Production Engineering (2019) 13:71–77
https://doi.org/10.1007/s11740-018-0858-4

PRODUCTION PROCESS

Adaption of tool surface for sheet-bulk metal forming by means of pressurized air wet abrasive jet machining

Dennis Freiburg[1] · R. Aßmuth[1] · R. Garcia Carballo[1] · D. Biermann[1] · J. Henneberg[2] · M. Merklein[2]

Received: 14 August 2018 / Accepted: 21 November 2018 / Published online: 29 November 2018

Abstract

Surface structures are used for several applications in industry to enhance the characteristics of surfaces and therefore processes. One example is the Sheet-bulk metal forming process which combines the advantages of bulk and sheet metal forming. Due to the complex material flow and load, the tool surfaces do need adapted tribological properties. High feed milled surface structures have been used in the past to control the material flow of the sheets. But due the high stresses appearing, the surfaces show a running-in behavior which altereds the tribological conditions. Within this study, a pressurized air wet abrasive jet machining (PAWAJM) process is used for adapting the high feed milled surface in order to manipulate the tribological conditions. Therefore, the surfaces characteristics, residual stresses as well as the tribological effects were investigated. It is shown that the PAWAJM process can be used to modify the surface characteristics and thus the friction of the surface. In addition, it can be seen that residual compressive stresses are applied during the PAWAJM.

Keywords Surface modification · Tribology · Sheet-bulk metal forming

1 Introduction

Sheet-bulk metal forming is a combination of sheet and bulk forming operations. It can be used to produce sheet metal parts with thickened elements, which can be teeth or interlocks [1]. In Japan, this process combination is known as plate forging [2]. Depending on the process combination as well as the complexity of the part to be manufactured, the die filling of such thickened elements can be insufficient [3]. Further investigations showed, that the die filling can be improved by varying the local friction in different zones of the forming tool, to control the material flow. Furthermore, by combining these findings with friction adapted sheets, the improvement can be larger [4]. One of the processes, which can be used to adapt the friction on tool surface, is high feed milling (HFM). Within this process, large areas of the die can be adapted by milling quasi-deterministic surface structures onto the surfaces. The effectiveness, by setting higher roughness in local areas, was shown for different sheet bulk metal forming operations. However, due to the high stresses arising, the surface structure do show a running-in phase. After approximately 250 forming tests, the structures are slightly smoothed, reducing the total roughness of the surface structure. This can be seen in a comparison between an initial surface structure and one after 250 strokes in Fig. 1. Although the basic structure of the surface remains unchanged, the micro-roughness in a nanometer range is slightly smoothed, which can be seen from the profile section shown. After the running-in phase they show no further signs of wear and remain unchanged up to 10,000 strokes [5]. This running-in phase will have direct influence on the friction of the surface structure and the sheet flow, which will be influenced, too. Therefore the aim of these investigations is to adapt the surface topographies used so far, by means of pressurized air wet abrasive jet machining (PAWAJM), in order to increase the wear resistance on the one hand and to modify the tribological properties to guarantee a constant sheet flow over the production time on the other. Influencing the roughness parameters of the initial high feed surface structure should avoid the running-in phase. Therefore, a selected HFM surface structure is modified by PAWAJM and subsequently analyzed in terms of its tribological properties by a ring compression test.

✉ Dennis Freiburg
Freiburg@isf.de

[1] Institute of Machining Technology, TU Dortmund University, Baroper Straße 303, 44227 Dortmund, Germany

[2] Institute of Manufacturing Technology, Friedrich-Alexander-University, 91054 Erlangen, Germany

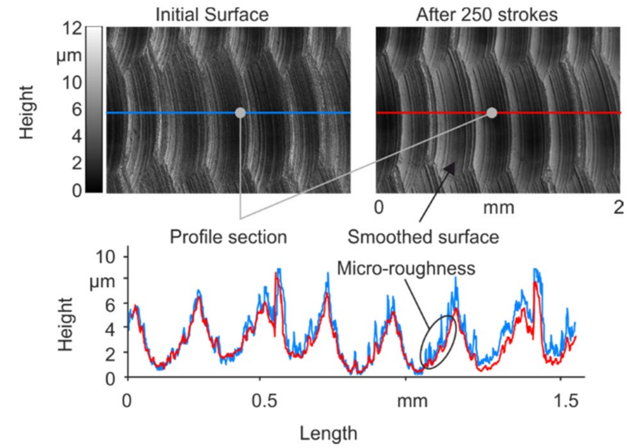


Fig. 1 Initial surface before forming and after 250 strokes [5]

