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Beneficial effect of stress superposition on damage reduction in trimming processes

WEIß Alexander[1,a *], FELDE Alexander[1,b], LIEWALD Mathias[1,c] and ZERFAß Helmut[2,d]

[1]University of Stuttgart, Institute for Metal Forming Technology (IFU), Germany

[2]Bilstein & Siekermann GmbH + Co.KG, Germany

[a]alexander.weiss@ifu.uni-stuttgart.de, [b]alexander.felde@ifu.uni-stuttgart.de, [c]mathias.liewald@ifu.uni-stuttgart.de, [d]h.zerfass@bsh-vs.com

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Abstract. Trimming processes are frequently used for the manufacturing of fastener heads and similar parts with high precision requirements for specific regions of the part. Compared to conventional cold forging processes, the desired geometry can be achieved with significantly lower forces. However, trimming of sharp-edged geometries often leads to a highly inhomogeneous material flow and stress state in the workpiece, resulting in crack formation at such edges. To address this shortcoming, superposition of compressive stresses can be used to reduce the damage in the trimming process significantly. In this paper, the beneficial effect of stress superposition on damage reduction in a trimming process of a splined part is presented. By means of a numerical investigation using the FE-software DEFORM 3D, the impact of compressive stress superposition on the damage respectively crack formation at the edges of a splined part was investigated. Afterwards, trimming dies were manufactured and experimental investigations with three different trimming die geometries and different preform geometries were conducted to manufacture the splined parts. The edges of the splined parts were then characterized with a digital microscope and compared to the numerical results.

Introduction and State of the Art

Cold forging is widely used due to its advantages regarding production of high-volume parts, the work hardening of the material due to the deformation and the possibility to obtain near net shape parts right after the forming process. Furthermore, high surface qualities and very low tolerances with regard to dimensional accuracy of the pressed components can be achieved [1]. Trimming processes are often used to trim scrap material from hot forged parts [2]. But trimming processes are also used e.g. for the manufacturing of complex, sharp-edged geometries with high accuracy requirements for which a conventional cold forging process would not lead to a sufficient filling of the die cavity [3]. One example of such a combined process is the production of fasteners. In particular, in the production of screws with hexagonal head and flange, the shape of the hexagonal head is trimmed while the trimmed material forms the flange in the simultaneous upsetting process. Afterwards, the flange is trimmed with a circular shaped tool. Hence, there are two different categories of trimming processes:

- Category A: Trimming processes in which the produced flange is relatively thin and gets sheared off directly at the initial trimming contour by the knock out pin while the punch is still in its end position (e.g. hexagonal screws without flange). [4]
- Category B: Trimming processes in which the produced flange is relatively thick and remains at the part (e.g. hexagonal screws with flange). Here, the flange is usually trimmed with a circular trimming punch in a following forming stage. [3]

Regarding trimming processes of category A, there are several scientific investigations. In [5], the trimming process of a fastener with a hexagonal head has been investigated numerically while the study was mainly focused on the tool load. It was found that the stopping distance has a major impact on the tool load but also affects the load of the knock out pin which is used to shear off the flange. In [6], a numerical investigation using 2D- and 3D-simulations was conducted to determine the impact of different trimming die geometries on the effective stress within the trimming die. Specifically, the corner geometry, land width, petal angle and rake angle were varied and beneficial values were obtained for these four parameters regarding screw sizes M6 and M20.

In [7], a trimming process of a fastener with a hexagonal head was investigated numerically using seven different damage models. Afterwards, the numerical results were compared to cracks that actually occurred on the sheared off chip of a real pressed part. Main objective of this study was the exact numerical modeling of the crack formation in the sheared off chip, whereby Cockcroft-Latham-Oh damage model was the most accurate model to reproduce those diagonal cracks numerically. Further investigations of the same authors show similar results [8].

In [9], the influence of different geometrical parameters on the target geometry of a fastener with a hexagonal head without flange was investigated. Three geometric phenomena were observed with respect to the target geometry – a roll-over at the top of the fastener head, an underfilling and a burr formation in the lower area of the head. The radius at the cutting edge was found to be the most significant parameter for these geometric deviations. A relatively new study from 2021 comprises an investigation on the die-service life of trimming dies for bolts with hexagonal head [10]. In this study, various combinations of geometric parameters of the trimming dies were investigated and the dies were used until failure due to, for example, broken cutting edges. Cutting edge radius and cutting width were found as the most significant parameters for die-service life.

