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Analysis of friction properties of DC04 using pin extrusion test with modified parameters

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Abstract. The current economic and ecological trend towards lightweight construction and functional integration is constantly increasing. In order to produce components with near-net-shape geometries in an eco-friendly process, forging is the ideal solution. The Sheet-Bulk metal forming (SBMF) process, which combines the benefits of both sheet metal and bulk metal forming, is an advantage in this context. To accurately replicate numerical simulation models as realistically as possible, it is essential to make adjustments to the parameters. Especially friction that occurs between the tool and the workpiece plays a critical role. It can affect the material flow as well as tool wear and product quality. Various methods can be employed to determine the friction factor, such as the ring compression test or the pin extrusion test. Both are suitable for investigating the tribological conditions in the SMBF. As the pin extrusion test is a full forward extrusion process that produces a pin, this process is suitable for the procedure to be used in the following studies. The objective of this research is to quantify the effects on friction by systematically varying modified parameters such as temperature, forming velocity and amount of lubricant, and integrate these findings into simulation models in the pin extrusion test. For this purpose, the pin extrusion test was first modeled numerically by using the simulation software Simufact.Forming. In order to validate the simulation model, experiments were conducted on a hydraulic deep-drawing press. The material DC04 was used for the drawing tests. It was possible to analyse the changes in the friction factor with additional influence on the manufactured geometry and its surface roughness.

Introduction

In the 21st century, the global focus on economic and environmental sustainability has driven significant advances in lightweight manufacturing technologies. The main goal of lightweight design in the field of metal forming is to reduce the weight of components, conserve resources, and achieve improvements in energy efficiency and emissions reduction [1]. Among many methods, Sheet-Bulk metal forming (SBMF) stands out as an innovative process that combines the advantages of sheet metal forming and bulk forming [2]. It enables the production of highly integrated near-net-shape components, making it an environmentally friendly and economically efficient solution. However, the efficient production of lightweight components by means of SBMF usually requires high-volume production. During the continuous operation of the process, it is essential to address various tool-related challenges, such as the rise in tool temperature [3]. Effective management of such issues can help minimize the production of defective parts caused by changes in tool conditions, thereby reducing resource waste and improving overall process efficiency. Tribology is a critical process influencing factor in overcoming tooling challenges as the interaction between the tool and the workpiece is particularly important for optimizing tool design, extending tool life, and ensuring superior product quality [4]. In addition, advances in finite element method (FEM) have enabled detailed modelling of tribological conditions in SBMF, but experimental validation remains essential to enhance the reliability of these models and determine the friction factor for industrial applications [5]. Experimental methods to identify the friction factor have been employed to investigate tribological conditions in metal forming. Vierzigmann [6] and Löffler [7] examined the tribological conditions in SBMF besides the strip drawing test mainly by using the ring compression test and a few investigations on the pin extrusion test. In order to gain a deeper understanding of the process by which material is extruded into a cavity in forming a pin, the results obtained from previous pin extrusion tests were examined more closely. The objective of this research is to quantify the effects on friction by systematically varying the modified parameters forming velocity, amount of lubricant and temperature. Vierzigmann previously analysed forming speeds of up to 10 mm/s in the pin extrusion test [6] and showed that the effect of forming velocity on friction can be neglected in the low speed range. To enhance production efficiency, it is essential to investigate the impact of high-speed forming on friction. Vierzigmann [6] and Löffler [7] also carried out tests with different surface coatings and a lubricant quantity of up to 20 g/m^2. In order to more closely reproduce the lubricant conditions applied during the continuous forming of pins in high-speed presses, this study extends the scope of investigation to analyse the impact of varying lubricant quantities. Additionally, no analyses have been performed regarding the influence of temperature, thus the effect of temperature on friction should be determined in the pin extrusion test. The results are analysed and integrated into the simulation model of the pin extrusion test.

Pin Extrusion Test / Process Setup

This section explains the experimental setup of the pin extrusion test. The forming process is a combination of full forward extrusion and compression to determine the friction factor. In order to realise pin extrusion tests, the double-acting hydraulic deep-drawing press TSP100S0 from Lasco Umformtechnik GmbH is used. The machine and the test setup are shown in Fig. 1.