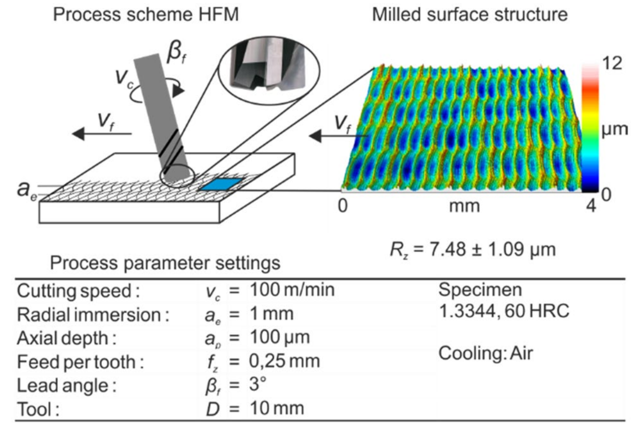


Fig. 2 Process parameter and surface topography of the HFM process

Furthermore the residual stresses after each modification are measured, too.

2 Surface modifications

2.1 High feed milling

High feed milling is a process, which is mainly used for rough milling with high material removal rates and hard machining of surfaces. Compared to conventional milling, the process uses high feeds per tooth, low axial cutting depth and nearly regular cutting speeds [6]. Due to the special form of the cutting geometry in combination with the high feed per tooth, various surface structures with different surface characteristics can be milled [7]. Furthermore the process induces compressive residual stresses which leads to improved fatigue strength of the forming tools [8]. For the investigations a surface structure was milled by high feed face milling on a DMG HSC 75 machining center using a conventional high feed milling cutter with a diameter of $D = 10$ mm. For the specimens a 1.3344 (ASP2023) high speed tool steel, which was prior hardened to 60 HRC, is used. All HFM surfaces were machined with a cutting speed of $v_c = 100$ m/min, a radial immersion of $a_e = 1$ mm, a feed per tooth of $f_z = 0.25$ mm and a lead angle of $\beta_f = 3°$. The process parameters and the topography of the HFM surface structure can be seen in Fig. 2.

The milled surface structure has a mean roughness of $R_z = 7.48 \pm 1.09$ µm. By using this surface structure in an SBMF process, the anisotropic surface roughness causes the material to flow transversely to the feed direction v_f, which can positively influence the forming of complex parts.

2.2 Pressurized air wet abrasive jet machining

Pressurized air wet abrasive jet machining is a process based on an energy-bound operating principle in which unbound abrasive in water is accelerated on the workpiece surface through a jet nozzle. In this regard, the acceleration of the abrasive is realized either by suction or by compression. In the present investigations, a pressurized air wet abrasive jet machine of the company Restec GmbH Nicolis Technology is used, which works with compressed air, by which the abrasive-water-mixture accelerates. The jet nozzle has an exit diameter of $d_d = 8$ mm.

PAWAJM is mainly used to optimize cutting tools with respect to the cutting edge preparation [9] as well as the coating pre- [10] and post-treatment [11]. In this regard, the process can be utilized to produce defined cutting edge micro shapes [12], to modify surface topographies [13] as well as to achieve residual compressive stresses [14]. Compared to the shot peening process, where the surface is more deformed plastically [15], the PAWAJM achieves a uniform material removal. In view of the given HFM structure, this approach seems to be more effective since the shape of the surface structure should not be influenced too much. Research results prove that by the preparation with PAWAJM the wear resistance of tool's cutting edges [14] and coatings can be improved [11]. Studies on PAWAJM of high speed tool steel are not yet known.