Regarding trimming processes of category B and especially crack formation in such processes, the authors proposed the topic "Process limits in trimming of non-circular and asymmetrical geometries" as a study in the German Cold Forging Group (GCFG) in 2020 [3]. The aim of this study was a deeper knowledge of damage development during trimming of sharp-edged workpieces. For this purpose, a numerical parameter study was carried out based on a real part geometry of a hexagonal screw with flange. The impact of the workpiece preform geometry and tool geometry on the damage development in the workpiece was investigated. Normalized Cockcroft & Latham criterion was used for damage calculation. Among other things, an approach to superimpose compressive stresses was investigated. This approach showed promising numerical results in terms of damage reduction at the edges of the hexagonal screw. However, the results were not validated with an experimental investigation resulting in the initiation of this present study with the aim of proofing the beneficial effect of stress superposition on damage reduction in trimming processes.

Superposition of compressive stresses for an increased formability is also used in other applications, such as fine blanking [11]. In addition, there are also approaches to use stress superposition in lateral extrusion of brittle materials [12,13] and hollow lateral extrusion [14]. A more in-depth investigation of the connection between the stress state and the pore size in the microstructure as well as the resulting damage was carried out by [15]. Besides an improved formability, there are also investigations on the influence of stress superposition on residual stresses within the workpiece [16].

Material and Methods

The numerical investigations were performed with the FE-software DEFORM. Since the non-alloyed carbon steel EN 1.0214 is a common material for fasteners, this material was chosen for the numerical investigations. The used flow curves for the numerical investigation are depicted in

Fig. 1 and comprise data for two different strain rates (20 s^{-1} and 1 s^{-1}) and four different temperatures ranging from 20°C up to 300°C.

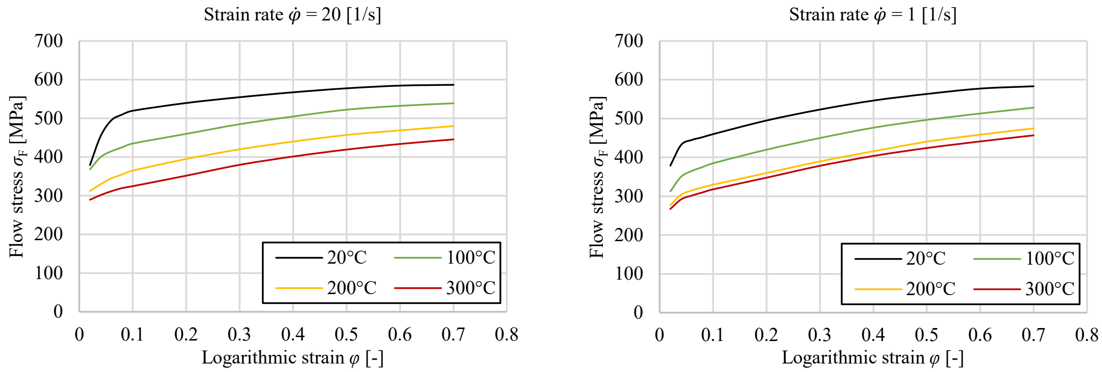


Fig. 1. Flow curves of the non-alloyed carbon steel EN 1.0214.

In order to proof the beneficial effect of stress superposition on damage reduction in trimming processes, a demonstrator geometry with a high susceptibility to crack formation during a conventional trimming process was chosen. In the previous GCFG-study, a screw with a trimmed hexagonal head was investigated (Fig. 2a) [3]. In coordination with the project partner, a gear-shaped geometry with a number of teeth of z_{spline} = 8 and a module of m_{spline} = 2 mm was selected for the present study as a demonstrator geometry (Fig. 2b). The large difference between the tip diameter and root diameter should most likely result in crack formation during conventional trimming. The shaft side of the demonstrator geometry was selected analogously to the hexagonal screw considered in the first study [3] which is based on a real process (Fig. 2c). In this way, it was possible to use the transfer system of the horizontal press without any modifications and the same process sequence. Just a modified trimming die had to be produced.