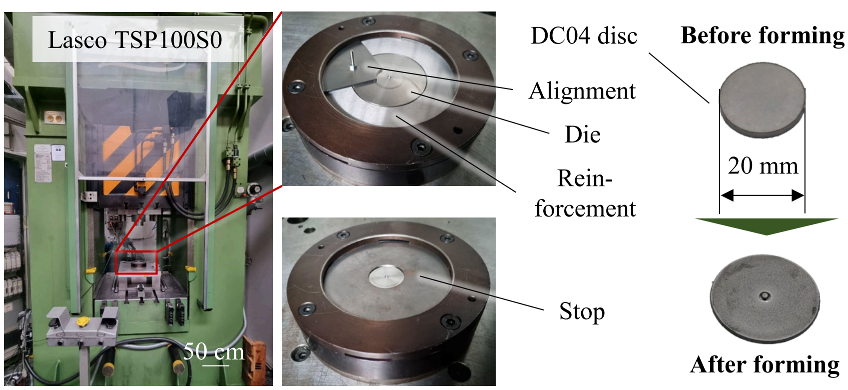

Figure 1 – Experimental test setup at the hydraulic press type TSP100S0 from Lasco and discs before and after the forming process.

The press can apply a maximum pressing force of 1000 kN. In order to avoid impairing shaping of the component due to the upper limit of the pressing force, Vierzigmann recommends including a safety factor of 25 % for the maximum force, which means 750 kN [6]. The machine achieves a maximum punch speed of 55 mm/s. In order to obtain results which are based on SBMF, for the punch the material ASP2023 was used and the surface of the punch was polished. The forming process will be performed in a reinforced die. The cavity of the die has an internal diameter of 1.5 mm and is integrated over the entire height of the die. The value used for the fillet radius is 1.0 mm. These components to be formed into pins are made from conventional low alloy steel, cold-rolled deep-drawing steel DC04 (1.0338) with an initial thickness of 2 mm. In order to position the disc, an alignment fixture was used to center the disc over the cavity between the two compressing paths. The workpiece before and after forming are shown in Fig. 1. The system's movement is measured by using a glass scale, which is installed in the machine with the physical resolution of 0.02 mm. This method can be used to measure the distance between the first contact of the punch on the blank and the penetration depth of 1.0 mm. In addition, the applied force is measured using a measuring ring type 9091 from Kistler with a maximum detectable force of 1200 kN and a calibrated Kistler 5073 amplifier. In order to achieve a maximum forming distance of 1 mm, a stop was manufactured to ensure this distance and to limit the maximum punch movement. The lubricant Beruforge 150DL, which was already used in preliminary tests [7], is used in this study. The lubricant was applied to both sides of the specimens by hand during the test. The high precision analytical balance Kern Aet 500-4 with a resolution of 0.1 mg was used to measure the weight before and after application to determine the amount of lubricant.

Numerical Setup and Validation

To further investigate the friction factor under varying conditions, a numerical identification approach was employed. A numerical model for the experiments was developed using Simufact.Forming 2021.1 from Simufact engineering GmbH. The design of the numerical model is illustrated in Fig. 2. The element type used in this study was the hexahedral element recommended by Tekkaya [8] for three-dimensional analyses, with a maximum element size of 0.25 mm. To reduce computational time, a symmetry plane was applied along the x-axis to simplify the process analysis. Moreover, to accurately capture the localized features of the pin-forming region, a hollow cylindrical refinement box with a diameter of 4 mm was designed around the forming area. Within this box, the element size was reduced to 0.0625 mm, achieving two consecutive levels of refinement. The mechanical behavior of the deep-drawing steel DC04 was provided by an upsetting test with miniaturized cylindrical specimens in accordance with the methodology proposed by Hetz et al. [9] and subsequently incorporated into the numerical model.

