Materials Research Proceedings 28 (2023) 523-532 https://doi.org/10.21741/9781644902479-57

Progression of plastic die deformation during copper extrusion

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Keywords: Copper Extrusion, Plastic Die Deformation, 3D Scanning, Numerical Analysis

Abstract. In copper extrusion, the dies are continuously subjected to high thermo-mechanical stress. This results in elastic and plastic die deformation as well as extensive wear. To estimate the strain of possible hard phase surface modifications during service, knowledge of the deformation behavior of the extrusion dies is required. Therefore, the plastic deformation of dies made of four different tool materials was investigated in the present study. The applied tool materials were hot-work tool steel 1.2367, special hot-work tool steel CS1, nickel-based alloy 2.4668 (Alloy 718) and cobalt-based alloy 2.4775 (Stellite 1). 3D scans of the dies were created, both in the initial state and after each of three extrusion cycles, utilizing structured-light scanning. The extrusion trials were carried out using an 8MN extrusion press configured for direct extrusion and billets made of commercially pure copper Cu-DHP (CW024A). By evaluation of the 3D scans, the progression of plastic die deformation was determined in dependence on the tool material. Finally, the results were compared to corresponding numerical investigations on die deformation.

Introduction

In the product portfolio of copper extrusion plants, semi-finished products such as rods and tubes represent one of the largest items. The processing temperatures of copper-based alloys are usually in the range of 600-1050°C, which is why the extrusion tools are subjected to high thermo-mechanical stresses [1]. This results in elastic and plastic die deformation as well as extensive wear [2]. In order to counteract plastic tool deformation, high-temperature nickel- and cobalt-based alloys are used as tool materials in addition to the widely used hot-work tool steels [3]. One possible approach to reduce adhesive and abrasive wear is the application of hard phase surface modifications like coatings or diffusion layers [4]. These can offer good resistance to abrasion and adhesion due to their great hardness and possibly high chemical inertness [5]. However, some of these surface modifications also exhibit quite brittle deformation behavior, which entails the risk of cracking or ablation when the substrate is overly deformed.

To estimate the strain of the surface modifications during service, knowledge of the deformation behavior of the dies is required. For this purpose, tool deformation was investigated in a previous study by means of FEM-based numerical analyses [6]. In the present study, the extrusion dies were 3D scanned to determine the actual die deformation and to compare it with the results of the simulations. One die each made of the tool materials hot-work tool steel 1.2367, special hot-work tool steel CS1, nickel-based alloy 2.4668 (Alloy 718) and cobalt-based alloy 2.4775 (Stellite 1) was 3D scanned in the initial state and after each of three extrusion cycles using structured-light scanning. Evaluating the 3D scans, the progression of plastic die deformation was determined in dependence on the tool material. In conclusion, the experimental results were compared with those of the numerical investigations.

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Experimental Procedure

In order to investigate the plastic deformation behavior of dies during copper extrusion, a die was designed according to literature [1] and four pieces were manufactured using different tool materials. A CAD-model of the die design is given in Fig. 1. The applied tool materials were hot-work tool steel 1.2367, special hot-work tool steel CS1, nickel-based alloy 2.4668 (Alloy 718) and cobalt-based alloy 2.4775 (Stellite 1). Due to the low toughness of the cobalt-based alloy and the resulting high risk of cracking, an insert (Ø60 x 20 mm) was shrink fit into a holder made of 1.2367. Furthermore, all dies were equipped with a thermocouple to measure the profile exit temperature. Billets were prepared from copper alloy CW024A (Cu-DHP) and extrusion trials were carried out on the 8MN extrusion press of the Extrusion Research & Development Center. The extrusion press was configured in direct extrusion setup and the extrusion forces were recorded with integrated load cells. The applied extrusion parameters as well as die and billet dimensions are listed in Table 1.