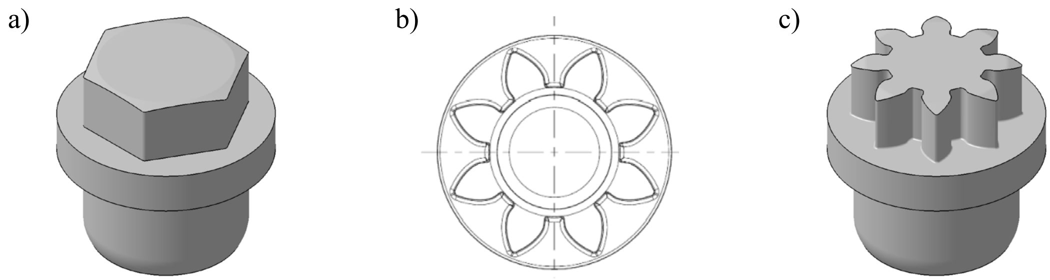


Fig. 2. a) Standard geometry with trimmed hexagonal shape [3], b) defined splined shape for the present study and c) modified geometry with trimmed splined shape.

For the numerical investigation, a multi-stage forming process has been developed in DEFORM comprising upsetting and heading as 2D-simulations, a 2D-3D-conversion and the trimming process as a 3D-simulation. The trimming process of the flange was not carried out, due to the fact that the damage at the edges can already be determined during the trimming process of the spline. Fig. 3 shows the developed multi-stage forming process for the numerical investigation in DEFORM. Since a high variety of different tool geometries was investigated, the workpiece was modelled as an ideal-plastic object whereas the tools were rigid objects. This approach has already been proven beneficial in the first study [3].

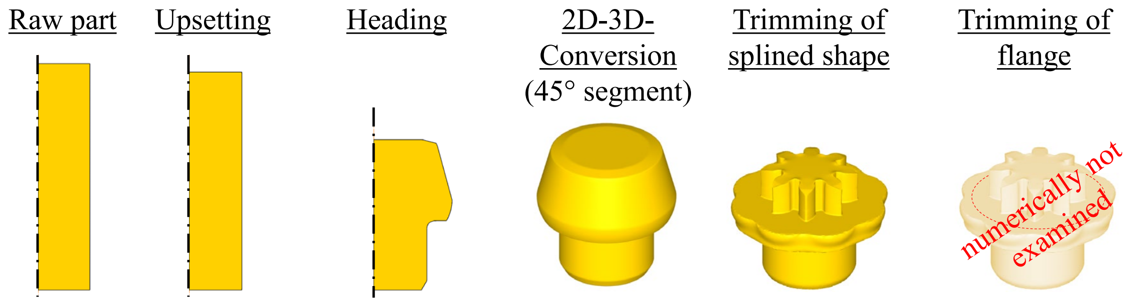


Fig. 3. Developed multi-stage forming process for the numerical investigation in DEFORM.

In the numerical investigation, shear friction model was used with a constant friction coefficient of $m = 0.1$. Furthermore, the velocity of the punch was set to 10 mm/s in each stage. For the upsetting and the heading process the number of elements for the FEM mesh was chosen to 2,500 elements with a minimum element edge length of 0.1 mm. Regarding the relatively simple geometries during upsetting and heading, this element edge length provides sufficient accuracy for the representation of the small radii. The raw part has a diameter of 19.7 mm and a length of 37.3 mm. After the upsetting process, the diameter is 20.75 mm and the length 33.62 mm. The initial preform angle of the conical shape in the heading stage is 16.5°. The preform angle was also varied to 25° since the tools were already available; a further increased value was not investigated based on the findings in [3] (the preform would need a very high radial dimension to meet the required height, and the amount of displaced material would increase disproportionately). The upsetting process is followed by an 2D-3D-conversion. Here, a 45° segment was investigated since this is the angle for simulate one complete tooth (Fig. 3 shows the 360° model for better overview). To decrease calculation time, also half of a tooth could be investigated. However, the relevant area of the tooth (the tooth tip) is directly in the symmetry plane which can influence the calculated workpiece properties. Therefore, one complete tooth was investigated. The hexagonal screw on which the demonstrator geometry is based on, has a wrench size of 19 mm to get an overall idea of the part size depicted in Fig. 2a. In the case of the demonstrator geometry of this study, the tip diameter is 21.6 mm and the root diameter is 12.6 mm.