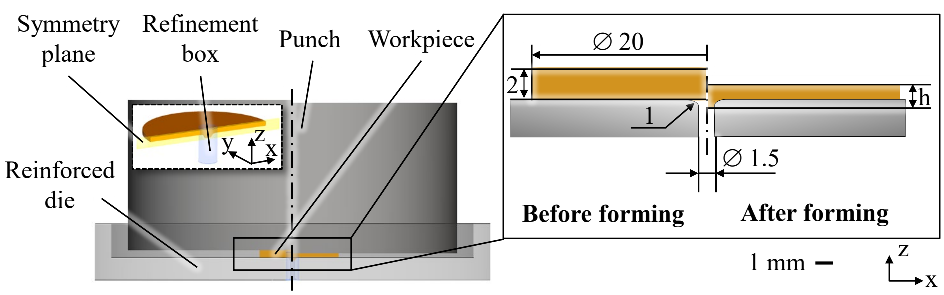

Figure 2 – Setup of the numerical model and component geometry.

The validation of the simulation model is particularly crucial for numerical identification of the friction factor, as it ensures the accuracy of the mapping the real process and the reliability of using this approach to quantify tribological conditions [6]. Similar to the real pin extrusion test, the specimen was set up with an initial diameter of 20 mm and initial thickness of 2 mm. The numerical models were created for friction factors ranging from m = 0.01 to 0.5, and the pin height and final specimen diameter were determined. However, as shown in Fig. 3 a), the required forming force for m = 0.3 is F = 834.5 kN, exceeding the maximum forming capacity with included safety factor of 25 %. In addition, the tool is designed for a maximum forming force of Fmax = 750 kN. Consequently, only friction factors in the range of m = 0.01 to 0.2 were considered in the subsequent analysis. A calibration curve was derived through interpolation of the data points, which is shown in Fig. 3 b), establishing the relationship between the pin height and the friction factor. The friction factor was determined by comparing the experimentally measured pin height with the following calibration curve.

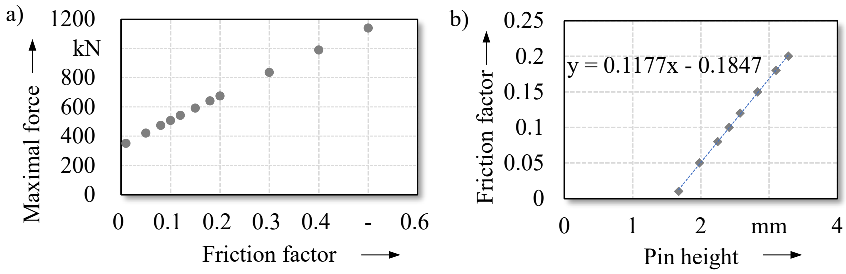

Figure 3 – a) Maximum forming forces at different friction factors from the numerical models and b) derived calibration curve for pin extrusion test.

In order to ensure an optimal match between simulation and experimental tests to determine reliable friction factors, validation of the simulation model for pin extrusion tests was carried out in four aspects: a) Pin height; b) Specimen diameter; c) Force-displacement curve and d) Microhardness and effective plastic strain distribution, as shown in Fig. 4.

