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Identification of tribological mechanisms of shot peened steel surfaces for an application in sheet-bulk metal forming

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Abstract: An increasing demand on highly-integrated high-strength lightweight components, especially in the automotive industry, motivates the need for the development of the new class of manufacturing processes sheet-bulk metal forming (SBMF). The use of SBMF for producing those components leads to many challenges. This is due to the fact that the processes are characterized by a successive and/or simultaneous occurrence of different load conditions regarding stress and strain states. These conditions influence the material flow and thus the geometrical accuracy of the produced parts. To improve the product quality, methods to control the material flow are needed. One possible approach is given by the local adaption of the tribological conditions. Within the present study shot peening as a method to impede the material flow and thus to increase the friction is investigated. The aim was to identify the tribological relevant effects determined by the surface properties. Thus, surfaces with different characteristics regarding roughness, work hardening and residual stress states were generated by peening. The influence of the varying surface properties on the material flow was identified using two laboratory friction tests. The results show that with increasing roughness and work hardening the friction increases. For the higher roughness values this can be explained by an enhanced interaction of the roughness peaks of tool and workpiece surface. To identify the influence of work hardening a numerical model of the pin extrusion test with an adapted modelling of the workpiece was used. The results revealed that a hardened surface layer leads to reduced flow velocities in lateral direction what is an indicator for an impeded material flow.

Keywords: Surface modification, tribology, sheet-bulk metal forming

Introduction

Legal requirements and a rising global competition associated with ecological challenges and growing customer expectations force the manufacturing industry to upgrade their products [1]. A promising approach to deal with the existing requirements such as material use minimization and lightweight construction is given by manufacturing of close tolerance highly integrated functional components. The production of those parts using conventional bulk and sheet metal forming processes is limited. An innovative approach to meet the existing challenges is the process class SBMF. Those processes are characterized by the application of bulk and sheet forming processes on sheets or plates [2]. The combination leads to a globally and locally spatial and temporal variation of load conditions. During one forming operation, low contact normal stresses combined with long sliding paths can simultaneously occur with very high contact normal stresses and short sliding paths. The resulting gradient leads to an uncontrolled material flow, in many cases yielding a reduced product quality. Figure 1 exemplarily shows the geometrical process limits of an extrusion process. The aim of the process is the manufacturing of a component with differently shaped functional elements. Both types of elements are characterized by an insufficient die filling, what will negatively influence the behavior of the components during the operating time. Thus, one challenge in SBMF is given by the control of the material flow. An appropriate method to realize this is given by the local adaption of the friction. The friction conditions are highly influenced by the surface properties of tool and workpiece and by the used lubricant. A local modification of the friction using different lubricant cannot be realized for SBMF processes. Suitable approaches to meet the requirements are given by the modification of the workpiece and/or the tool surface.

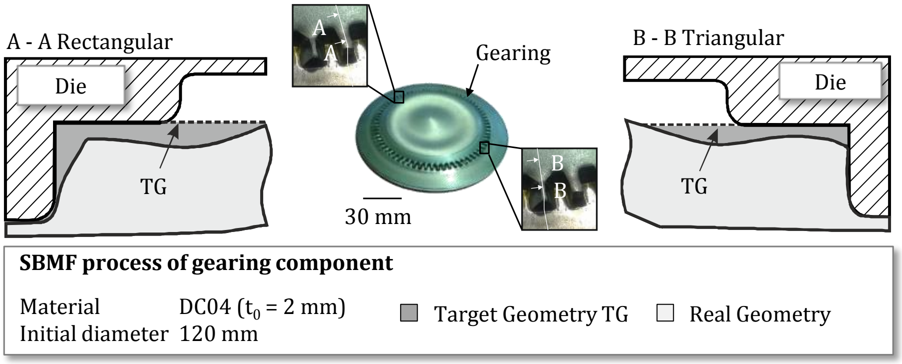

Figure 1: Process limits of a SBMF process

The current study focuses on the modification of the tribological conditions using shot peening as a workpiece-sided surface adaption. To use the full potential of these kinds of surfaces the surface integrity and the resulting tribological conditions of shot peened workpiece surfaces needs to be investigated. These analyses are used to identify the tribological relevant mechanism.

