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Influence of Shear Cutting Process Parameters on the Residual Stress State and the Fatigue Strength of Gears

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Abstract Shear cutting is used for manufacturing various parts ranging from e.g. simple washers to complex gears. The latter are typically subjected to cyclic loading and fail foremost due to fatigue damages. Hereby, the parts lifetime is mainly determined by: the geometry, the applied load, the material, the hardness, the roughness and the residual stress state. While numerous research works deal with the influence of the process parameters on the hardness and the parts geometry, the influence of the process parameters on the residual stress state and on the resulting fatigue strength has not been investigated in detail, yet. In an earlier publication, suitable shear cutting techniques, which allow to achieve a high amount of clean-cut and a favorable residual stress state were compared. In this paper, the influence of the process parameters on the residual stress state and the resulting bending fatigue strength are addressed. To simulate the bending stress occurring in the tooth root, C-shaped specimens were manufactured by different blanking techniques. The die-clearance and punch and die edge radii were varied with these blanking techniques. After measuring the cut-surface geometry, the hardness distribution and the surface roughness, the fatigue strength was determined in a pulsating test rig. By carrying out residual stress measurements using x-ray diffraction and simulating the material flow behavior using the Finite-Element-Method, basic mechanisms, which are influencing the residual stress state and the resulting bending fatigue strength, were identified and will be presented and discussed in the paper.

Keywords Shear Cutting · Fineblanking · Near-Net-Shape Blanking · Residual Stresses · Fatigue · Gears

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1 Introduction

Many authors, like for example [4] and [3] have addressed the fatigue behavior of shear-cut parts. Still, there is no work known to the authors that deals with this topic regarding the use for shear-cut gears, i.e. for blanking processes which are able to achieve a high amount of clean cut and therefore a high amount of load bearing surface.

To achieve an improved fatigue behavior, compressive residual stresses are used in many applications, for example in shot-peened gears [7]. Still, the targeted use of residual stresses is scarce in shear cutting, although it has been published for additional process steps like coining [8].

Therefore, the topic of residual stresses induced by different blanking processes which are able to achieve a high amount of load bearing surface, so called Near-Net-Shape Blanking processes (NNSBPs), was adressed in [6]. It was discovered that the sheet metal strip is commonly subjected to a compressive stress state while the blank shows a tensile stress state for most NNSBPs. This work was extended by the effect of the residual stresses on the fatigue behavior of parts manufactured by NNSBPs in [5]. Beside the beneficial effect of compressive residual stresses, the part bending was identified as a major influence parameter in common fatigue test rigs.

While the influence of the chosen NNSBP on the residual stress state and the fatigue behavior has been discussed in these earlier works, this paper focuses on the influence of the process parameters punch and die edge radius as well as die clearance on the residual stress state and the resulting fatigue behavior.

2 Experimental setup and test equipment

2.1 Shear cutting setup

Five different Near-Net-Shape-Blanking Processes are investigated: Fineblanking (FB), blanking with small die clearance and v-ring (BV), precision blanking without blank holder (PBwBH), precision blanking with blank holder (PB), and blanking with small die clearance (B). When changing from one NNSBP to another, only one active element is changed which allows to draw conclusions on the effect of this active element on the residual stress state of the manufactured part.

For FB and B, three different relative die clearances u_r were investigated, 0.5 %, 1 %, and 3 % while a die clearance of 0.5 % of the sheet metal thickness was chosen for the remaining processes.

Two different cutting edge strategies were chosen: One with a punch edge radius of $r_S = 200\,\mu\text{m}$ and a sharp die edge $r_M < 20\,\mu\text{m}$ and one with a sharp punch edge $r_S < 20\,\mu\text{m}$ and a rounded die edge $r_M = 200\,\mu\text{m}$. The punch velocity was set to $50\,\text{mm}\,\text{s}^{-1}$.

A detailed description of the used tool can be found in [6], [5], or [2]. The experiments were carried out on a Feintool HFA 3200 plus fineblanking press with a nominal press force of 3200 kN. Here, the v-ring force of 450 kN was set for the NNSBPs involving a v-ring, otherwise a blank holder force of 200 kN was chosen. The counter punch force was set to 200 kN.