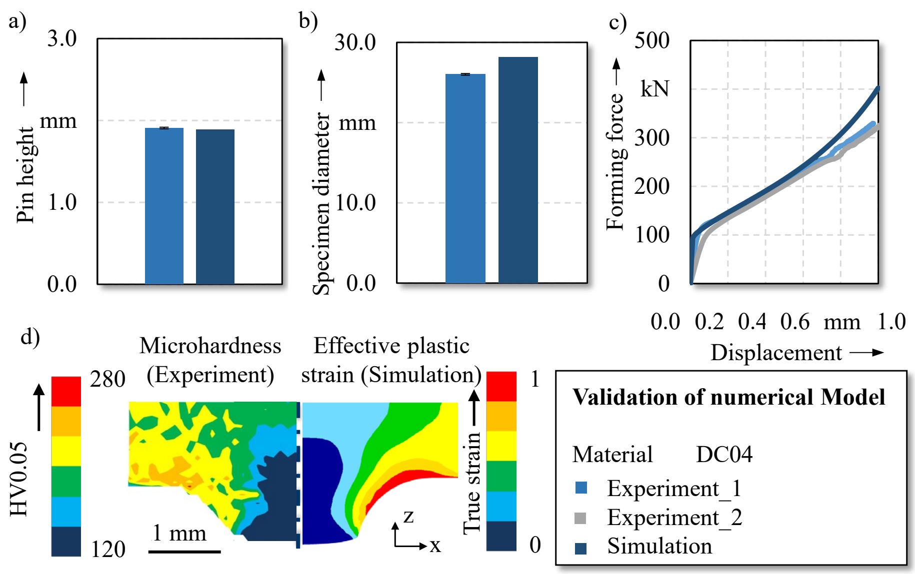

Figure – 4. Validation of numerical model for pin extrusion test: a) pin height, b) specimen diameter, c) force-displacement curve d) microhardness and effective plastic strain distribution.

Comparing the simulated and experimental geometries, i.e., the pin height and the diameter of the final specimen, they show good agreement with deviations of 0.7 % - 2.2 % and 7.1 % - 7.8 %, respectively. To validate the simulation, specimen diameters and pin heights from five experiments were compared with the results of the numerical model. Those results with the smallest deviation were used for validation of force-displacement curve. After comparison, the validation results about force-displacement curve reveal both consistencies and deviations between the simulation and experimental data. Overall, the trends in both curves are similar, but deviations are evident in the maximum forming force and displacement. The maximum forming force in the simulation reaches 402.1 kN, which exceeds the experimentally measured value of 329.2 kN. Additionally, the maximum forming displacement observed in the experiment is approximately 0.8 mm, whereas the simulation predicts a value close to 1.0 mm. These indicate that the elastic deformation in the simulation may differ from the actual experimental setup. The effect of elastic springback contributes to the mismatch between the curves, particularly at the end of the forming process. To address these discrepancies, blind compression tests were performed without specimens to account for the elastic deformation of the system and improve the accuracy of the simulation. The force-displacement curves of blind compression tests were subtracted from the results of experimental

tests to achieve these results. These corrections ensure that the numerical model can more accurately replicate the experimental results, particularly under complex tribological conditions.
The final step of the validation is to compare the numerically determined true strain distribution with the experimentally determined microhardness distribution in order to qualitatively analyze the accuracy of the finite element simulations with respect to the plastic behavior of the workpiece material. Since an increase in the degree of deformation during the forming process leads to hardening [10] of the workpiece material, this can be used as an important indicator. This means that at high hardness values occur at points with high degree of deformation. In order to simplify the analysis process, only the relevant area of the forming process - around the pin, was compared. The microhardness HV0.05 measurements were made with the Fischerscope® HM2000 from Helmut Fischer GmbH. The samples to be measured were divided, embedded, sanded and finally polished. The comparison results shows that the entrance of the cavity has the local maximum deformation degree and the numerical deformation distribution corresponds to the experimental microhardness distribution. The simulation and experiment show good agreement for all four aspects. It can therefore be assumed that the simulation and the derived calibration curve are suitable for determining the friction factors for the experimental results.

Evaluation of the Influencing Parameters

To fully understand the tribological conditions and forming behavior under various process parameters, it is essential to evaluate the influence of factors such as forming velocity, amount of lubricant and temperature on the forming process. These parameters significantly impact material flow, friction conditions, and the resulting geometrical accuracy of the formed part. Changes in material properties are not taken into account in temperature analyses, as the results are used for investigations in cold forming. The following subsections discuss the influence of each parameter, beginning with forming velocity.

Influence of Forming Velocity. The reference process was conducted at room temperature of 20 °C with a press speed parameter which is set at 60 % of the maximum possible speed of 55 mm/s, which is 33 mm/s. Vierzigmann [6] used velocities of a maximum of 10 mm/s in comparison. The amount of lubricant also remains constant at 0.1 g Beruforge 150DL for the top and bottom of the disc shown in Fig. 1. By varying the punch speed to 50 % (27.5 mm/s) and 70 % (38.5 mm/s) of the maximum press speed, the influence of the speed on the pin height can be analysed. For this purpose, the force-displacement curves as well as the pin height and the friction factor were compared for the three experiments per variant. The results are shown in Fig. 5. The force-displacement curve for all three variations shows a greater increase in force up to 0.1 mm displacement. As far as this point is reached, the punch moves axially onto the workpiece. Then the DC04 disc is deformed both radially and axially. The material is pressed into the cavity in order to form the pin. Once the first material enters the cavity, further material flows inside and shapes the pin. The force therefore increases significantly at the beginning and then proceeds linearly. At a displacement of 0.40 mm, a mean force value of $F = 188.67 \pm 2.69$ kN is achieved in the reference process, which decreases to $F = 177.00 \pm 10.18$ kN compared to the variant with 50 % process speed and reaches a value of $F = 195.59 \pm 5.28$ kN at 38.5 mm/s. Based on the comparison of the force-displacement curves, it can be concluded that the force is slightly higher at greater velocities for the same displacement.