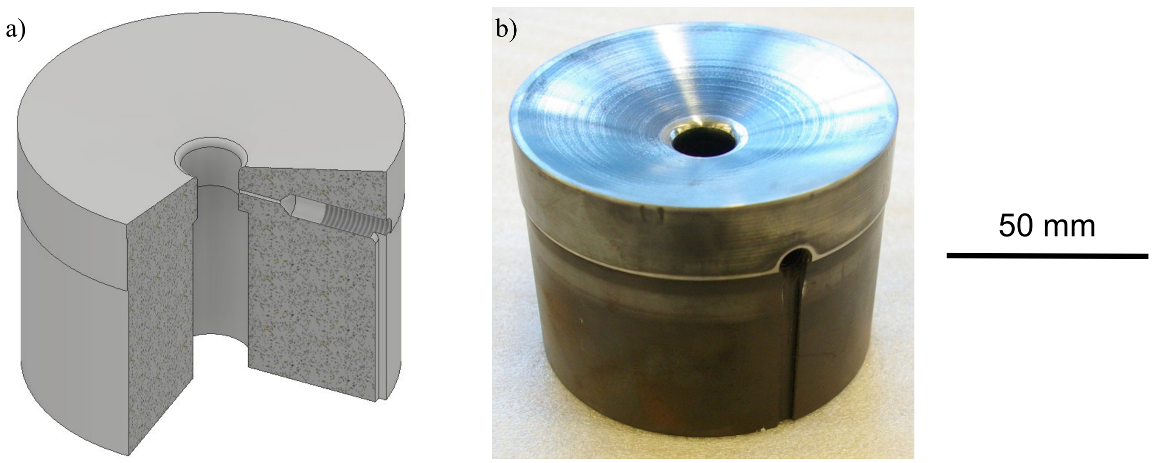

Fig. 1. Illustrations of the die geometry: a) CAD model and b) photograph.

Table 1. Die dimensions and extrusion parameters.

Semi die angle	Outer Diameter	Bearing channel diameter	Bearing channel length	Inlet radius
75°	95 mm	15 mm	10 mm	2 mm
Ram speed	Extrusion ratio	Billet temperature	Billet dimensions	Tool temperatures
20 mm/s	40.1 : 1	850 °C	Ø92 x 300 mm	500 °C

Structured-Light 3D Scanning.

The creation of virtual copies of the dies enables the study of the progression of plastic deformation and the comparison with numerical analyses. Therefore, the dies were scanned using an AICON smartSCAN-HE structured-light scanner. The test volume was 161 mm x 208 mm x 130 mm and with a test distance of 397 mm the resulting average distance between measuring points was 0.064 mm. To keep measurement time and data volume low, only the upper third of the dies, which contains the functional surface, was scanned (see Fig. 2, a). Each die was scanned in the initial state to set a benchmark and after each of three extrusion cycles. Prior to each scan an anti-reflective coating was applied to the dies to avoid interfering reflections. The 3D scans generated surface meshes, which were imported in the software GOM Inspect 2019 for further analysis. In order to determine the plastic deformation of the dies after individual extrusion cycles, a scan of a die in its current state was superimposed on the scan of the initial state in each case (see Fig. 2, b). Using the local-best-fit function of the software and the thermocouple receptors as reference point, an accurate positioning of the two surface meshes was achieved. Subsequently, an area comparison was performed, in which the distance to the nearest point of the mesh in the current state is output for each point of the benchmark mesh (see Fig. 2, c).