The model of the 3D-simulation of the trimming process is shown in Fig. 4a. A 45° segment was investigated. This segment was modelled with a FEM mesh consisting of 180,000 elements. Mesh windows were used to obtain an accurate numerical result in the relevant area of the trimming zone. The smallest element size was 0.06 mm. Fig. 4b shows the stop-criterion of the process (flange height of 5.4 mm). The calculated workpiece geometry is depicted in Fig. 4c.

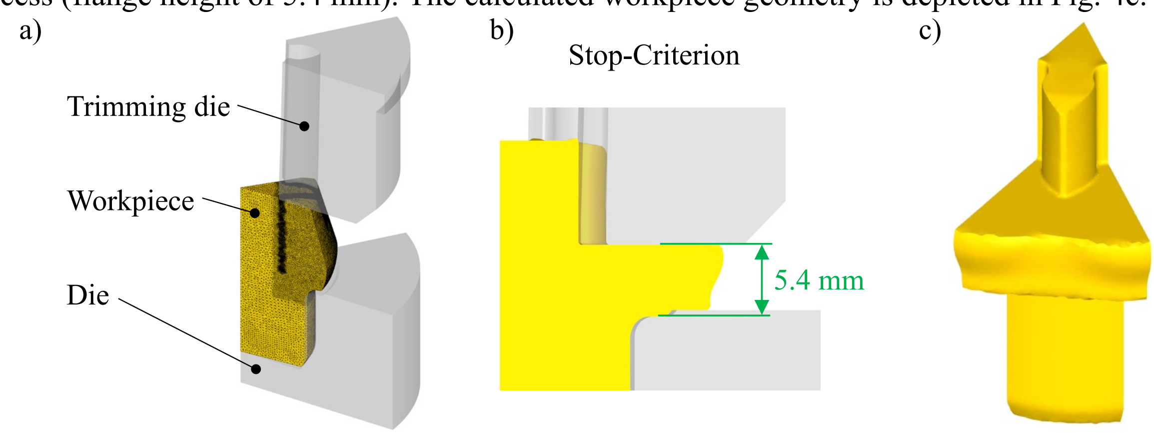


Fig. 4. a) Simulation setup, b) final height of the flange as a stop criterion and c) calculated workpiece geometry.

Regarding the stress superposition, five different trimming dies were used initially. Fig. 5 shows the dies considered for the numerical investigation. The reference die is designed like a conventional trimming die with a cutting edge radius of 0.25 mm. All other dies have the same cutting edge radius. Variant V1 features an indentation of 0.25 mm relative to the face of the die, which is applied close to the contour as an offset at a distance of 0.5 mm. Variant V1b is based on variant V1, but has an increased offset geometry distance of 1.0 mm (with regard to the tooth tip without the tooth root). Variant V2 features an annular indentation of 0.25 mm with a radial offset relative to the tip diameter of 0.5 mm. Variant V3 is designed to apply a compressive stress only in the local area of the tooth tip. For this purpose, the entire surrounding area is designed as a indentation. The offset of V3 was also selected to 0.5 mm, like V1 and V2.

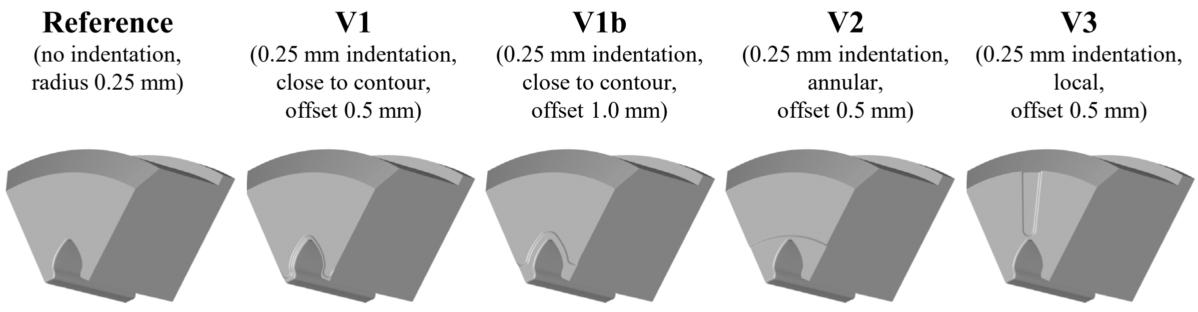


Fig. 5. Initially used trimming dies for the numerical investigation.