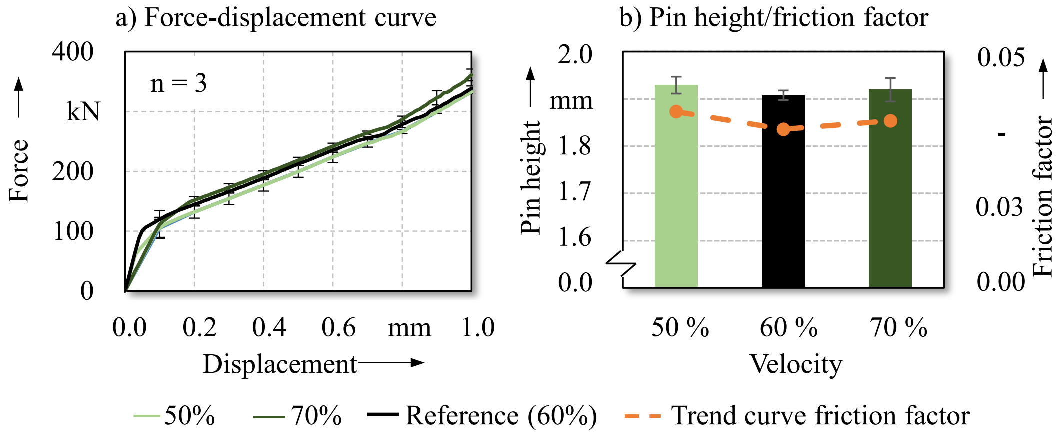

Figure 5 – Force-displacement curve and pin height/friction factor depending on velocity.

This is caused by the material properties. A higher strain rate results in a higher flow stress, which facilitates elastic deformation of the disc. Lichtenfeld et al. confirmed this behaviour for steels used in the automotive industry [11]. However, if the resulting pin heights are compared with each other, the lowest value occurs at 60 % of the pressing speed with a height h = 1.91 ± 0.01 mm. The mean values of the pin heights are 1.93 mm at a speed of 27.5 mm/s and 1.92 mm at 38.5 mm/s. Since the deviation of 0.02 mm is higher for these two values, the pin heights overlap. That indicates there is no significant change in the pin heights as the process speed increases. Vierzigmann [6] also observed this behaviour at speeds of up to 10 mm/s. The friction factors are calculated using the calibration curve from the validation. The height-dependent mean values of the friction factors are between 0.0401 and 0.0424. Moreover the measurement of the surface topography of the disc shows a higher roughness at a faster forming velocity. The measured values are shown in Fig. 6. The roughness of the variant with 27.5 mm/s process speed is approximately 0.2 µm lower with Ra = 2.123 ± 0.143 µm than the variant with 38.5 mm/s. This indicates that the roughness peaks are continuously reduced and consequently smoothed by a slower approach of the punch to the surface. Due to higher forming speeds, the relative movement between the punch and the flow of material rises, resulting in an increase in material elongation.

