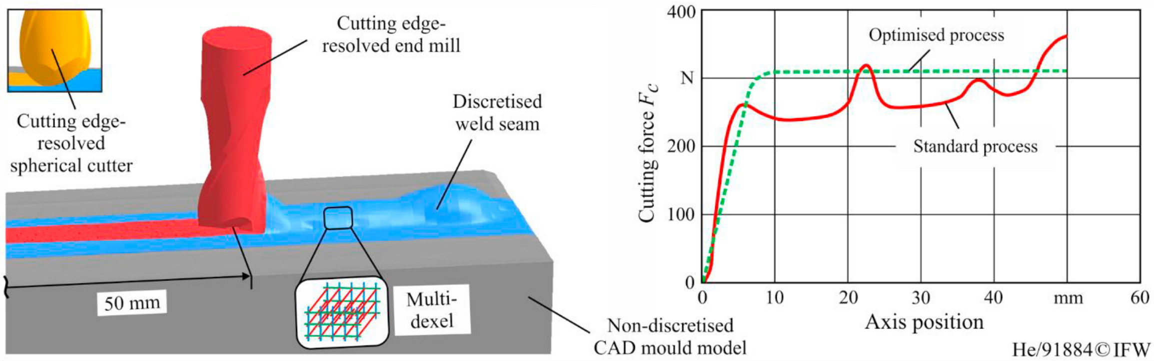

Figure 5: Geometric material removal simulation with cutting force prognosis for weld seam machining

2.3 Material removal simulation

To test the adapted process, the generated toolpath and the cutting parameters are verified using a material removal simulation with a multi-dexel model. High-resolution dexel-based simulation models require high memory effort. To reduce memory requirements, only the weld seam and transition area are converted into a dexel body. The actual milling tool geometry is used in the simulation to enable accurate cutting force predictions. For this, a spherical cutter and an end mill were optically scanned (focus variation) by Alicona Infinite Focus G5. The high resoluted point cloud data is reduced by up to 80% by removing unnecessary elements (see Fig 5).

Using an expanded Kienzle force model [21] with specific cutting force k_c, aera of cut A and correction coefficients K_i, the cutting forces F_c during the re-contouring are simulated and the cutting parameters, such as feed speed v_f and depth of cut a_p, as well as the tool paths, are optimised for a consistent force profile (see Fig. 5 and Eq. 1).

$$F_c = k_{c\,\text{(Welded material + hardness)}} \cdot A_{\text{(Calculation by dexel cut)}} \cdot k_i$$
$$k_i = k_{vc\,\text{(Cutting speed)}} \cdot k_{bw\,\text{(Machining + tool type)}} \cdot k_{vw\,\text{(lead + tilt angle)}} \cdot k_{wb\,\text{(Tool coating)}} \cdot k_{wv\,\text{(Tool wear)}} \tag{1}$$

For the prognosis of cutting forces and surface quality, experimental investigations are necessary. The starting base for the following investigations were weld seams, which were produced with a robot welding machine and a MAG welding process. The MAG-wire consisted of hot work steel 1.2343, which is used in tool and mould making in many cases. To compare and evaluate the results, the experiments were also carried out on Toolox 44 and 1.2343 (soft-annealed) workpieces (see Tab. 1). Toolox 44 is a novel tool steel pre-hardened to 44 HRC (Rockwell hardness), which was developed by the Swedish steel company SSAB to eliminate the working step of tool hardening [22].

Table 1. Steel grades used in the experiments, data in wt % [22-24]

Identification	C	Si	Mn	Cr	Mo	V
MAG-wire electrode Lava WA 4 (1.2343, AISI 11)	0.38	1.00	0.40	5.00	1.10	0.45
Toolox 44	0.32	1.10	0.80	1.35	0.80	0.14
1.2343 (ESU), AISI 11	0.37	1.00	0.40	5.30	1.30	0.40

Figure 6 shows microsection and hardness profile (Vickers) of a multi-layer weld seam welded onto a Toolox 44 sample workpiece. The weld structure shows a relatively homogeneous microstructure. The overlapping between the welded layers and a thin-outer layer is visible. The hardness measurement in vertical direction showed a hardness profile from 619 to 673 HV1 and in horizontal direction from 671 to 697 HV1. Hardness of 453-571 HV1 was measured in the transition range. With a single seam, a hardness of up to 725 HV1 could be detected.