2.2 Materials and specimen geometry

The finegrain, hot rolled, microalloyed structural steel S355MC (material number 1.0976 in [1]) with a thickness of 6 mm was chosen as it is a typical steel used in fineblanking. Measured mechanical properties can be found in [6]. A flow curve for specimen taking out of the sheet in 0° and 90° to the rolling direction can be found together with the used extrapolation in figure 1 a). After milling the contour illustrated in figure 1 c), the specimens were subjected to a stress relief heat treatment. Afterwards, a hole with a diameter of 60 mm was cut by the different NNSBPs, followed by abrasive cutting to get the final geometry used for fatigue testing.

2.3 Measurement techniques

Factors that are known to affect the fatigue strength are the geometry and roughness of the manufactured edge. Additionally, the part bending was identified as a major factor influencing the fatigue behavior in [5]. Accordingly, these part properties were measured. Finally, the fatigue testing setup is explained.

The cut surface characteristics were measured with a tactile surface measurement device with a resolution of 0.5 µm for the used arm length. The part bending was measured optically on the burr side of the part and is given as the deviation from a mean plane. Further information on the measurement methods and devices can be found in [6] and [5].

Residual stresses were measured by X-ray diffraction with a Seifert XRD 3003 PTS System and evaluated with the $sin^2\psi$-method. A 1 mm collimator was used and is positioned in the middle of the sheet thickness with 10 mm distance between collimator and specimen surface. For parts that show a significant fracture zone, three positions were evaluated: In the middle of the sheet thickness and additionally in the middle of the clean-cut and in the middle of the fracture zone. Further information on setup and method can be found in [6].

A servo-hydraulic pulsating test rig was used for the fatigue experiments. With a specimen holder the profiles were loaded with tensile swelling loads at a test frequency of 50 Hz. The fatigue strength was determined on two different load stages, 19 kN and 16 kN, in the limited lifetime range. The lower load limit of the pulsating load is always zero (R=0).

2.4 Finite-element model

A finite-element (FE) model of the NNSBPs was built in Simulia Abaqus 2018 as illustrated in figure 1 b). This explicit, rotationally symmetric model uses CAX4R elements for all deformable bodies (punch, die, sheet metal) while the counter punch and the blank holder were modelled as rigid bodies. Mass scaling and ALE are used to cope with the long calculation time and the severe mesh distortion.

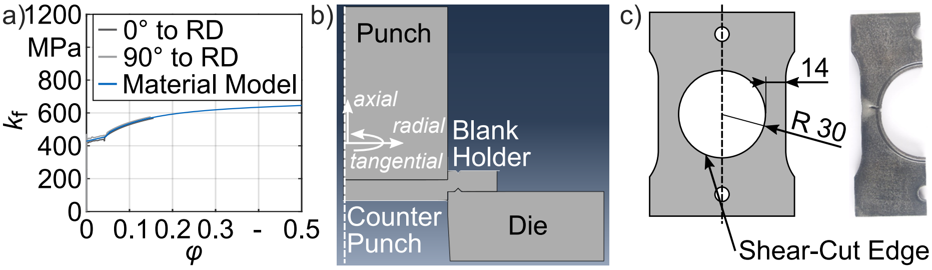

Fig. 1 Stress strain curves of the material together with the flow curve extrapolation (a), the simulation setup of the fineblanking process (b), and the specimen geometry (c).

Table 1 Clean-cut height and fracture zone height (in brackets) in percent of the sheet metal thickness together with the values published in [6].

NNSBP	FB			BV	PBwBH	PB	B		
u_r	3 %	1 %	0.5 %	0.5 %	0.5 %	0.5 %	0.5 %	1 %	3 %
$r_S = 200\,\mu m$; $r_M < 20\,\mu m$	81.3 (14.8)	93.7 (3.2)	97.6	97.0	90.3	93.2	93.7	87.7 (5.7)	63.8 (29.2)
$r_S < 20\,\mu m$; $r_M = 200\,\mu m$	67.7 (29.5)	95.2 (2.3)	97.5	97.9	91.6	94.6	94.2	90.9 (3.7)	51.9 (42.3)

3 Results and discussion

3.1 Cut-surface characteristics and part bending

The clean-cut height and the fracture zone height are given in percent of the sheet metal thickness in table 1. For $u_r = 0.5\,\%$ and $1\,\%$, the configuration with the sharp punch leads to a slightly higher amount of clean cut, except for FB where similar values were measured. For $u_r = 3\,\%$ this tendency changes and a much lower clean cut height is observed for this configuration. While specimen show no fracture zone for the small die clearance, a small amount of fracture can be observed for $u_r = 1\,\%$, a significant amount of fracture of up to 42.3 % of the sheet thickness is observed for $u_r = 3\,\%$.