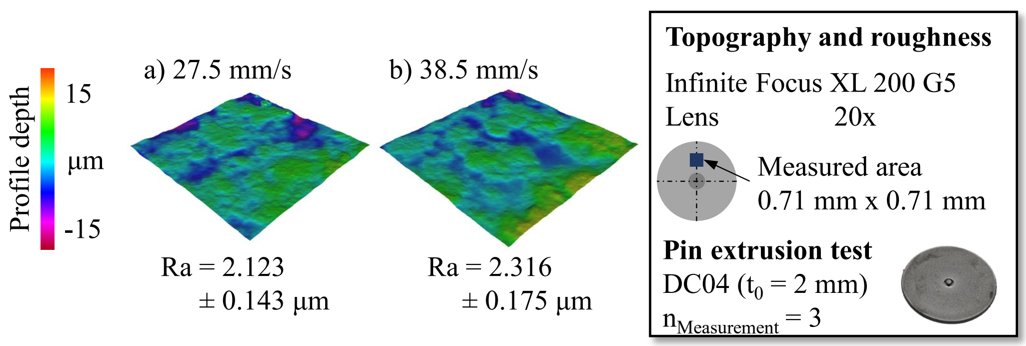

Figure 6 – Topography and roughness of the a) 27.5 mm/s velocity and b) 38.5 mm/s velocity.

Influence of Amount of Lubrication. In order to determine a further influence on the friction factor, the amount of lubricant was varied. The parameters of the reference process were kept constant. This includes the temperature at 20 °C and the press speed, which is 60 % of the maximum speed of 55 mm/s. In the reference process, a total lubricant amount of 0.1 g is used on the top and bottom side of the disc, which has an initial diameter of 20 mm. In addition, two additional variants were studied with lubricant quantities of 0.05 g and 0.2 g. Using the modified lubricant quantities, experiments were carried out and the force-displacement curves and pin heights were determined. The results are shown in Fig. 7.

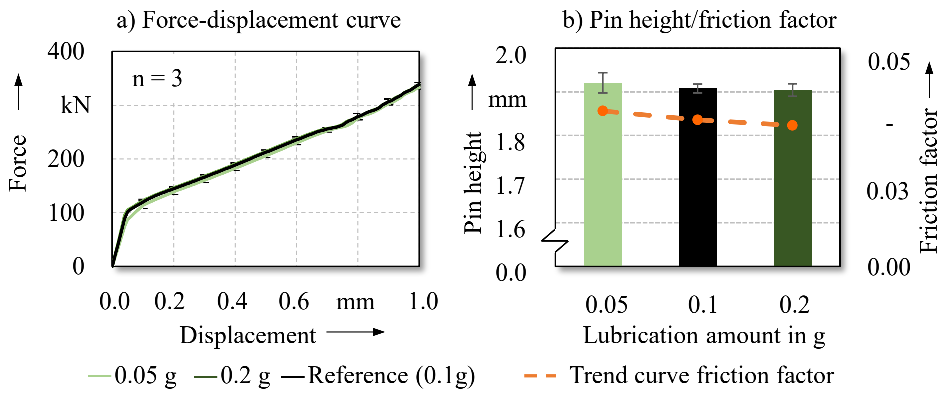

Figure 7 – Force-displacement curve and pin height/friction factor depending on the varied lubrication amount.

According to the results of the force-displacement curve, it can be determined that the force increases more strongly up to a displacement of 0.1 mm. As described for the variation of the press speed, this is due to the punch positioning on the blank and the resulting axial and radial distribution of the material that is pressed into the pin cavity. Comparing the lubricant amounts, the subsequent linear curve shows that the force increases with a higher lubricant amount. For a displacement of 0.4 mm, a force of 188.67 ± 2.69 kN is achieved for the reference process with 0.1 g of lubricant. In comparison with a lubricant amount of 0.2 g, a force of 190.30 ± 3.14 kN occurs and with 0.05 g a force of 182.65 ± 4.05 kN. Thus, as shown in Fig. 7, pin heights of 1.91 ± 0.01 mm occur in the reference process. The largest pin height of 1.92 ± 0.02 mm occurs with a lubrication of 0.05 g. Accordingly, the pin height-dependent friction factor decreases with increasing lubricant quantity. Since the material on the pin cavity surface is restricted from flowing during the forming process due to the higher friction factor, forming only occurs in the center of the pin. Therefore, forces required for this process are lower, since the material flows more easily in the center of the pin. This is also due to the contact between the punch and the workpiece. There is no longer direct contact due to the use of a larger quantity of lubricant, which reduces the friction factor. In addition, a higher friction factor decreases the possibility of the material flowing radially, which leads to a higher pin height. This has already been established in analyses by Zhu [12]. However, the results cannot be categorised as significant, as the measured values including the deviation overlap. Nevertheless, a tendency can be recognised which shows that the formed pin heights decrease with a higher amount of lubricant. In addition to the force-displacement curves and the pin height, the topography and roughness were measured. The results are shown in Fig. 8. Due to the relative movement between punch and specimen surface, the radial elongation, described in [13] is encouraged in the variant with 0.2 g lubricant with a lower friction factor. The greater elongation in the sample results in less force being required to flatten asperities.