For the preparation of cemented carbide, aluminum oxide as abrasive medium is usually used. Due to the abrasive hitting onto the target surface a characteristic dimple microstructure results. Compared to dry abrasive jet machining the use of water offers the advantage of achieving a cooling effect with simultaneous cleaning effect on the workpiece [9]. Among others the essential process variables are the jet feed speed $v_{f,st}$, the jet pressure p_{st}, the relative jet inclination angle α_{st}, the jet nozzle distance h_d, the specification of the abrasive medium and the jet mass concentration σ_{st} [12].

For the investigations, the high feed milled surfaces were prepared by a PAWAJM, which is motion controlled by an industrial robot. Therefore, it is possible to run complex NC-paths. In this case, it was necessary to achieve a large area treatment which was processed by linear NC-paths with a path distance of $b_d = 2$ mm. The distance between the nozzle outlet and the specimen with $h_d = 20$ mm as well as the inclination angle of the jet, hitting orthogonal on the surface of the specimen, were set fix for the investigations.

To adjust the surface parameters using PAWAJM, the jet pressure p_{st}, the jet feed speed $v_{f,st}$ and two different FEPA grain sizes of new sharp-edged aluminum oxide abrasive were considered. The concentration of the abrasive in water was $\sigma_{st} = 10\%$. The process scheme and process variables can be seen in Fig. 3.

2.3 Preparation of tool surfaces by pressurized air wet abrasive jet machining

In order to investigate the influence of the PAWAJM, the high feed milled surface structure (shown in Sect. 2.1) is taken as the initial surface. The setup of the PAWAJM process is shown in Sect. 2.2. As an experimental plan, a latin hypercube design (LHD) [16] was chosen with 15 parameter variations for each FEPA grain size. Therefore a jet feed speed between $v_{f,st} = 1$ mm/s and $v_{f,st} = 15$ mm/s, a jet pressure between $p_{st} = 4.5$ bar and $p_{st} = 9$ bar and the FEPA grain sizes 220 and 360 were considered.

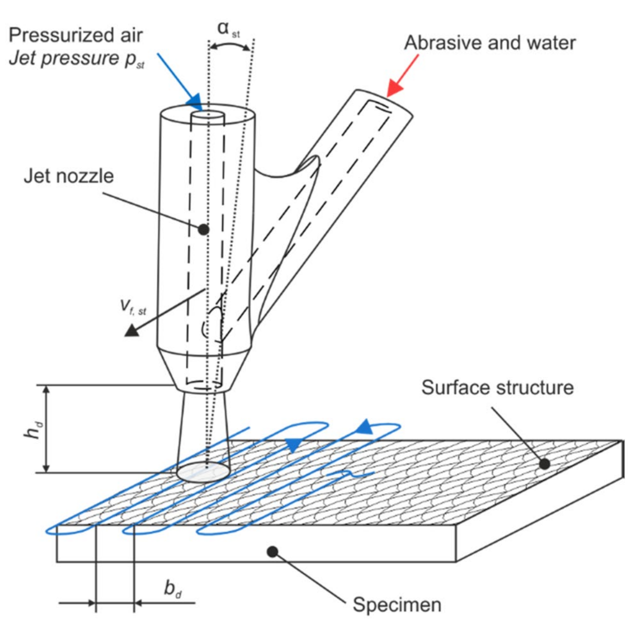


Fig. 3 Process scheme of PAWAJM-Process

To analyze the differences between the initial high feed milled surface structure and prepared ones, a confocal white light microscope NanoFocus µsurf measured all topographies in feed direction of the HFM process. The measurements are filtered by a Gaussian filter of $\lambda_c = 0.8$ mm and the mean value of all standard deviations of the mean roughness R_z is $\sigma = 0.98$ µm.

To show the influence of the PAWAJM regarding to the change of the surface characteristics, statistical DACE-models were computed using MatLab [17].

2.4 Influence on surface characteristics

The surface characteristic like the mean roughness R_z is an important influence regarding the friction conditions [18]. Therefore, the mean roughness R_z in feed direction of the high feed milled surface structure was considered for both grain sizes. Figure 4 shows the statistical models between jet pressure and jet feed speed, as well as selected surface topographies and profile sections of those.