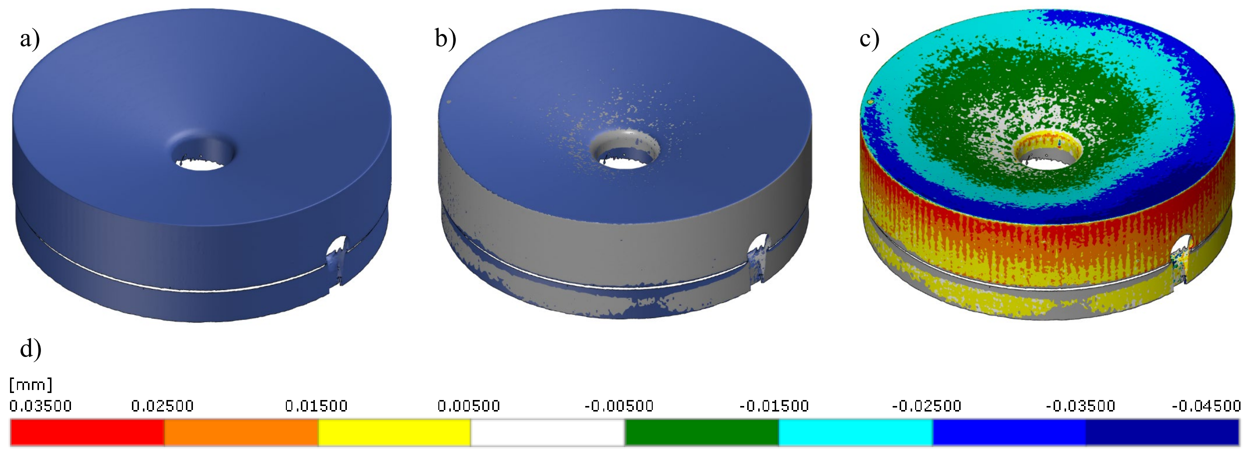

Fig. 2. Data processing sequence for the analysis of 3D scans: a) import of the generated surface mesh, b) superimposing two meshes from different states of the die, c) surface comparison of both meshes, and d) legend for surface comparisons.

Results and Discussion

Extrusion Trials and Structured-Light 3D Scanning.

As basis for the investigation of the progressive tool deformation, a reference scan was made of each of the four dies in their initial state. Subsequently, a total of twelve extrusion trials with consecutive 3D scans was carried out using the four dies made of different tool materials and performing three repetitions per die. On average, the maximum die force was 3.4MN and the highest temperature measured in the bearing channel was approximately 800 °C [6]. The results of surface comparisons of the die made of hot-work tool steel 1.2367 are presented in Fig. 3. Detail a) of Fig. 3 depicts the comparison between the benchmark scan and the state after the first extrusion cycle. Considering the lateral surface, an expansion of approx. 0.03 mm is observed. Since the dies were manufactured with an undersize of 0.25 mm with respect to the container bore, at least elastic expansion of the lateral surface is to be expected during the extrusion process. However, the measured expansion suggests that the yield strength of the material has been exceeded and plastic deformation has occurred. Corresponding to the radial expansion of the lateral surface, a significant lowering of the outer area of the conical face was observed (0.02-0.04 mm). This lowering diminishes towards the center of the die. Inlet radius and bearing channel also exhibit a plastic change in geometry. On average, a diameter reduction of approx. 0.02 mm and 0.01 mm is found at the radius and in the bearing channel, respectively. This deformation is due to an exceeding of the yield strength, considering the very high temperatures present in the bearing channel (superficially above 800°C). A more detailed discussion of the acting forces and resulting deformations is provided in a later section of this study by means of numerical investigations. The comparison between benchmark scan and the state after the second extrusion cycle is shown in

Fig. 3, b). No significant differences can be observed on the lateral surface compared to the state after the first extrusion cycle. There are two reasons for this. On the one hand, plastic deformation induces strain hardening at small strains, as is shown in Fig. 4. Thus, the stress required to cause further plastic deformation is higher than in the first extrusion cycle. However, since the process conditions and therefore the acting forces are approximately equivalent for all extrusion cycles, the stress present in the material is not sufficient to cause further plastic deformation. On the other hand, the deformation of the die in this area is geometrically limited by the inner diameter of the container bore. At the inlet radius and bearing channel, a slight diameter enlargement was measured. This does not correspond to the expected material behavior, since an increase in plastic deformation is to be expected due to the high temperatures and stresses. One possible explanation is the mechanical post-processing of the dies functional surfaces in preparation for the respective 3D scan. Due to the strong adhesion of copper to the die materials, it was necessary to remove adhering copper and lubricant residues (graphite-based) using fine sandpaper and polishing fleece. A slight removal of tool material could not be completely avoided. Following the third extrusion cycle, this phenomenon can also be observed on the lateral surface of the die (see Fig. 3, c). In the area of the bearing channel, in turn, a significant increase in plastic deformation and thus reduction of diameter was measured. This amounts to approx. 0.02-0.03 mm after three extrusion cycles.