Methodology

The peening process influences the surface properties: surface roughness, compressive residual stress state and work hardening of the surface layer [3]. For the identification of the tribological relevant surface properties, surfaces with different surface characteristics were generated by peening with different pressures. This parameter was chosen since it is well known as a major influencing factor of peening operations. For the investigation, as shot peening medium a zirconium oxide ceramic shot with a grain size of 338 ± 87 µm was used. As peening pressure 0.1, 0.2, 0.3 and 0.4 MPa was applied. Lower pressure values do not change the surface properties significantly. Higher values would lead to a cracking of the shot media during peening. Nozzle distance, peening angle and peening time were chosen constant. 90° is used as peening angle. The distance between nozzle tip and specimen was 40 mm. Peening time was set to 15 sec. After peening roughening and work hardening was maximized. For an identification of material specific characteristics the deep-drawing steel DC04 (1.0338) and the high-strength steel DP600 (1.0936) with an EDT surface structure and an initial sheet thickness t_0 of 2.0 mm were used as workpiece material. Both materials vary regarding their initial yield stress and their hardening exponent. The initial yield stress of DC04 amounts 169 ± 0.5 N/mm^2. The hardening exponent has a value of 0.21. The initial yield stress of DP600 is more than twice as high as the yield stress of DC04 with a value of 366 ± 1.7 N/mm^2. The hardening exponent of DP600 amounts 0.16. The surface roughness of the peened surfaces was characterized optically using the confocal laserscanning microscope Keyence VK-X200. To characterize the roughness the reduced peak height *Rpk* was used. The *Rpk* value is as an appropriate value to evaluate the roughness peaks and thus the influence on the material flow. The higher the *Rpk,* the higher is the impedance of the material flow. Work hardening and residual stresses were measured by X-ray measurements using the Seifert XRD Stress Analyzer 3003. To determine the work hardening the half width HW of X-ray interference lines is used. The HW value is an indicator for lattice distortion in the surface layer. A broadening of the half width illustrates an increase of the scatter of the micro strain in the crystal [4]. The friction of the modified specimens was analyzed using a ring compression test and a pin extrusion test. The pin extrusion test is close to the conditions which occur when functional elements are formed. The higher the pin height, the higher is the friction. The ring compression test is a well known friction test which displays general bulk forming conditions [5]. High friction is characterized by low resulting inner diameters. Both tests are adapted to the conditions in SBMF and are presented in [5]. The friction factors are determined using the principle of numerical identification. The resulting surface characteristics and friction conditions were correlated to identify tribological relevant surface properties. To derive cause-effect relationships regarding the tribological mechanisms of shot peened surfaces a FEA of the pin extrusion test with a simplified modelling of hardened surfaces layers was used. As FE software simufact.forming V12.0.1 was applied.

Analysis of peened surfaces

To identify the tribological relevant mechanisms the mentioned surface characteristics in dependency on the different peening pressures were investigated. The results were additionally correlated with the friction values.

1 Surface characteristics

Surface roughness, compressive residual stresses and work hardening of DC04 and DP600 surfaces are significantly influenced by the peening process, Figure 2.