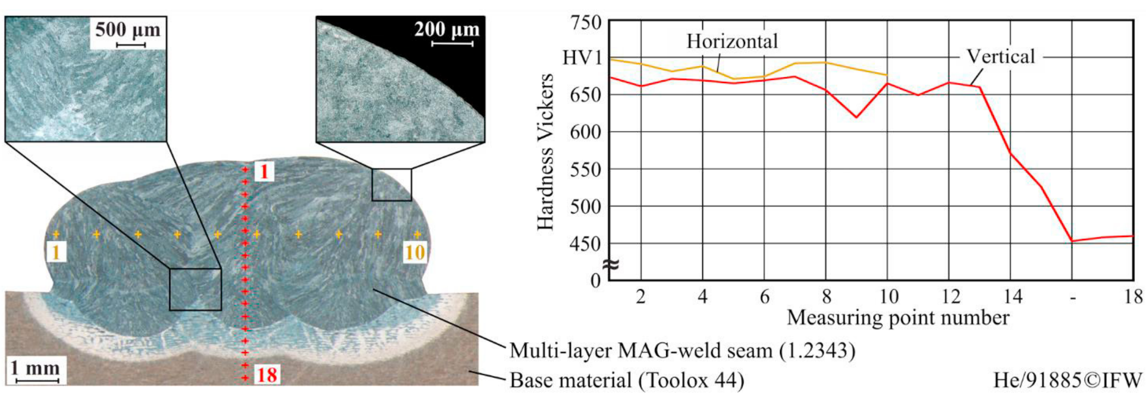

Figure 6: Micrograph and hardness profile of a multi-layer weld seam

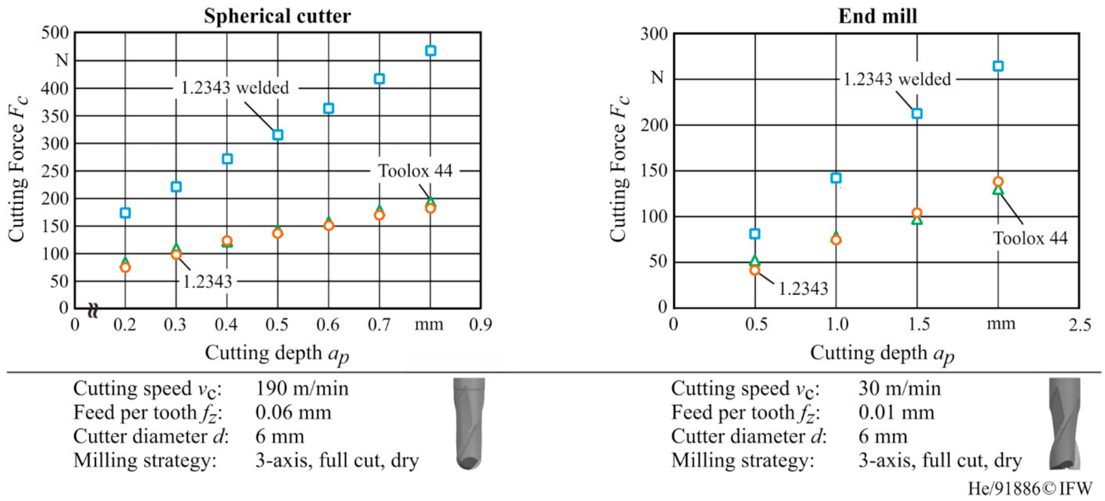

Figure 7: Cutting force profile during machining of 1.2343 welded, 1.2343 and Toolox 44

To investigate the machinability of the welded seam, the cutting forces during milling were measured. A spherical cutter was used in the experiments to analyse the machining of curved and freeform surfaces, and an end mill to investigate roughing processes and finishing of plane surfaces. Table 2 lists the test milling cutters.

Table 2. Milling tools used in the experiments

Identification	Material	Coating	Diameter	Number of teeth
Format spherical cutter WN	Solid carbide	TiAlN-S	6 mm	2
Gühring end mill DIN 6527K	Solid carbide	TiAlN-Fire	6 mm	2

The experiments illustrate that significantly higher cutting forces occur during machining of the welded seam (55 HRC) compared to the softer base material 1.2343 (< 20 HRC) and Toolox 44 (43.5 HRC). For the spherical milling test, cutting depths were varied from 0.2 to 0.8 mm (0.1 mm step width) and for end milling from 0.5 to 2 mm (0.5 step width). The forces measured during spherical milling of the welded seam were doubled at a cutting depth of 0.2 mm and 2.5 times higher at a cutting depth of 0.8 mm compared to the two base materials. During end milling, 1.5 to 2 times higher cutting forces were measured for the welding seam machining. Toolox 44 and 1.2343 showed similar forces, although Toolox is much harder than the 1.2343 base material. For both milling tests, the dry cutting method was used and the cutting data were based on the manufacturer's specifications (see Fig. 7).