It can be stated that the PAWAJM-process is capable of modifying the surface parameters of the initial high feed milled surface structure. For both grain sizes the models show a decreasing mean roughness in feed direction of the structure by applying a higher jet pressure and a lower jet feed speed. When using the lowest jet pressure of $p_{st} = 4.5$ bar and the highest jet feed speed of $v_{f,st} = 15$ mm/s, the roughness even exceeds the initial roughness of the high feed milled surface structure, which can be caused by superposition of micro and macro roughness.

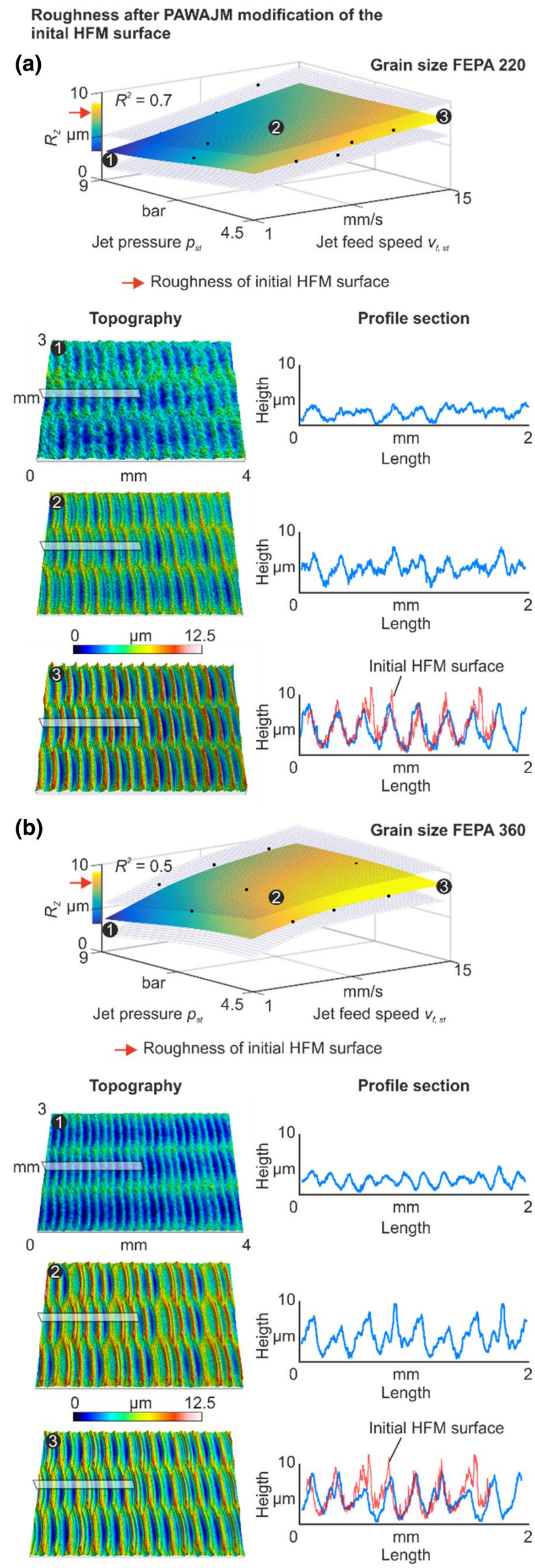
Comparing the models for both grain sizes, they show a similar interrelation. But the modified surface topographies and the profile sections do vary between the grain sizes.

The coarser grain size FEPA 220 seems to remove more material from the surface compared to the finer one FEPA 360, which damages the initial structure of the topography. Mostly this can be stated in Fig. 4a, b by the surface topographies 1, which were modified using a jet pressure of $p_{st} = 9$ and a jet feed speed of $v_{f,st} = 1$ mm/s.

While the initial surface modified with the FEPA 220 grain is nearly destructed by the PAWAJM-process, the surface machined by the FEPA 360 grain looks more regular. This can as well be proofed by the profile section where all feed tooth can be seen for the finer grain, while the section of the coarser one looks irregular. However, it should be noted, that very low jet feed speeds are not advisable, as too much of the initial surface structure is removed and long machining times are required.