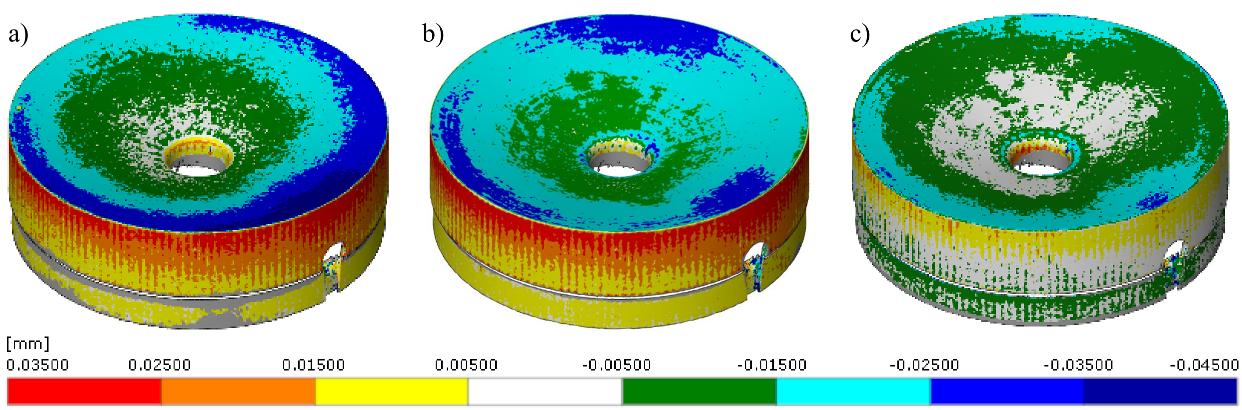

Fig. 3. Surface comparisons for the die made of hot-work tool steel 1.2367 in different states: a) after one, b) after two, and c) after three extrusion cycles.

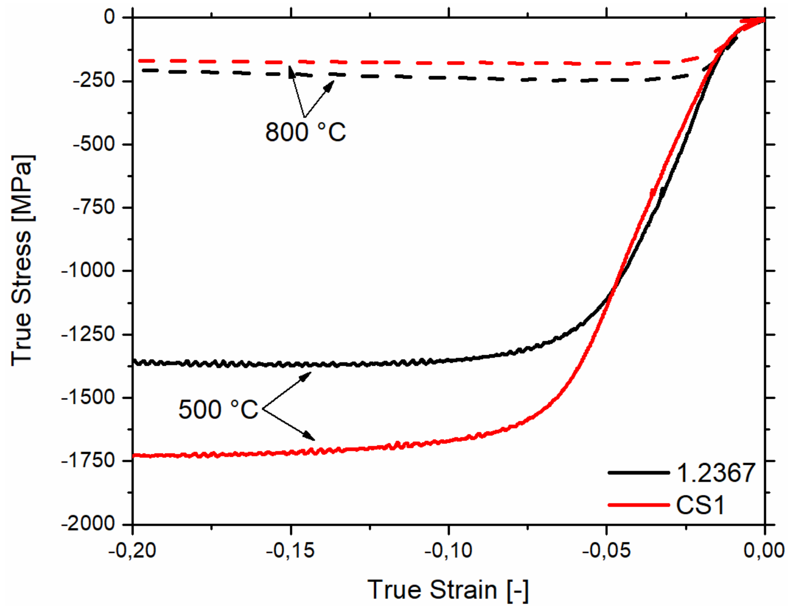

Fig. 4. True stress-true strain curves of hot-work tool steel 1.2367 and special hot-work tool steel CS1 at 500°C and 800°C, obtained by means of hot compression tests at a strain rate of 0.005 s^{-1} [6].

Compared to the hot-work tool steel 1.2367 shown so far, the lateral surface of the die made of special hot-work tool steel CS1 does not expand to any significant extent (see Fig. 5). This is due to the elevated hot strength of CS1 in the temperature range of 500-650°C (see Fig. 4). The slight decrease in lateral surface diameter can be explained, analogously to the die made of 1.2367, by the mechanical post-processing for cleaning the die. In the bearing channel, on the other hand, a strong increase in plastic deformation with the number of extrusion cycles is seen. As a result of the reduced hot strength at temperatures above 750°C, significantly greater deformation occurs in the vicinity of the inlet radius and bearing channel than with hot-work tool steel 1.2367. At the inlet radius, a mean lowering of 0.01-0.02 mm (1st cycle), 0.04 mm (2nd cycle) and 0.04-0.06 mm (3rd cycle) was observed. In the bearing channel, the diameter reduction after the first cycle is 0.01-0.02 mm on average with a local peak of 0.04 mm, followed by 0.02-0.04 mm (2nd cycle) and 0.05-0.06 mm (3rd cycle).