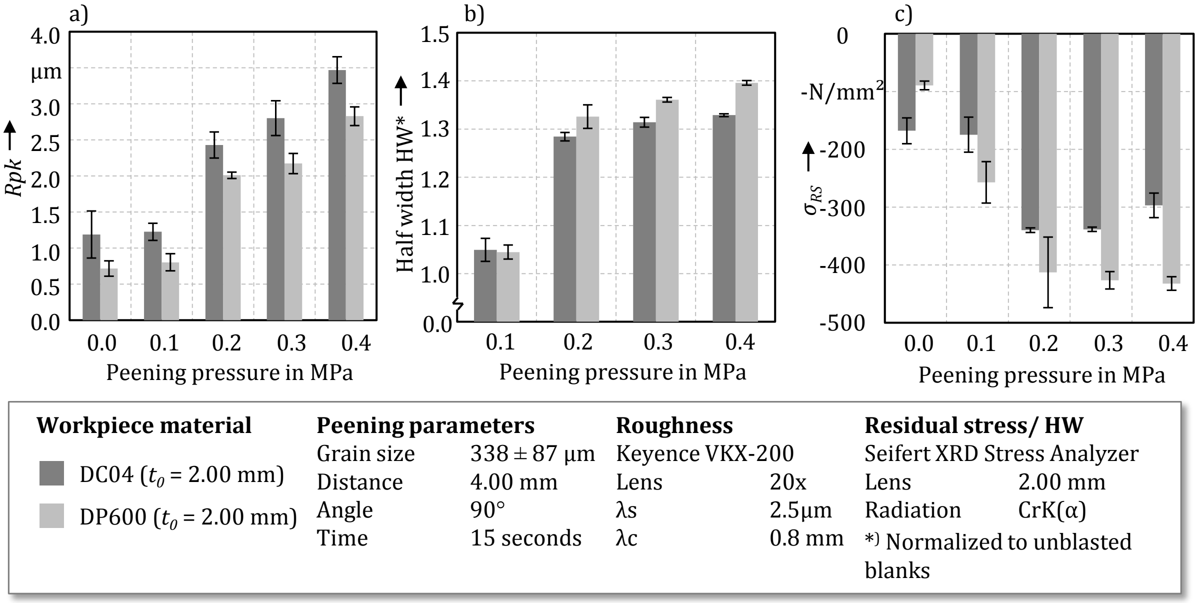

Figure 2 : a) Reduced peak height, b) work hardening and c) compressive residual stress states of peened surfaces compared to reference surfaces (0.0 MPa peening pressure)

The analysis of the reduced peak height *Rpk* reveals that the peening process leads to an increase of the surface roughness compared to the reference surfaces, Figure 2 a. With higher values of peening pressure the *Rpk* value constantly increases. Thus, the peening of workpiece surfaces should lead to an increased friction and an impeded material flow. The shot peening effect on the roughness of DP600 blanks is lower compared to DC04. This is due to the higher strength of DP600. Figure 2 b) shows the results of the analysis of the near surface work hardening. The values are referenced to the work hardening of the initial DC04 and DP600 surfaces. All peening combinations lead to an increase of the work hardening of the surface layer. During the investigation a maximum depth of the work hardened zone of 0.05 mm was detected. DP600 blanks are characterized by higher HW values than DC04 blanks. This can be explained by the different strain hardening behavior of both materials. Additionally, the peening process leads to increasing residual compressive stresses, Figure 2 c. Compared to the analysis of the half width the residual stress seems to be saturated for pressures of 0.2, 0.3 and 0.4 MPa. The increase of roughness, work hardening and residual compressive stress with increasing peening pressures can be explained by the higher induced kinetic energy. This leads to a higher plastic surface deformation and surface dimpling.

2 Correlation between surface characteristics and friction conditions

The investigation of the tribological behavior of peened surfaces using the pin extrusion test and the ring compression test revealed that the peening process leads to an increase of the friction factor, Figure 3. The higher the peening pressure, the higher is the friction. Thus, peening can be used to locally impede and thus control the material flow in SBMF. A local application of peening processes should lead to an increased die filling of functional elements. To understand what affects the impedance of the material flow the friction values are correlated with the respective values of the surface characteristics, Figure 3.