The differences in the resulting surface characteristics are significantly dependent on the grain size used. While the mean grain size of FEPA 220 is about $d_{K,m} = 55$ µm, the mean grain size of the FEPA 360 is $d_{K,m} = 22.8$ µm. The difference is clearly visible by comparing both mean grain

Fig. 4 Statistical models and topographies of PAWAJM prepared HFM surfaces



sizes with two feed per tooth sections of the high feed milled surface structures, shown in Fig. 5. Furthermore, this can be proved with respect to the (micro) roughness of the surfaces. By filtering with a Gaussian filter of $\lambda_c = 25$ µm the (micro)-roughness of the surface can be compared. Because of the larger impact area, caused by the larger grain size, the root mean square roughness $R_a = 0.16 \pm 0.007$ µm is larger for the FEPA 220 grain compared to the FEPA 360 grain with $R_a = 0.11 \pm 0.007$ µm.

The larger grain size causes an impact with an higher kinetic energy on the surface [13], which leads to a higher roughness. That the impact of different grain sizes and forms cause different roughness parameters is shown in [19], too. For further experiments, the FEPA grain size 360 was chosen.

2.5 Influence on internal stresses

Besides the topography, fatigue strength of forming tools is an important characteristic. In [8] it is shown that HFM surfaces are characterized by higher fatigue strength compared to polished surfaces. It is assumed that the fatigue strength is improved by the residual compressive stresses which are induced by HFM and prevent the growth of fatigue cracks. Thus, the influence of PAWAJM on the residual stresses orthogonal to the milling marks was investigated for three surfaces and is presented in Fig. 6. After HFM, the surfaces show residual compressive stresses of − 575 ± 102 MPa. The PAWAJM raise the residual compressive stresses. PAWAJM with a jet pressure of p_{st} = 5.5 bar and a jet feed speed of $v_{f,st}$ = 14 mm/s increases the residual stresses to − 974 ± 31 MPa. Machining with a higher pressure of p_{st} = 8 bar and lower jet feed speed of $v_{f,st}$ = 2 mm/s causes the highest residual compressive stresses of − 1118 ± 29 MPa. This effect can be explained by the grains impacting the tool surfaces. When the grains impact, they release a part of their kinetic energy to the surfaces. It can be assumed that this causes local plastic deformation of the tool surface and consequently increases the residual compressive stresses. By an increase of the jet pressure or a reduction of the jet feed speed, more energy is induced into the surface, resulting in higher residual compressive stresses. The same interrelationships are shown for shot peening in [20]. Summarizing it can be assumed that PAWAJM of HFM tool surfaces has the potential to improve the fatigue strength of forming tools due to higher compressive stresses.

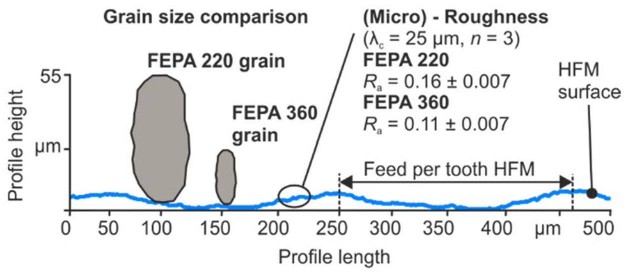


Fig. 5 Mean grain size comparison

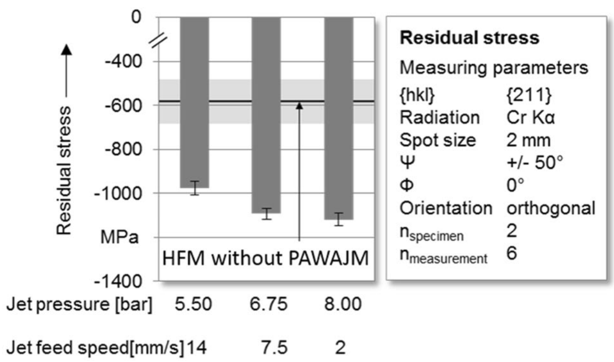


Fig. 6 Residual stresses of modified surfaces

Table 1 Varied parameters and grain size of the surfaces modified by the PAWAJM process