The experimental investigations were carried out on a mechanical press. In preparation, the series process for the production of a hexagonal screw with flange shown in Fig. 6 was equipped on the horizontal multi-stage press. Afterwards, the parts were pressed using the splined dies and the parts with cracks were analyzed using a Keyence digital microscope VHX-5000. Finally, the critical damage value was determined by comparing the numerically determined damage distribution with the measured crack height.

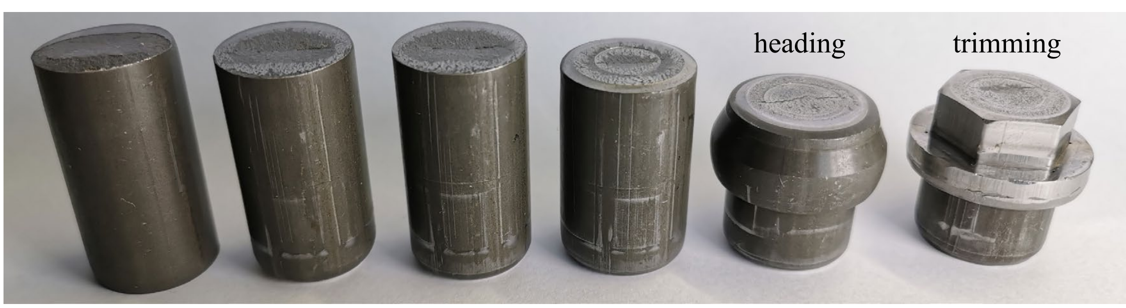
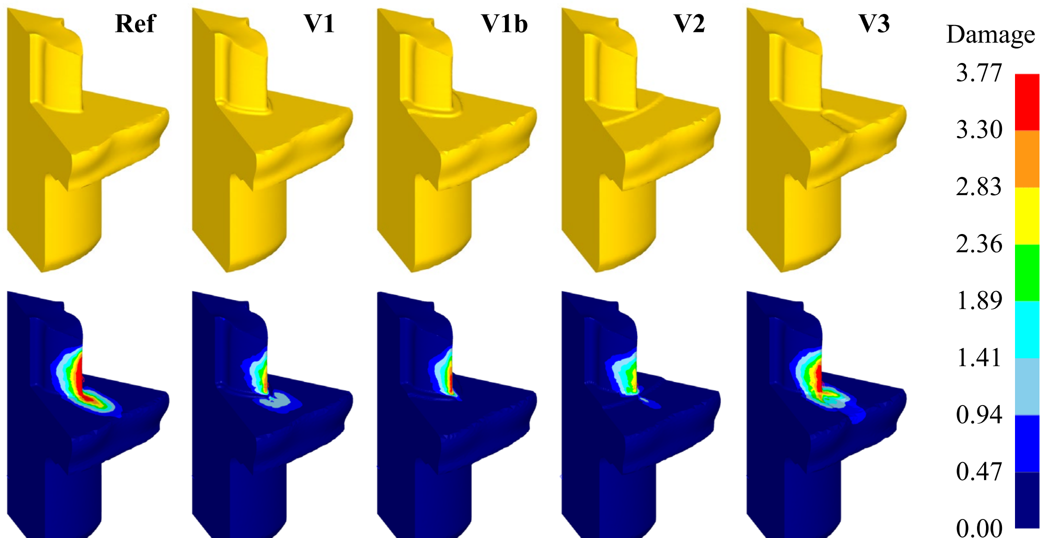


Fig. 6. Multi-stage process for production of a hexagonal screw with flange.

Results and Discussion

At first, the numerical results are evaluated. The geometry and the respective distribution of damage with Normalized Cockcroft & Latham damage model is shown in Fig. 7. The modified die geometry is well visible on the top side of the flanges. Regarding the determined damage values, also the maximum damage value for each variant is listed. As expected, the highest damage values occur at the tooth tip of the splined geometry. The reference die leads to the highest value of $D_{max,ref} = 5.41$. For all other variants the damage value is reduced due to the superposition of radial compressive stress. This can be explained by the additional redirection of the material flow at the transition of the indentation, which leads to an additional radial force. Owing to the highly inhomogeneous material flow caused by the large differences between tip and root diameter, the modified variants have a different impact on the damage values. Variant V2 leads to the most homogeneous material flow due to the annular indentation and, as a result, provides the smallest damage value of $D_{\mathrm{max,V2}} = 2.94$. With regard to the forces, there are only minor differences between all variants with 525 kN to 575 kN (Fig. 7). This can be explained with the only slightly varying volume differences of the indentations. Without an experimental test, the damage value only indicates the potential area of possible damage, but must always be validated with an experimental test. Therefore, it cannot be determined solely from the numerical results whether a crack will occur or not.