The part bending is displayed in figure 3 b). It can be observed that the parts manufactured by PBwBH show the biggest bending, followed by those manufactured by PB and B. A higher deviation is visible for the parts manufactured with $r_S = 200\,\mu m$, especially for PBwBH although this tendency can be observed for PB and B as well. For B, a bigger die clearance leads to a smaller bending. For the processes with a v-ring, i.e. FB and BV, is so small that a comparison is not possible.

3.2 Residual stresses

The axial and tangential residual stresses were measured at the shear cut surface of the specimen geometry respective to the coordinate system shown in figure 1 b). The measured residual stresses for all five NNSBPs, the two different active

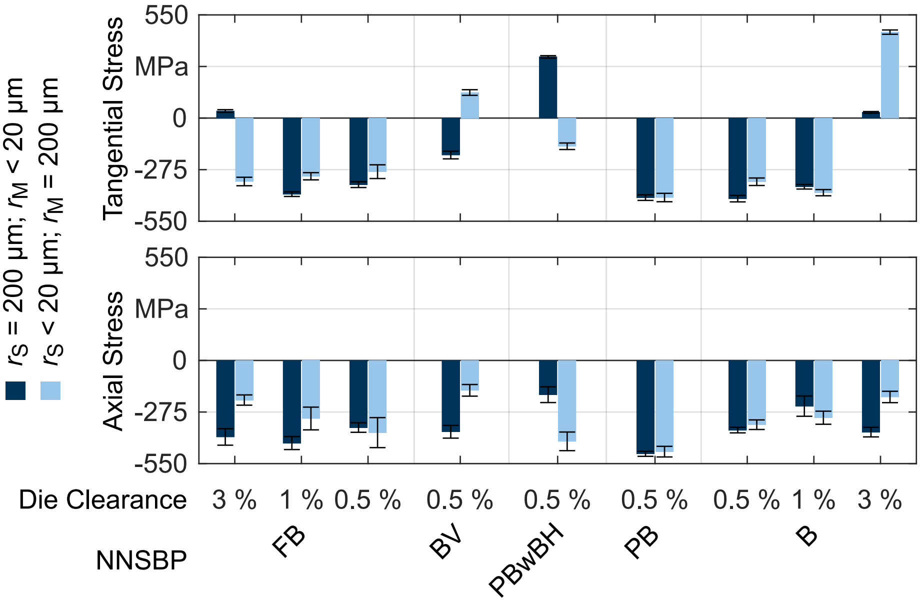

Fig. 2 Residual stresses in tangential and axial direction measured in the middle of the sheet thickness for the five NNSBPs with different die clearances and active element edge radii together with the results published in [6].

element edge preparations and the three die clearances are displayed in figure 2. For $u_r = 0.5\,\%$ and $1\,\%$, the parts manufactured by FB, PB, and B show compressive residual stresses in tangential direction independent of the used active element edge preparation. Only BV and PBwBH show tensile stresses at $u_r = 0.5\,\%$, in the case of BV for the configuration with the sharp punch edge and for PBwBH for the configuration with the rounded punch edge. For the small die clearance of $0.5\,\%$, the configuration with the rounded punch leads to higher compressive residual stresses in tangential direction compared to the configuration with the sharp punch edge for all parts except those manufactured by PBwBH. For FB, $u_r = 1\,\%$ leads to higher compressive stresses for both edge preparations. For a die clearance of $3\,\%$ only the configuration with the sharp punch edge leads the even higher compressive residual stresses while the rounded punch edge leads to tensile stresses. When changing u_r from $0.5\,\%$ to $1\,\%$ for B, only the sharp punch edge leads to increased compressive residual stresses. For $u_r = 3\,\%$, the parts manufactured by B show tensile stresses in tangential direction which are not as high for the configuration with the rounded punch.