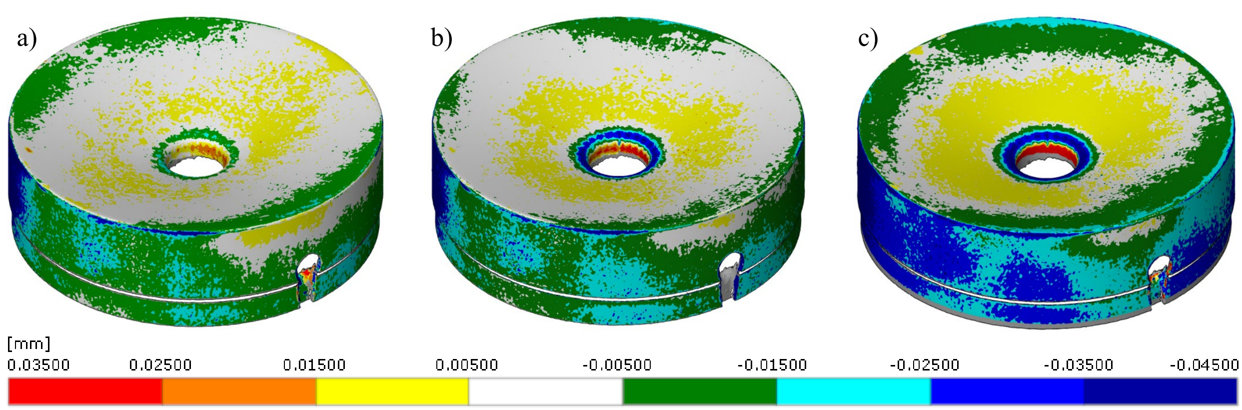

Fig. 5. Surface comparisons for the die made of special hot-work tool steel CS1 in different states: a) after one, b) after two, and c) after three extrusion cycles.

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In contrast to the two hot-work tool steels investigated, the die made of the nickel-based alloy 2.4668 (Alloy 718) shows only very slight plastic deformation overall. As shown in Fig. 6, no remarkable increase in plastic deformation is observed over three extrusion cycles. The evaluation of the 3D scans showed only a diameter reduction of up to 0.02 mm in the bearing channel. At this point, the excellent high-temperature properties of the nickel-base alloy become apparent [7]. Due to almost invariant high-temperature strength up to temperatures of 700°C [6] and the work hardening occurring in the area of the inlet radius and bearing channel, the unchanged process conditions of the three extrusion cycles do not lead to any significant change in die geometry.

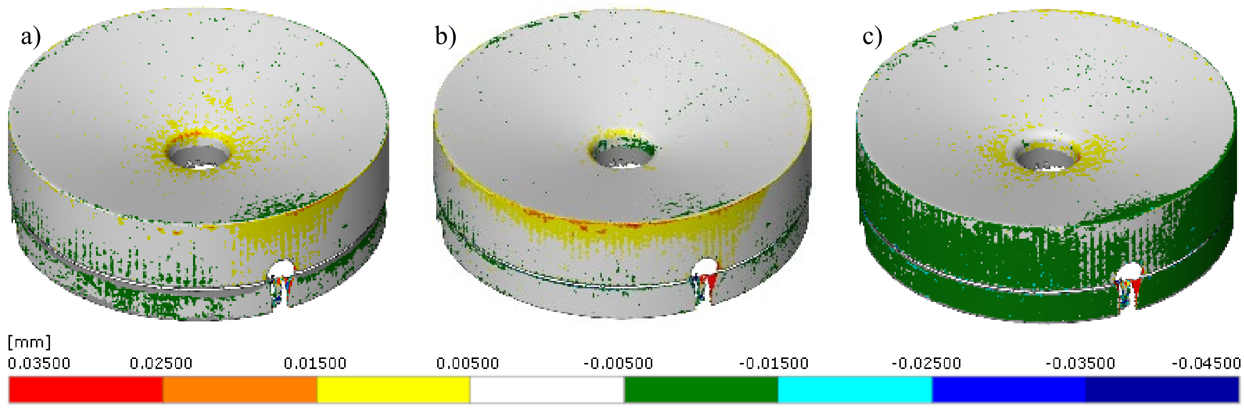

Fig. 6. Surface comparisons for the die made of nickel-based alloy 2.4668 in different states: a) after one, b) after two, and c) after three extrusion cycles.