$D_{\mathrm{max,ref}} = 5.41$ $D_{\mathrm{max,V1}} = 3.42$ $D_{\mathrm{max,V1b}} = 3.80$ $D_{\mathrm{max,V2}} = 2.94$ $D_{\mathrm{max,V3}} = 4.49$

$F_{\mathrm{max,ref}} = 557$ kN $F_{\mathrm{max,V1}} = 570$ kN $F_{\mathrm{max,V1b}} = 575$ kN $F_{\mathrm{max,V2}} = 573$ kN $F_{\mathrm{max,V3}} = 525$ kN

Fig. 7. Calculated geometries and respective distribution of damage with Normalized Cockcroft & Latham.

Due to the smallest numerically determined damage values, variant V2 was selected for the experimental investigations. The manufactured die with the splined contour replaced the hexagonal die in the process sequence depicted in Fig. 6. Initially, several parts were pressed with the conventional machine setting. Fig. 8 a shows the reference trimming die for the spline shaped parts. A pressed part is depicted in Fig. 8b. The crack formation at the sharp edges of the tooth tips is clearly visible. A detailed view of one tooth is shown in Fig. 8c. Thus, it can be concluded that the selected demonstrator geometry has a high vulnerability to crack formation with respect to conventional trimming processes.

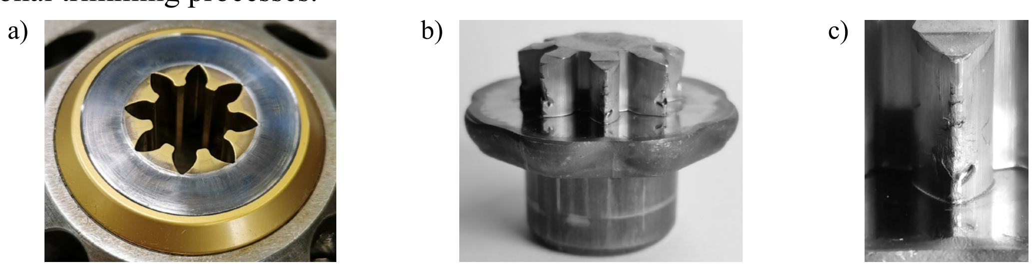


Fig. 8. a) Trimming die without indentation (reference), b) pressed part with cracks and c) detail of tooth tip.

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Subsequently, the experimental investigation with the trimming die with an annular indentation of 0.25 mm was conducted. The pressed parts showed also cracks at the sharp edges of the tooth tips (Fig. 9b and Fig. 9c). At first, the initiation position of the cracks looked quite similar compared to the variant without compressive stress superposition. Therefore, also a comparison of Fig. 8c and Fig. 9c doesn't show much difference. But in fact the initiation position of the cracks was slightly lower which is made clear in Fig. 11 later.

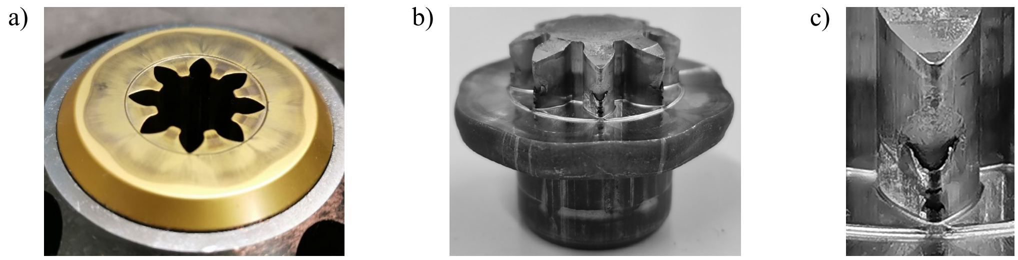


Fig. 9. a) Trimming die with annular indentation of 0.25 mm, b) pressed part with cracks and c) detail of tooth tip.

In a further investigation, the indentation was increased from 0.25 mm to 1.0 mm (Fig. 10a). As a result, there is a larger deflection of the material and, thus, higher induced compressive stresses occur. With this adjustment it was possible to press parts without any cracks. One exemplary part is shown in Fig. 10b with a detailed view in Fig. 10c.