Surface	1	2	3
Jet pressure p_{st} (bar)	5.50	6.75	8.00
Jet feed speed $v_{f,st}$ (mm/s)	14	7.5	2
Jet nozzle distance h_d (mm)	20	20	20
Grain size FEPA 360 (µm)	22.8	22.8	22.8

3 Tribological verification

Since the PAWAJM significantly affects the topography of HFM tool surfaces, their tribological behavior as well as their potential to influence the friction and to control the material flow has to be analyzed. Therefore, the tribological behavior of three modified surfaces with the machining parameters presented in Table 1 was investigated. A jet pressure between p_{st} = 5.5 bar and p_{st} = 8.0 bar and a jet feed speed between $v_{f,st}$ = 14 mm/s and $v_{f,st}$ = 2 mm/s are chosen. Previously, it was shown, that the jet pressure positively and the jet feed speed negatively influence the roughness decline caused by PAWAJM. Thus, both parameters are varied simultaneously in opposite directions.

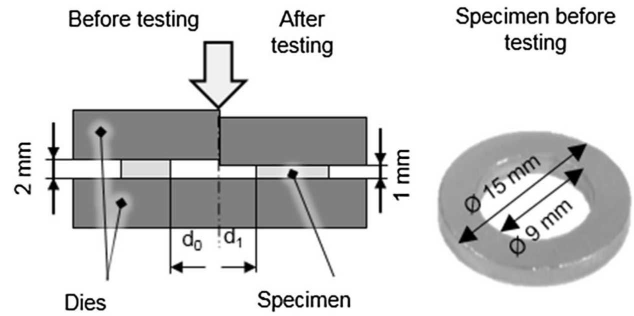


Fig. 7 Setup of the ring compression test

These machined tools represent the range of surfaces that can be produced by a combination of HFM and PAWAJM. Additionally, lapped and HFM tool surfaces as references are investigated. For the analysis of the tribological behavior the ring compression test (RCT) is used. In the RCT a ring with an outer diameter of 15 mm and an inner diameter of 9 mm is compressed between two punches made out of ASP2023 (1.3344) with a hardness of 61 ± 2 from an initial height of 2 mm to a height of 1 mm, as shown in Fig. 7. The forming velocity is 10 mm/s. The inner diameter of the specimen after forming is sensitive to the friction. A high friction causes a smaller inner diameter [21].

The geometry of the specimen is selected based on numerical studies to guarantee a high sensitivity of the inner diameter to friction. The friction factor is calculated with Eq. 1, which is identified in [4] for the specific specimen geometry and material. Were *d1* is the diameter of the inner ring and *m* the friction factor to be calculated.

$$m = (-0.07722 \times d1 + 0.9696) / (d1 - 5.834) \quad (1)$$

The specimens are made out of the deep drawing steel DC04 (1.0338) and are lubricated with 10 g/m^2 of Beruforge 150DL.

Fig. 8a reveals that the HFM tool surfaces cause a high friction factor of $m = 0.30 \pm 0.01$ compared to the lapped tool surfaces with a friction factor of $m = 0.13 \pm 0.01$. The friction factors of all analyzed HFM and PAWAJM surfaces are between the friction factors of lapped and only HFM tool surfaces. The PAWAJM reduces the friction compared to the only HFM surfaces by 10 up to 40%. An increase of the jet pressure from p_{st} = 5.5 bar to p_{st} = 8.0 bar and a simultaneously decrease of jet feed speed from $v_{f,st}$ = 2 to 14 mm/s results in a decline of the friction factor from $m = 0.27 \pm 0.02$ to $m = 0.18 \pm 0.01$. As previously discussed, both machining parameters have a positive respectively negative effect on the roughness reduction of the tool surface. Hence, the functional relation between the tool roughness and the friction is analyzed in Fig. 8b. The mean roughness R_z is chosen as a roughness parameter. HFM surfaces have a significantly higher roughness of $R_z = 7.48 \pm 1.09$ µm