In axial direction, all produced parts show compressive residual stresses. These are higher for the configuration with the rounded punch edge, except for those manufactured by FB and PB with $u_r = 0.5\,\%$ where similar values were measured and for those manufactured by PBwBH and B with $u_r = 1\,\%$. For FB and the configuration with the rounded punch edge, a bigger die clearance leads to increased compressive stresses compared to the configuration with $u_r = 0.5\,\%$ while a opposing trend is observed for the configuration with the sharp punch edge. For B with

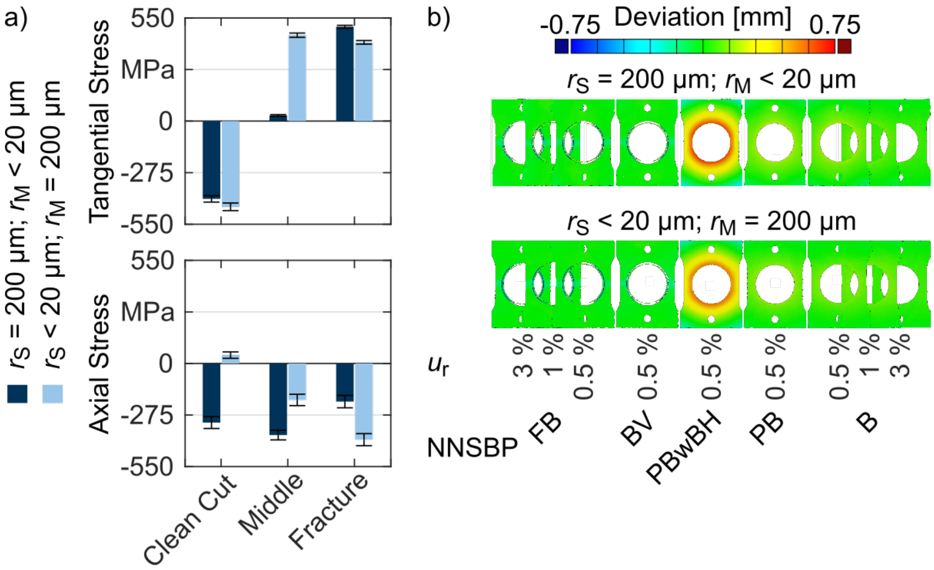

Fig. 3 Residual stresses in tangential and axial direction measured on three positions of specimen manufactured by Blanking (B) with a die clearance of 3 % with two different active element edge radii (a), and the surface deviation of the produced sheet metal strips together with the result published in [5] (b).

a sharp punch edge, the same tendency can be observed while the configuration with the rounded punch edge shows no clear trend.

To address the influence of a fracture zone on the residual stress state, additional measurements were carried out on the strips produced by B with a die clearance of 3 % for both active element edge preparations. The first measurement position is in the middle of the clean cut, the second in the middle of the sheet thickness, and the third in the fracture zone. The results are displayed in figure 3 a). It is visible that the fracture zone is subjected to significant tensile residual stresses. As the fracture zone reaches till the middle of the sheet thickness for the variant with the sharp punch, high tensile stresses are measured there as well.

3.3 Finite-element analysis

A comparison of the stresses in tangential direction after the cutting operation but before springback calculated with the FE-model is illustrated for FB in figure 4. It can be observed that the variant with the rounded punch edge leads to higher stresses in the sheet metal strip.

3.4 Fatigue behavior

The fatigue behavior of the parts is illustrated in figure 5. The fatigue tests are described in [5]. In figure 5 a), a decreased number of cycles to failure is observed

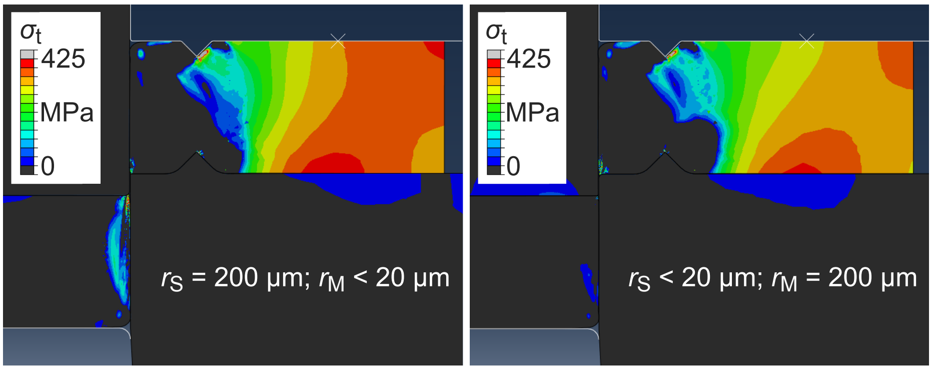

Fig. 4 Tangential stress after the fineblanking operation (but before springback) with a die clearance of 0.5 % for $r_S = 200\,\mu\text{m}$ and $r_M < 20\,\mu\text{m}$ on the left, and $r_S < 20\,\mu\text{m}$ and $r_M = 200\,\mu\text{m}$ on the right.