To characterise the surface roughness of the welded material compared to the base material 1.2343 and Toolox 44 as well as the impact of process force on the surface roughness, the milling paths were tactile measured (Mahr Perthometer PGK). Machining with the spherical cutter showed a slight reduction of the surface roughness (Ra) by increasing the cutting depth / cutting force. For the materials 1.2343 and Toolox 44, the roughness varied. During end milling, an increase in roughness was detected by increasing the cutting depth / cutting force across all three materials. In regard to the experimental results, there is evidence that the surface roughness of the weld seam is higher for spherical and end milling in comparison to 1.2343 and Toolox 44 (see Fig. 8).

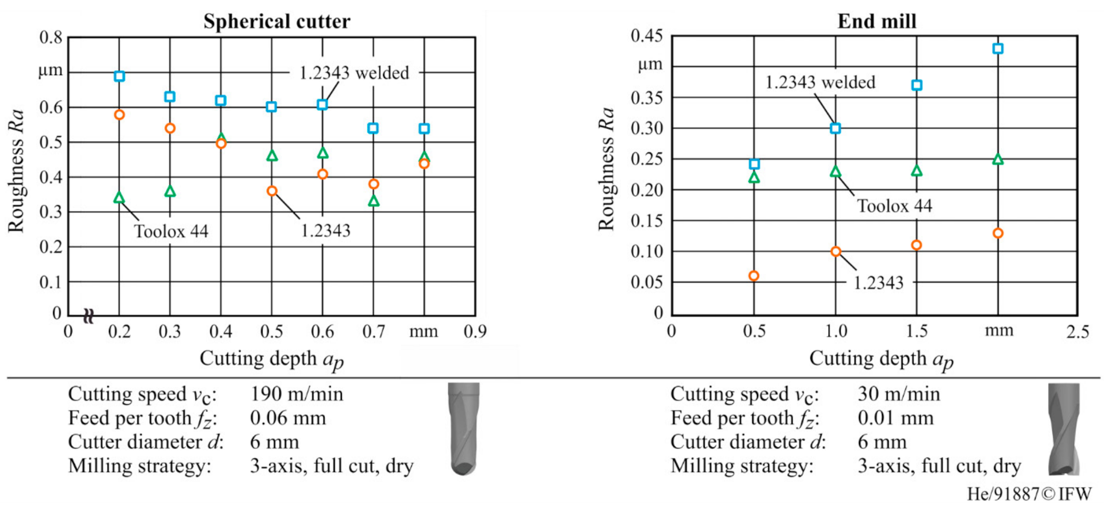

Figure 8: Roughness profile (*Ra*) after machining of 1.2343 welded, 1.2343 and Toolox 44

The experiments indicate significantly higher cutting forces during the machining of hard weld seams compared to the soft-annealed base material. With increasing cutting depth, the cutting force and the force difference between weld seam and base material machining rises. The surface roughness (Ra) slightly reduces with rising cutting force during re-contouring of weld seams with a spherical cutter and increases during end milling. These research results provide the basis for further investigations. The experimental data will be applied to parameterise the force model and to generate a surface model.

3. Conclusion and Outlook

This paper introduces an innovative concept for the re-contouring of repair-welded tool moulds with the goal of improving mould surface quality, reducing repair time and preventing human errors by using an optical laser line scanner, automated path planning and an interconnected material removal simulation. Experiments carried out show that machining of MAG-welded hard repair seams made of hot work tool steel 1.2343 results in a higher process force and higher surface roughness in spherical milling and end milling compared to the base material 1.2343 and Toolox 44 steel. In addition, a tool / process-dependent change of the surface quality was detected by increasing the cutting force. These results indicate that there is a dependency between process force and surface quality and that the process parameters for re-contouring hard weld seams have to be investigated.

In future work, further investigations with different cutting data, cutting tools, tool geometries and tool coatings will be carried out and the surface quality achieved analysed. On the basis of these and the presented results in this paper, force coefficients will be generated for the force simulation model implemented and a surface model will be elaborated. Both models are validated by real re-contouring experiments. In addition, the effects of different toolpath strategies such as zig, zig-zag, trochoid with regard to the repair time, surface quality and cutting forces will be investigated for different weld seams / mould surface geometries and implemented in the assistance system.

4. Acknowledgements

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