The surface comparisons for the die made of cobalt-based alloy 2.4775 are shown in Fig. 7. With regard to the use of an insert in combination with a tool holder, there are some distinctive features to be considered when evaluating the 3D scans of this die. Since the shrink-fit of the insert was realized only by insertion and not by pressing, setting of the insert occurred during the first extrusion cycle. As the relative positioning of insert and tool holder no longer corresponds to the benchmark, the alignment of the surface meshes in the evaluation was carried out taking only the insert into account. Therefore, a strong displacement results for the tool holder, as can be seen in Fig. 7. The asymmetry of this displacement suggests that the insert was slightly tilted relative to the holder either in its initial state or after setting. For the insert a lowering of the conical face by 0.01 mm was detected in proximity to the tool holder. Furthermore, a large-area and uniform lifting of the area around the inlet radius by 0.01 mm, and a diameter reduction of the bearing channel by 0.01 mm were measured (see Fig. 7, a). These dimensional alterations remained unchanged over the course of the further extrusion cycles (see Fig. 7, b and c). Due to the excellent hot strength of the cobalt-based alloy [3], no measurable plastic deformation was expected in the material under the stresses and temperatures encountered. Rather, it is suspected that due to an inaccurately manufactured fit in the tool holder, the insert experienced a bending during setting, causing the outer area to lower and the area close to the center to raise.

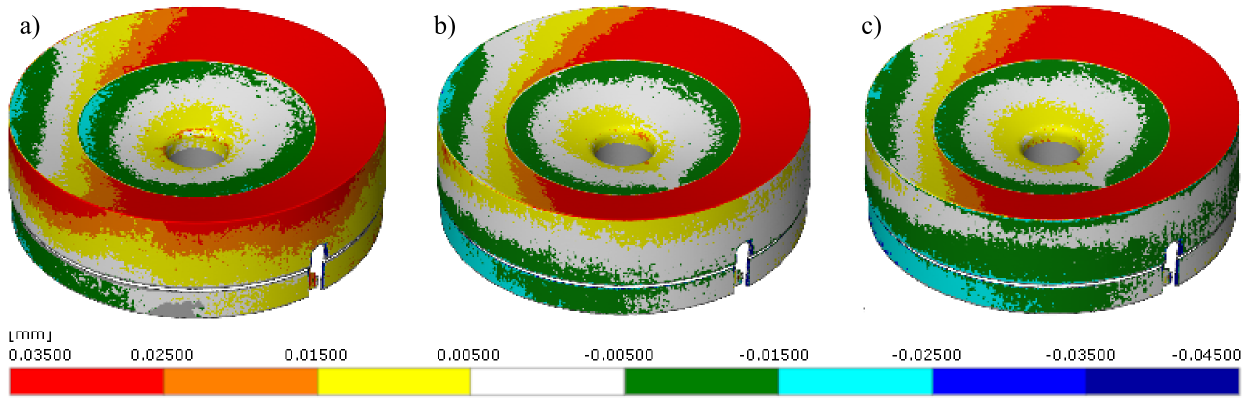

Fig. 7. Surface comparisons for the die made of cobalt-based alloy 2.4775 in different states: a) after one, b) after two, and c) after three extrusion cycles.

Comparison of Experimentally and Numerically Obtained Die Deformation Data.

In parallel to the extrusion trials, FE analyses were carried out in order to numerically model the die deformation. For this purpose, the FE-software DEFORM 2D was used and a rotationally symmetric model was built. The visco-plastic deformation behavior of copper was modeled using flow stress data gained by means of hot compression tests. In the first step of the FE analysis, which represents the extrusion process, the dies were modeled rigid. In the subsequently performed decoupled die stress analysis, elasto-plastic models were implemented to describe the material behavior of the different die materials. The identification of the required flow behavior of the tool and billet materials as well as model design and verification are described in detail in [6]. Since only very small deformations in the range of a few microns are predicted for the two tools made of 2.4668 and 2.4775, solely the two hot-work tool steels investigated will be discussed below. Fig. 8 and 9 illustrate the deformation of the dies estimated by the numerical analyses. The contour of the die in the initial state is represented by the green line and the deflection of the bulk material (magenta) has been scaled up by a factor of 10 for better visualization. The displacement after the third extrusion cycle is indicated by vectors. Fig. 8, b) and c) depict the total displacement at the edge between lateral surface and outer perimeter of the conical face. Analogous to the 3D scans of the extrusion dies, the simulation predicts a significantly pronounced plastic deformation of the hot work tool steel 1.2367 (0.017 mm) compared to CS1 (0.006 mm). While the value for 1.2367 is underestimated by about 40%, simulation and 3D scans match for CS1.