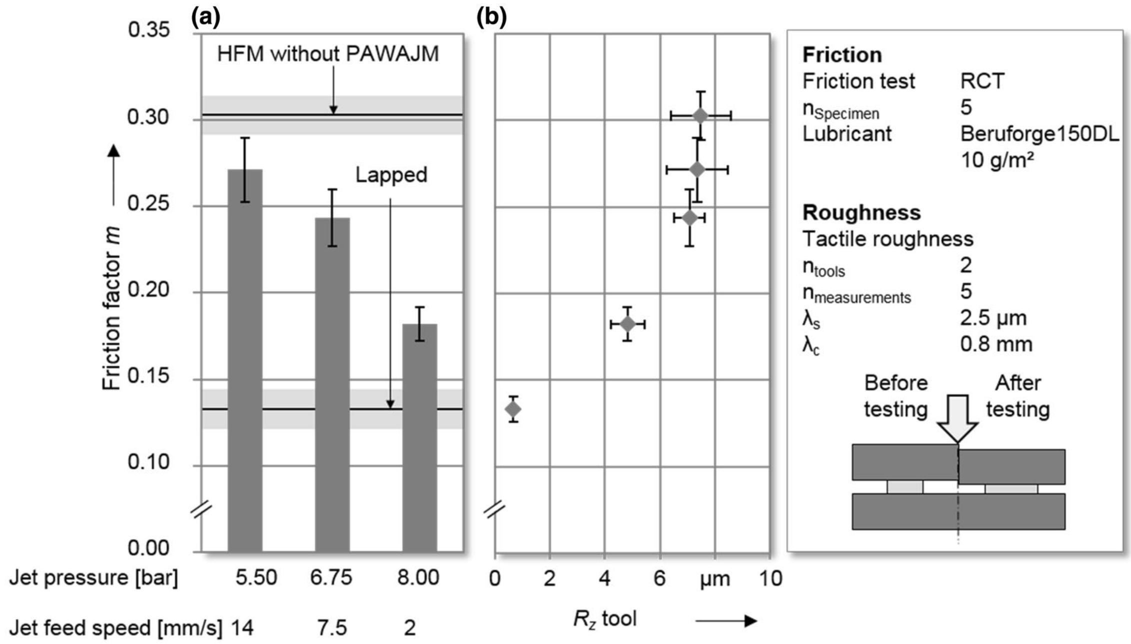


Fig. 8 **a** Friction factors for differently modified tool surfaces and **b** relation between tool roughness and friction factor

compared to the lapped surfaces with $R_z = 0.67 \pm 0.04$ µm. Due to the higher roughness, the HFM tool surfaces cause mechanical interlocking between tool and workpiece during forming and thus increase the friction. The mean roughness of all HFM and PAWAJM surfaces is between the mean roughness of the only HFM surfaces and lapped surfaces. Consequently, the effect of mechanical interlocking between tool and workpiece is reduced for the HFM and PAWAJM tools. As shown in Fig. 8b, a lower roughness causes a lower friction. Nevertheless, the friction factor of all HFM and PAWAJM surfaces is higher than the friction factor of lapped tool surfaces due to their greater roughness. Hence, all HFM and PAWAJM surfaces have the potential to be used as local tool surface modifications for SBMF to locally adjust the friction and control the material flow. However, their ability to control the material flow by an adjusted friction is reduced compared to only HFM surfaces due to their lower resulting friction factor.

4 Summary and outlook

Based on defined requirements for the SBMF processes, it could be shown that the roughness and thus the friction on tool surfaces can be modified. By preparing a HFM surface structure with a PAWAJM process, the topographies, roughness parameters and the residual stresses could be adapted for each specific application. The PAWAJM process showed the greatest dependencies for the jet pressure and the jet feed speed. In this regard, a larger jet pressure in combination with lower jet feed speed reduces the roughness. Beside these two parameters, the grain size has also an influence on the (micro) roughness of the surface while a larger grain size produces a larger (micro) roughness. The results are inversely for the residual stresses where the compressive stress increases. Tribology shows a clear correlation between roughness and friction factor. The higher the roughness, the higher the friction factor.

Looking ahead, a wear test would be advisable that simultaneously determines the changing tribological properties of the surfaces.

Acknowledgements This work was supported by the German Research Foundation (DFG) within the scope of the Transregional Collaborative Research Centre on sheet-bulk metal forming (CRC/TR 73, Subprojects B3 and C1).