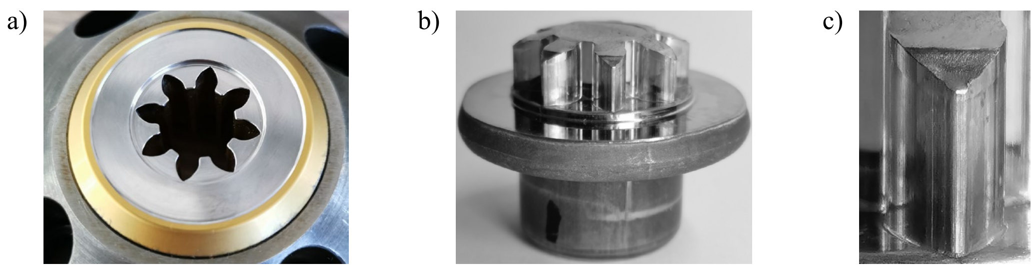
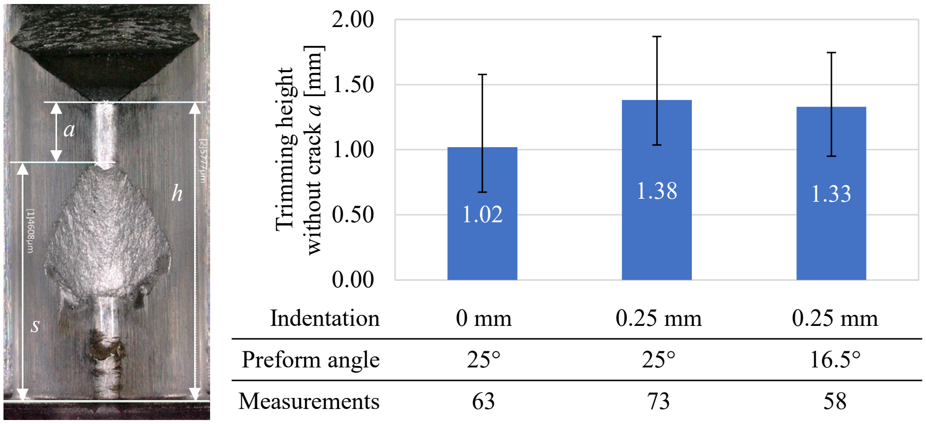


Fig. 10. a) Trimming die with annular indentation of 1.0 mm, b) pressed part without cracks and c) detail of tooth tip.

Besides those different die geometries, also the preform angle was varied in the experimental investigation using the trimming die with a 0.25 mm deep indentation. For comparison of the experimental results with the numerically determined damage values over 400 teeth were characterized using the Keyence digital microscope VHX-5000. In particular, the total trimming height h from the top edge to the flange, the trimming height s from the crack initiation to the flange and the difference between those two heights - the trimming height without crack a - were measured.

Fig. 11 shows the measured heights for characterization of crack initiation as well as the impact of the investigated variants with respect to the indentation and the preform angle on the trimming length without crack a. Furthermore, the number of measurements is indicated, since at some parts the very sharp edges were deformed due to the impact in the container after the forming process. Without a compressive stress superposition, an average trimming height without crack of $a = 1.02$ mm was determined. With a compressive stress superposition by the indentation of 0.25 mm, a 35 % higher value of $a = 1.38$ mm could be achieved for the same preform. The preform which was used initially in the numerical investigation comprising an angle of 16.5° has only a slight impact on the height a. Here, the average value is 1.33 mm. Regarding the variant with 1 mm indentation, no cracks occurred on any of the pressed parts. The height a therefore always corresponded to the total trimming height *h*, with an average value of *h* = 5.22 mm. The maximum value of the total trimming height for one part with a very low end position of the trimming die was *h* = 5.80 mm.



Indentation	0 mm	0.25 mm	0.25 mm
Preform angle	25°	25°	16.5°
Measurements	63	73	58

Fig. 11: Measured heights for characterization of crack initiation and impact of the investigated variants on the trimming length without crack a.