for all parts manufactured with $r_S < 20\,\mu\text{m}$ compared to those manufactured with $r_S = 200\,\mu\text{m}$. Only those manufactured by PBwBH stands out. The results in figure 5 b) show that a bigger die clearance causes a lower number of cycles to failure. To further identify the effect of the residual stress state, a comparison between parts manufactured by BV with subjected to a stress relief heat treatment after the blanking operation is given in figure 5 c). This heat treatment causes a significantly lower number of cycles to failure for the high test load.

3.5 Discussion of parameters influencing the residual stress state and effect on the fatigue strength

Influence of punch and die edge radius: A rounded punch leads to material flow towards sheet metal strip which leads to higher stresses in the strip in tangential direction, as shown by the FE-model. After springback, these result in higher compressive residual stresses. This is not strictly true for variants with a fracture zone as the earlier fracture changes the material flow behavior.

Also, this effect can not be observed for PBwBH. Due to the heavy bending of the part, the tangential stress is overlayed by an additional stress from the bending spring back. As the bending spring back is opposed to the parts initial bending direction, this leads to tensile stresses on the die-roll side of the sheet metal strip and to compressive stresses on the burr side. As the bending of the part manufactured with a sharp punch is lower compared to the part manufactured with the rounded punch, this effect is most likely responsible for the tensile tangential residual stresses of the PBwBH configuration with the rounded punch.

Axial compressive residual stresses are measured for all configurations in the middle of the sheet independent of the process parameters. As material is drawn in axial direction, which is necessary for the formation of a die roll, axial tensile stresses occur during blanking. After springback these lead to compressive residual stresses. For $u_r = 0.5\,\%$, the axial stresses are not very sensitive regarding the active element edge preparation for FB, PB and B. Only BV and PBwBH show different values for different edge preparations. For PBwBH this is most likely

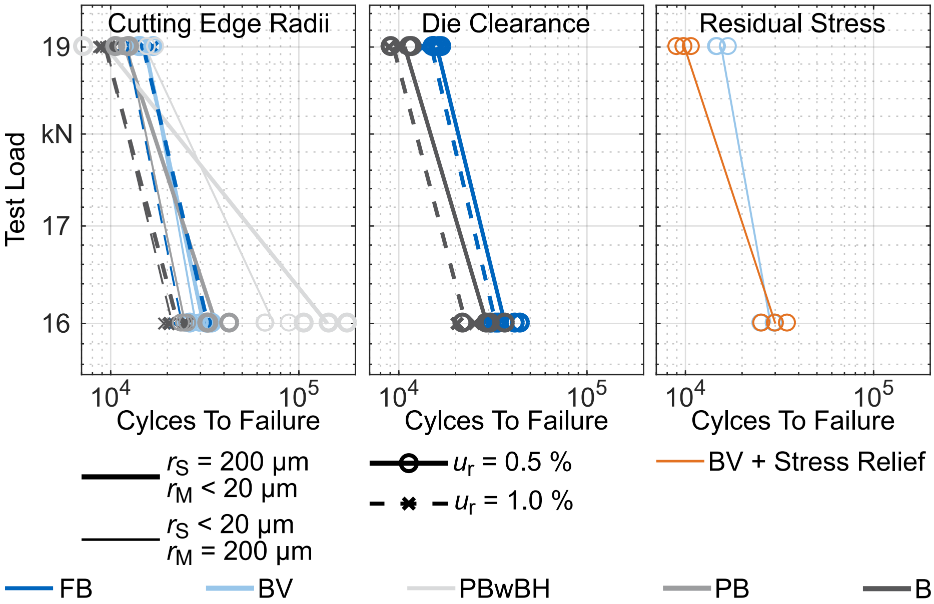

Fig. 5 Fatigue strength of parts manufactured by the five NNSBPs for the two different active element edge radii (r_S = 200 µm and r_M < 20 µm with thick line, r_S < 20 µm and r_M = 200 µm with thin line) on the left, for two different die clearances (u_r = 0.5 % with solid line, u_r = 1.0 % with dashed line) in the middle, and a comparison between parts with and without a stress relief heat treatment after the blanking operation (stress relief heat treated part in orange) on the right together with the data published in [5].

caused by the early fracture of the blank (see [6]) which reduces axial stresses and causes smaller residual stresses after springback. The same behavior may be responsible for the differences between the parts manufactured with a rounded punch and a sharp punch for the die clearances bigger 0.5 %.