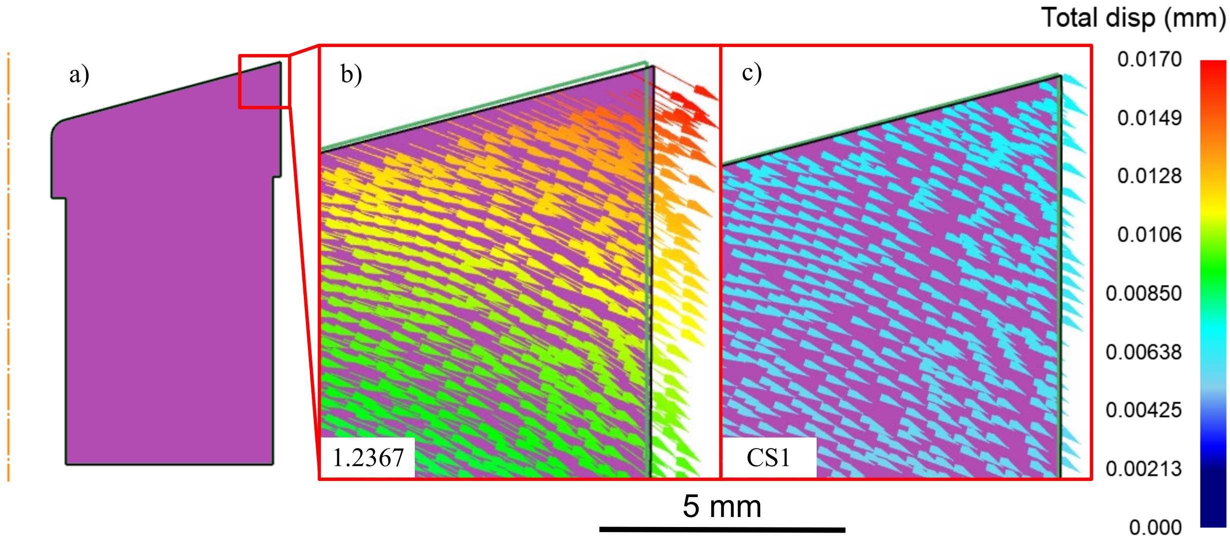

Fig. 8. a) 2D FE-Model of the extrusion die and estimated totals displacement at the lateral surface after three extrusion cycles for the use of b) hot-work tool steel 1.2367 and c) special hot-work tool steel CS1.

Fig. 9, b) and c) show the absolute displacement of the die material in proximity to the inlet radius and bearing channel. For hot-work tool steel 1.2367, the estimated lowering is approx. 0.02 mm. The diameter reduction of the bearing channel by 3 microns is negligible. This again reveals a considerable underestimation of deformation by the numerical model, since the measured diameter reduction was 0.02-0.03 mm. The same applies for CS1, which is estimated to have both a major lowering of the inlet radius (0.035 mm), and a noticeable diameter reduction of the bearing channel (0.016 mm). These values are again underestimated by up to 40% and 70%, respectively. One reason for the inaccuracy of the simulation is the underlying simplicity of the elasto-plastic material model chosen, since neither creep nor fatigue phenomena are taken into account.