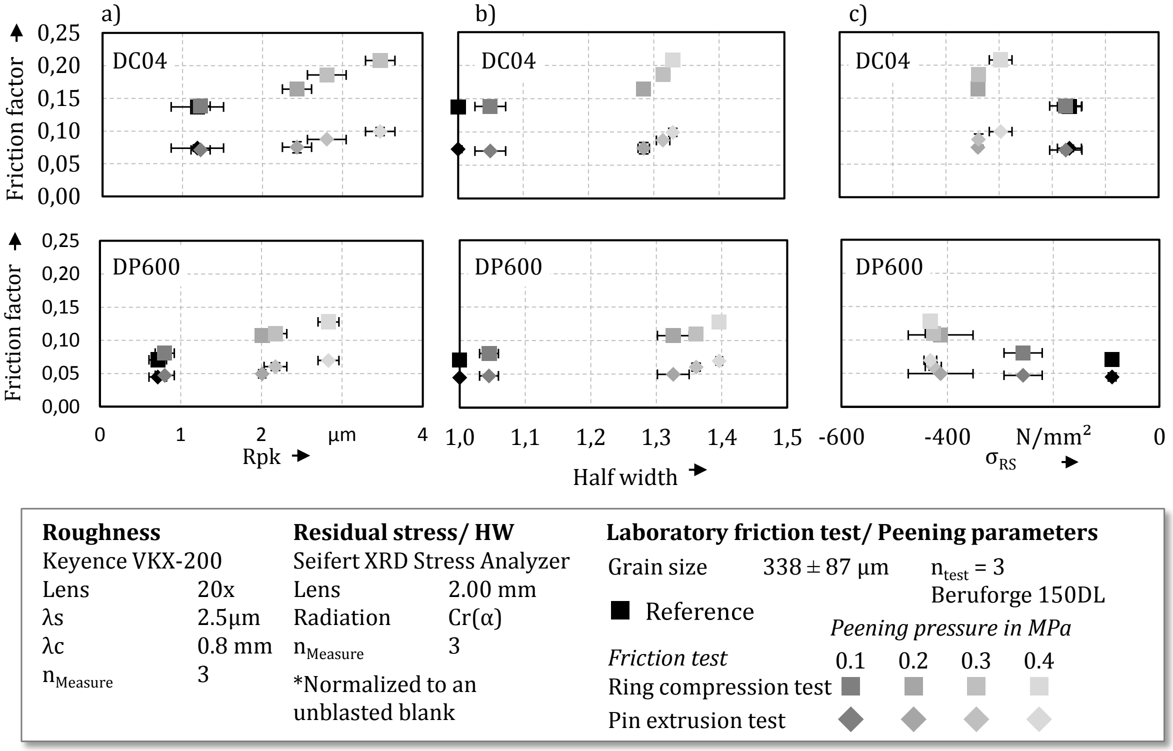

Figure 3 : Correlation between friction factor and the respective values of a) roughness, b) work hardening and c) residual stress states

Both materials show similar trends especially for the correlations between friction and roughness respectively half width. The correlation between friction factors and *Rpk* values respectively half width values reveals a linear trend, Figure 3 a and b. Increasing roughness values and work hardening values lead to an increased friction shear stress and thus higher friction. The higher friction leads to a more restricted material flow. The correlation between roughness and friction can be explained by an enhanced interaction of the roughness peaks of tool and workpiece surface. To understand how work hardening affects friction, further investigations are needed. For the compressive residual stress states in Figure 3 c no significant trend is detectable. Thus, roughness and work hardening seem to be the tribological relevant surface properties, which need to be considered while modifying workpiece surfaces by peening for controlling the material flow in SBMF.

Simplified numerical modelling of work hardened surface layers

To understand how work hardening affects the material flow a special FEA of the pin extrusion test with a three-layer modelling of the workpiece was used, Figure 4 a. The workpiece consists of two boundary layers and a middle layer. The height of the whole workpiece amounts 2 mm. The boundary layers have a height of h_{Bl} = 0.05 mm. This was the maximum depth of the work hardened zone identified for peened surfaces. The upper and lower boundary layers of the workpiece are characterized by different hardening properties than the middle layer. The transition between the different areas is modelled discontinuously. This simplifies the real conditions. The different properties are realized assigning different true strain-true stress curves to the boundary layers σ_2 and the middle layer σ_1, Figure 4 b.