To compare the numerical and experimental results, the additional preform with an angle of 25° and the additional trimming die geometry with an indentation of 1 mm were first added in the numerical investigations and further simulations were carried out. Based on the average trimming height without crack *a*, the critical damage value was then identified for the reference die and the die with an indentation of 0.25 mm as well as for the preform angles 25° and 16.5°. Using this procedure, an average critical damage value of 0.93 was identified. The preform angle has no major impact and the penetration depth has no impact on the critical damage value. Fig. 12a shows the comparison of an edge of a pressed part (no indentation, preform angle 16.5°) and the numerically calculated damage distribution. The color scale is formatted in such a way that the critical damage value represents the transition from orange to red color (red circle).

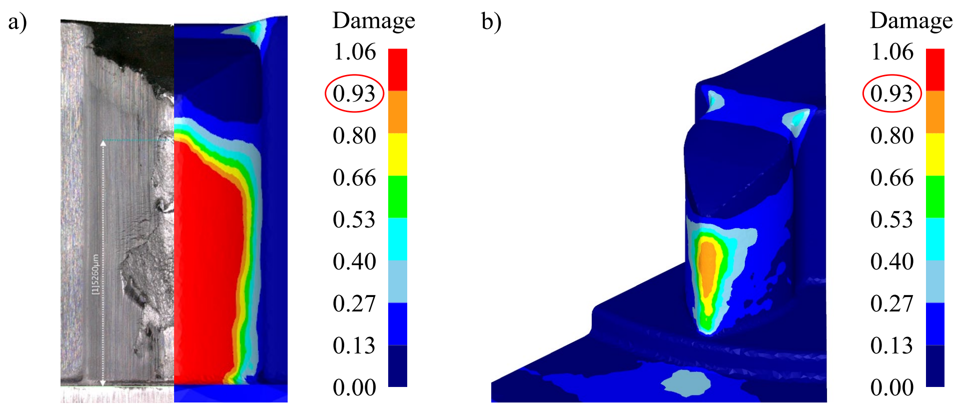


Fig. 1. a) Comparison of an edge of a pressed part (no indentation, preform angle 16.5°) and the numerically calculated damage distribution and b) calculated damage distribution of the variant with an indentation of 1 mm.

According to the damage distribution illustrated, the crack initiation height can be estimated quite accurate with ± 0.1 mm in height for all investigated variants. However, there is a difference in the shape of the cracks on the real part and the area with damage values higher than 0.93, which is probably due to the lack of element deletion. Using element deletion would in particular affect adjacent elements, which could lead to a more realistic representation of the shape of the crack.

The analysis of the variant with an indentation of 1 mm in Fig. 12b demonstrates, that the calculated damage values are lower than the critical damage value of 0.93. Since no cracks occurred during the experimental investigations with this trimming tool, it can be concluded that the numerical model can represent the crack initiation behavior realistically. In summary, compressive stress superposition can be used to improve trimming processes of parts which are vulnerable to crack formation.

Summary

In this contribution, a numerical study with a subsequent experimental investigation regarding superposition of compressive stresses in trimming processes of bulk forming parts has been conducted. At first, a gear-shaped demonstrator geometry which is vulnerable for crack formation during a conventional trimming process was defined. Afterwards, different trimming die geometries for stress superposition were investigated and their impact on the damage development in the workpiece was evaluated. Based on the numerical results, the trimming die which leads to the lowest damage values in the workpiece was selected and manufactured for the subsequent experimental investigation.

In the experimental investigations, different trimming die geometries and preform geometries were conducted to manufacture the splined parts. Besides the initially investigated trimming die geometries, also an additional geometry was investigated comprising an indentation of 1.0 mm for stress superposition. The edges of the splined parts were then characterized with the Keyence digital microscope VHX-5000 and compared to the numerical results for identification of the critical damage value. It was found that a minor compressive stress superposition (indentation of 0.25 mm) leads to slightly reduced damage values in the workpiece compared to a conventional die without compressive stress superposition. Using a further increased compressive stress superposition (indentation of 1 mm), it was even possible to press components without crack formation entirely.

In summary, it was shown that the superposition of compressive stresses is a useful method for improving trimming processes of parts that are vulnerable to crack formation. Since damage is very specific in terms of material and geometry, it is not possible to directly transfer the determined critical damage value to completely different geometries or materials. Experimental validation is always required to investigate on damage development. However, the developed simulation model can be used as a comprehensive basis for the investigation of similar splined geometries and other materials in the future. The method of compressive stress superposition in trimming processes can be transferred to other parts for which no trimming process could be applied so far, thus the existing process limits of trimming processes can be improved significantly.

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