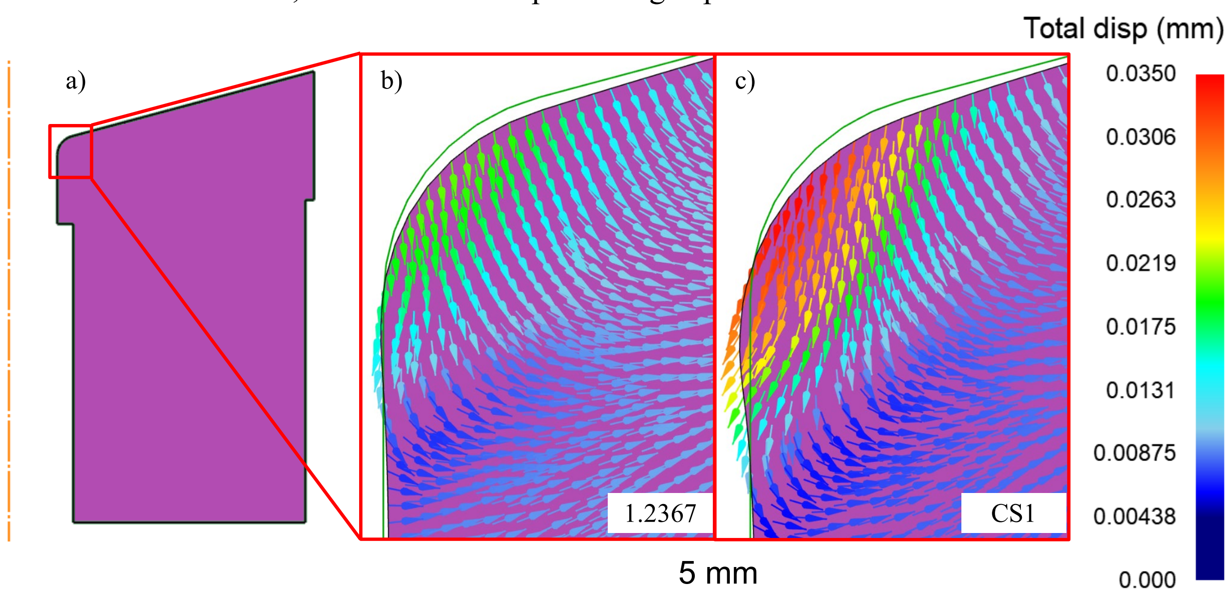

Fig. 9. a) FE-Model of the extrusion die and estimated totals displacement at the inlet radius after three extrusion cycles for the use of b) hot-work tool steel 1.2367 and c) special hot-work tool steel CS1.

The cause of the observed displacements are pressure differences in the extruded material. As illustrated in Fig. 10, the normal pressure acting on the die decreases from the conical face towards the bearing channel. Consequently, stress states are created in the die material which, if sufficiently intense, cause a plastic material displacement in extrusion direction and towards the die center. This effect is more pronounced for the special hot-work tool steel CS1, since its yield strength at temperatures above 750°C is lower than that of 1.2367 (see Fig. 4). At lower temperatures, strain-induced hardening would counteract the increasing plastic deformation as the yield strength shifts to higher stresses under repeated loading [8]. However, in the case of high temperatures, softening mechanisms take effect that counteract strain-induced hardening and prevent a significant increase in yield strength. Therefore, further plastic deformation occurs upon re-loading.

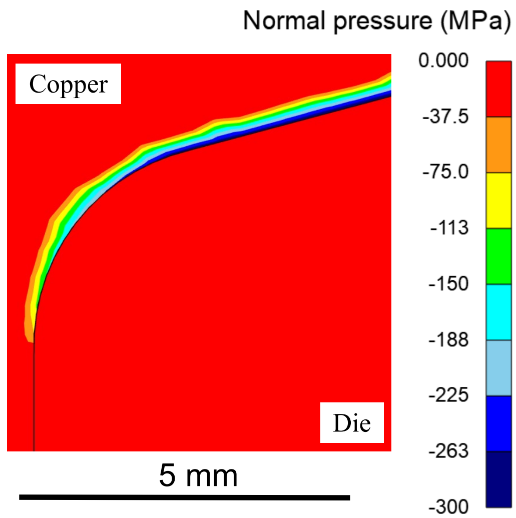

Fig. 10. Normal pressure acting on the die surface in proximity to the inlet radius.

Summary

For the purpose of studying the progression of plastic die deformation during copper extrusion, trials with dies made of four different tool materials were performed. Geometric measurement of the dies was conducted before and after each of three extrusion cycles using 3D structured-light scanning. The evaluation of the scans and the comparison with numerical investigations resulted in the following findings:

- Due to their limited hot strength in the temperature range above 600 °C, the hot-work tool steels investigated are subject to significant plastic deformation that progresses with the number of extrusion cycles.
- Both the nickel- and cobalt-based alloy exhibit very little plastic deformation, irrespective of the number of pressing cycles.
- The results of the numerical investigations indicate a very good agreement with the 3D scans. Both the direction of the displacement and the influence of the tool material can be reproduced accurately by the simulation. However, with the given material models, the absolute values of displacement are underestimated by the simulation.

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