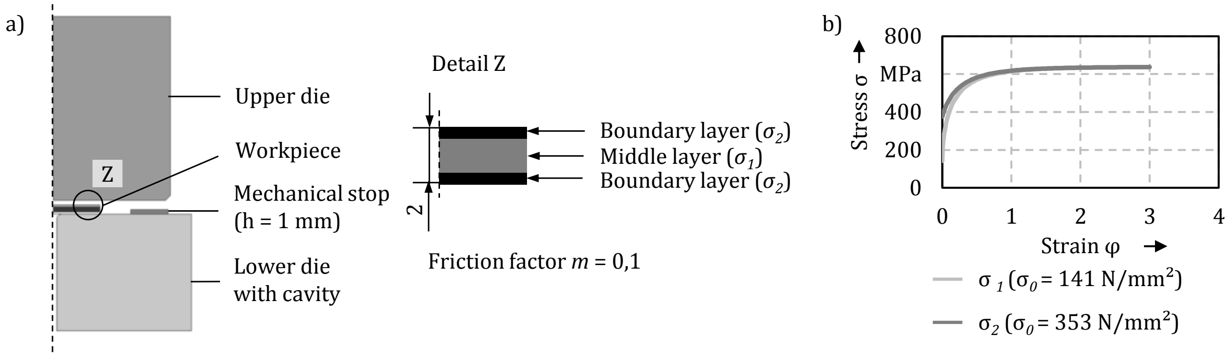

Figure 4 : a) FE Model and b) used true strain true stress curves

Both true strain-true stress curves vary regarding the initial yield stress σ_0. The initial yield stress σ_0 of the true strain-true stress curve σ_2 is by a factor of 2.5 higher than the initial yield stress of σ_1. This should model a work hardening caused by the peening process. The chosen factor of 2.5 is an extreme case and thus simplifies the real conditions. As friction factor a medium value of 0.1 was used. To identify how hardened boundary layers affect the material flow, the FEA with boundary layers (h_{Bl} = 0.05 mm) was compared to a reference simulation without boundary layers (h_{Bl} = 0.00 mm). For the simulation without boundary layers σ_1 was used as true strain-true stress curve for the whole workpiece. For the reference simulation a pin height h_P of 2.42 mm was detected. Using boundary layers leads to a pin height of 2.46 mm. Thus, a work hardened boundary layer leads to an increase of the pin height and thus the friction. This result is congruent to the experimental results in Figure 3 b. To understand the reason for this behavior the flow velocities in x- and z-direction were analyzed, Figure 5.