References

1. Kleiner M, Geiger M, Klaus A (2003) Manufacturing of lightweight components by metal forming. Ann CIRP 52(2):521–542
2. Mori K, Nakano T (2016) State-of-the-art of plate forging in Japan. Prod Eng Res Devel 10(1):81–91
3. Merklein M, Allwood JM, Behrens BA, Brosius A, Hagenah H, Kuzman K, Mori K, Tekkaya AE, Weckenmann A (2012) Bulk forming of sheet metal. Ann CIRP 61(2):725–745
4. Löffler M, Schulte R, Freiburg D, Biermann D, Stangier D, Tillmann W, Merklein M (2018) Control of the material flow in sheet-bulk metal forming using modifications of the tool surface. Int J Mater Form 52(2):1–10

5. Freiburg D, Löffler M, Merklein M, Biermann D (2017) Surface structuring of forming tool surfaces by high-feed milling. In: Schmitt R, Schuh G (eds) 7. WGP-Jahreskongress Aachen, 5.-6. Oktober 2017. Apprimus Wissenschaftsverlag, Aachen, p 63–70
6. Abele E, Dewald M, Heimrich F (2010) Leistungsgrenzen von Hochvorschubstrategien im Werkzeug- und Formenbau. Werkzeug und Formenbau 105:737–743
7. Zabel A, Surmann T, Peuker A (2008) Surface structuring and tool path planning for efficient milling of dies. In: Seventh international conference on high speed machining, p 16
8. Pilz F, Gröbel D, Merklein M (2018) Investigation of fatigue strength of tool steels in sheet-bulk metal forming. In: Proceedings of the 21st international ESAFORM conference on material forming: ESAFORM, p 160022
9. Denkena B, Biermann D (2014) Cutting edge geometries. CIRP Ann Manuf Technol 63:631–653
10. Bouzakis K-D, Skordaris G, Michailidis N, Asimakopoulos A, Erkens G (2005) Effect on PVD coated cemented carbide inserts cutting performance of micro-blasting and lapping of their substrates. Surf Coat Technol 200:128–132
11. Bouzakis K-D, Bouzakis E, Skordaris G, Makrimallakis S, Tsouknidas A, Katirtzoglou G, Gerardis S (2011) Effect of PVD films wet micro-blasting by various Al2O3 grain sizes on the wear behaviour of coated tools. Surf Coat Technol 205:128–132
12. Biermann D, Aßmuth R, Schumann S, Rieger M, Kuhlenkötter B (2016) Wet abrasive jet machining to prepare and design the cutting edge micro shape. Procedia CIRP 45:195–198
13. Mohlfeld A (2000) Trockenbohren mit PVD-beschichteten Hartmetallwerkzeugen. PhD Thesis, Leibniz University, Hannover
14. Terwey I (2011) Steigerung der Leistungsfähigkeit von Vollhartmetallwendelbohrern durch Strahlspanen. PhD Thesis, Technische Universität Dortmund, Vulkan Verlag, Essen
15. Harada Y, Fukaura K (2008) Influence of shot peening on surface characteristics of high-speed steels. Int J Mod Phys B 22(31n32):6094–6099
16. Montgomery Douglas C (2010) Design and analysis of experiments, minitab manual, 7th edn. Wiley, Oxford
17. Wagner T (2013) Planning and multi-objective optimization of manufacturing processes by means of empirical surrogate models. Vulkan (Schriftenreihe des ISF), Essen, p 71
18. Sedlaček M, Vilhena L, Podgornik MS, Vižintin B J (2011) Surface topography modelling for reduced friction. SV-JME 57(09):674–680
19. Bouzakis K-D, Klocke F, Skordaris G, Bouzakis E, Gerardis S, Katirtzoglou G, Makrimallakis S (2012) Influence of dry microblasting grain quality on wear behaviour of TiAlN coated tools. Wear 271(5–6):783–791
20. Vöhringer O (1978) Changes in the state of the material by shot peening. Conf Proc ICSP 3:185–204
21. Klocke F (2013) Manufacturing processes: forming. Springer, Berlin