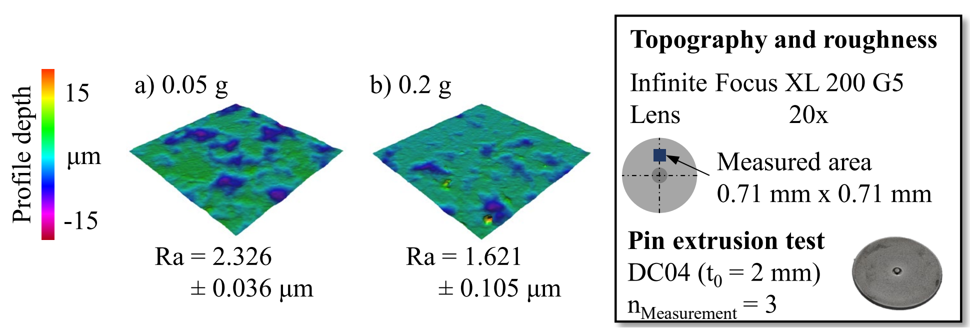

Figure 8 – Topography and roughness of a) 0.05 g und b) 0.2 g.

Influence of Temperature. The influence of temperature on wear of the tool should be analysed in further experiments, thus an investigation of the temperature on the friction factor is crucial.

Therefore, in addition to the variation of the forming velocity and amount of lubricant, the temperature was also changed, which Vierzigmann [6] and Löffler [7] have not analysed so far. The reference process was conducted at room temperature (20 °C) with a forming velocity of 33 mm/s, equivalent to 60 % of the maximum press speed of 55 mm/s. The amount of lubricant applied remained constant at 0.1 g of Beruforge 150DL. To isolate the influence of temperature on the forming process, a controlled variable approach was implemented, maintaining all other parameters unchanged. For the elevated temperature tests, specimens were preheated in a furnace 10 °C higher than 130 °C. Upon reaching the desired temperature, the specimens were immediately removed and lubricated. The temperature was measured with a thermocouple and once 130 °C was reached, the forming process was performed using identical conditions as at the room temperature reference process. The results in Fig. 9 show the effect of temperature on the forming process. The force-displacement curves show that while the overall trends remain consistent, the maximal forming force at 130 °C (344.6 ± 4.1 kN) is slightly lower than at 20 °C (346.5 ± 5.2 kN). This deviation can be attributed to thermal softening of the material, which reduces its yield strength, making it easier to deform.

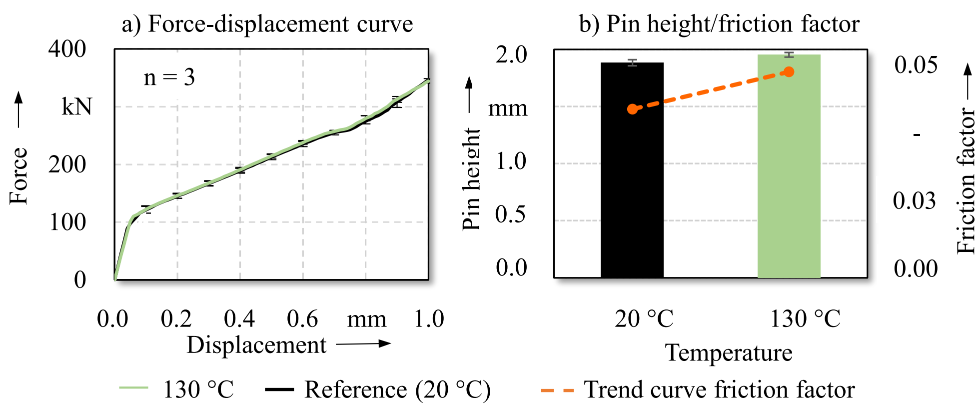

Figure 9 – Force-displacement curve and pin height/friction factor depending on the temperature.