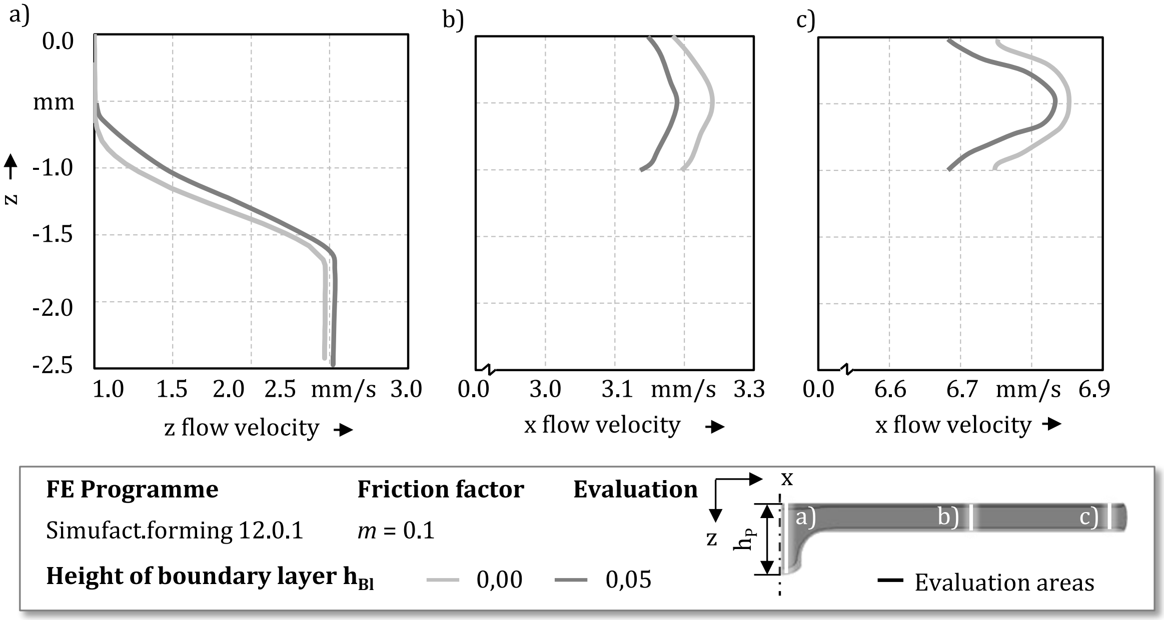

Figure 5 : Flow velocity of simulations with and without boundary layers in the area of a) the pin, in b) the middle and c) in the edge area of the flange

The flow velocities of both simulations differ in each area. The analysis of Figure 5 b and c reveals that the hardened boundary layers reduce the flow velocities and thus the material flow in x-direction. Especially in the edge of the flange a significant difference is detectable, Figure 5 c. For both simulations the flow velocities in the middle layer of the workpiece are higher than in the boundary area. This can be explained by the fact that the material flow in the middle area is not restrained in x-direction. Thus, there is an enhanced material flows into that direction and the gradient of the flow velocities increases. The gradient is higher for the simulation with boundary layer. This is an indicator for a higher impedance of the material flow in the contact area between boundary layer and tool surface. Thus, the hardened boundary layer leads to a more impeded material flow in lateral direction. This result is confirmed by the analysis of the z flow velocities in the area of the pin, Figure 5 a. The flow velocities of the simulation with boundary layer are higher compared to the reference simulation without hardened layers. Thus, due to the impedance of the material flow in x-direction more material flows into the cavity of the lower die what results in higher pin heights and thus higher friction. The analysis of the flow velocities revealed that a work hardening of the near surface acts like a flow restriction in lateral direction.

Summary and outlook

SBMF processes are characterized by an insufficient geometrical accuracy of the produced components what negatively influences the in-service behavior. This process limit motivates the need for methods to control the material flow. A suitable approach is the local modification of the tribological conditions using surface modifications. To use the full potential of the modifications, the knowledge of the tribological mechanisms is of high importance. Within the present study, the tribological mechanisms of shot peened workpiece surfaces, which are used to increase the friction, were investigated. Using two laboratory friction tests roughness and work hardening were identified as main influencing factor on the friction and thus the material flow. The higher roughness and work hardening, the higher is the impedance of the material flow. The influence of the roughness can be explained by an enhanced interaction of the roughness peaks of workpiece and tool surface. To explain the influence of work hardening a special FEA of the pin extrusion test with a simplified modelling of hardened near surface areas was used. The investigation of the flow velocities during forming revealed that the hardened boundary layers acts as a flow restriction what leads to a higher impedance of the material flow in lateral direction. Thus, high roughness values and work hardening values should be preferred during the application of shot peened workpiece surfaces for an impedance of the material flow in SBMF. Further investigations should analyze the effectiveness of locally peened surfaces in different SBMF processes. Additionally, the combination of a workpiece- and tool-sided surface modification should be investigated. The combined modification might be a promising approach for a further increase of the friction.

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