For a die clearance of 0.5 %, the fatigue behavior shows the expected result: As the parts manufactured with a sharp die edge show smaller compressive residual stresses, these show a lower number of cycles to failure. The effect is also visible for the specimens subjected to a stress relief heat treatment after the blanking operation even though the overall stress state (mean from tangential and axial stress) is comparably low. Again, the parts manufactured by PBwBH stand out. Their behavior confirms the theory on the influence of the part bending on the fatigue behavior given in [5], which is the dominant mechanism in this case.

For u_r =1 % and 3 % the effect of residual stresses is overlayed by the additional notch caused by the fracture zone. It should be noted that for FB with u_r = 1 % the configuration with the round punch edge still shows higher number of cycles to failure than the one manufactured with a sharp punch edge although the fracture zone is bigger. This is caused by the significant higher residual stresses in both directions for the rounded punch edge.

Influence of the die clearance: For FB, when the die clearance is changed from 0.5 % to 1 %, higher compressive residual stresses are observed in tangential direction for both active element edge preparations. For B, this effect can only be observed for the configuration with the sharp punch edge while a opposing trend is observed for the rounded variant. Again, the stresses caused by the radial springback are overlayed by those caused by the bending springback. As the bending is small for the parts manufactured by FB, the radial springback mode dominates in this case. Therefore, the different effect of the parts manufactured by B, that show a visible bending and differences in bending regarding the die clearance and the active element edge preparation, seem to be responsible for this behavior. Due to the occurrence of a significant amount of fracture zone, the results for a die clearance of 3 % are challenging to interpret. Still, the results from FB with $u_r = 3\,\%$ show, that the fracture zone is subjected to significant tensile residual stresses in tangential direction.

Even for the bigger die clearances the axial residual stresses are negative in the middle of the sheet. For the variant with the sharp punch edge, the residual stresses get smaller when a bigger die clearance is chosen. However, the variant with the round punch edge does not strictly show that behavior. This is most likely caused by a different material flow behavior caused by the combination die clearance and active element edge condition in the middle of the sheet. Again, the results for $u_r = 3\,\%$ are challenging to interpret due to the big fracture zone.

The comparison between the parts manufactured with a die clearance of 0.5 % and 1 % show the effect of the residual stresses on the fatigue strength: While the difference is small for FB, the negative effect of the fracture zone can be partly compensated by the higher compressive stresses, the parts manufactured by B show a significantly lower number of cycles to failure for $u_r = 1\,\%$ as a fracture zone and a smaller compressive stress state reduce the fatigue strength.

4 Conclusion

A rounded punch edge in combination with a sharp die edge leads to higher compressive residual stresses in tangential direction compared to parts manufactured with a sharp punch edge and a rounded die edge. Due to the rounded punch, material flow is more likely towards the sheet metal strip, which leads to higher elastic stresses that cause higher residual stresses after springback. This is only valid for configurations without a fracture zone, i.e. for the small die clearance of 0.5 %, and without significant part bending, i.e. all processes except PBwBH. The influence of the active element edge radii on the residual stress state is small compared to the influence of the chosen NNSBP.

A fracture zone should be avoided as the rough fracture does not only lead to stress concentrations but also shows significant tensile residual stresses. These effects significantly reduce the parts fatigue strength. Therefore, a die clearance of 0.5 % should be chosen instead of a die clearance of 1 % or 3 %.

The results lead to the conclusion that the residual stress state of the manufactured parts can be explained by a bending springback, a radial springback and an axial springback. Furthermore, the residual stresses can be adjusted by the process parameters and may be used for an improved fatigue behavior. As the fatigue strength is caused by a combination of the material properties, the surface geometry and the residual stress state, all of these factors should be considered to achieve a long part life under cyclic loading.

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