The effect of temperature on pin height was also analyzed. As temperature increases, the pin height rises. This is due to the fact that the viscosity of the lubricant decreases significantly as the temperature increases. This leads to a reduction in the lubricant's carrying capacity between the contact surfaces, resulting in higher friction [14]. More material flows out into the cavity of the die and the height of the pin increases as a result, which is well corroborated by the friction factor obtained from the simulation. In addition, the topographies after forming were analyzed to investigate surface smoothing, as shown in Fig. 10. At room temperature, the surface roughness (Ra) of the specimen is 1.307 ± 0.063 µm, showing a relatively smooth texture. Compared to the undeformed sheet with the roughness of 1.300 ± 0.075 µm, the roughness of the blank with room temperature is higher. In order to create comparable lubrication conditions at different temperatures, the lubricant was portioned manually, which results in deviations in the roughness of the reference process. However, as the temperature increases the surface roughness rises to 1.638 ± 0.021 µm, indicating a rougher surface. This also indicates that the friction between the tool and the material is getting higher.

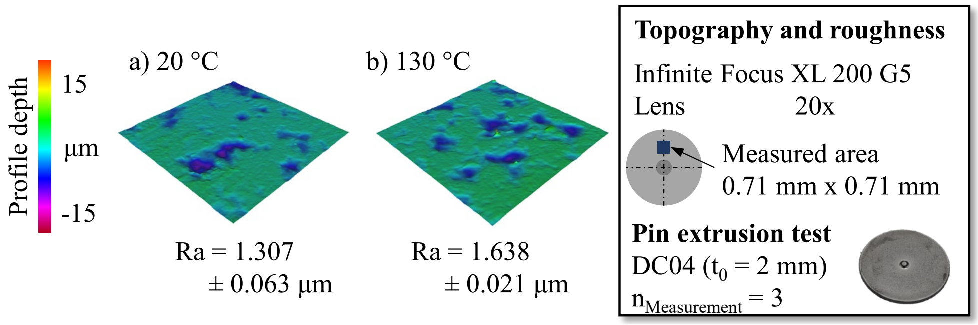

Figure 10 – Topography and roughness of the a) 20 °C and b) 130 °C.

Summary and Outlook

The objective of this research is to determine the influence of temperature, forming speed and lubricant quantity upon the friction factor and thus flow behaviour of the material as well as the topography. In order to analyse the friction factor of a full forward extrusion process, one possibility is to carry out the pin extrusion test. Vierzigmann and Löffler analysed this experiment partially, but not within the relevant scope for future experiments. In the current experiments, the material DC04 was used and the influencing parameters temperature, forming velocity and lubricant amount were conducted. It was shown that the height of the formed pin rises with an increase in temperature. The friction factor will grow while the viscosity of the lubricant drops. It has been established that the height of the formed pin increases with rising temperature, which reduces the friction factor. This is associated with a radial material flow that correlates with the movement between punch and specimen surface. It was also revealed that an increase in the forming velocity leads to an increase in force. A higher force is achieved more quickly due to the elastic deformation in the disc. However, the influence of velocity cannot be categorised as significant. In addition, it has been determined that the friction factor and pin height decrease with increasing amount of lubricant, which can be attributed to the reduced contact between punch and specimen. Although the results cannot be classified as significant due to the standard deviations, a trend towards a decrease in friction factor is recognisable. Future research should focus on incorporating the effects of temperature, forming velocity and lubricant amount into numerical models by adjusting friction factors. These parameters are critical to the accuracy of the simulation in representing real forming conditions. Additionally, the impact of these parameters on tool wear requires further investigation. Understanding their influence will not only improve the predictive capability of numerical models but also contribute to optimizing tool design and extending tool life, ultimately enhancing the overall efficiency and sustainability of the forming processes.

Acknowledgement

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