The Influence of Residual Stresses Induced by Near-Net-Shape Blanking Processes on the Fatigue Behavior under Bending Loads

J. Stahl\textsuperscript{1}, D. Müller\textsuperscript{2}, I. Pätzold\textsuperscript{1}, R. Golle\textsuperscript{1}, T. Tobie\textsuperscript{2}, W. Volk\textsuperscript{1} and K. Stahl\textsuperscript{2}

\textsuperscript{1} Chair of Metal Forming and Casting (utg), Department of Mechanical Engineering, Technical University of Munich, Germany
\textsuperscript{2} Gear Research Center (FZG), Department of Mechanical Engineering, Technical University of Munich, Germany

E-mail: jens.stahl@utg.de

Abstract. Gears manufactured by blanking can be found in many different products like hammer drills or automobiles. Here, only the functional surface, the clean shear, can be used to transmit torque. Therefore, parts in serial production demand a high amount of clean shear, so the required torque can be transmitted with a minimal thickness and part weight. To achieve this, these parts are usually manufactured by fineblanking or related Near-Net-Shape Blanking processes (NNSBPs). Furthermore, the gears are subjected to cyclic loading which can, especially in the highly stressed tooth root, lead to tooth breakage. The effect of different process variants and process parameters on the residual stresses and the fatigue behavior under a pulsating bending load has not been investigated yet. Due to the potential of endurance improvement of blanked gears, this topic is addressed in this paper. To accomplish this, C-shaped profiles are manufactured by five different Near-Net-Shape blanking processes. The investigated processes are fineblanking, precision blanking with and without blank holder, and blanking with a small die clearance with and without a v-ring. The sheet metal material, S355MC (material number 1.0976) with a thickness of 6 mm, is first subjected to a stress relief heat treatment to minimize residual stresses induced by the specimen preparation and to ensure a defined initial residual stress state. After blanking, the residual stresses of the parts are measured. Finally, fatigue strength tests are carried out under a pulsating bending load on the C-shaped profiles with shear-cut edges. The results show that the residual stress state, as well as the part’s fatigue behavior are strongly influenced by the chosen blanking process.

1. Introduction

Near-Net-Shape Blanking processes (NNSBPs), as described in [1] or [2], are suitable processes for the manufacturing of parts with functional surfaces due to their high amount of clean shear on the cut surface. This makes them suitable for the manufacturing of gears.

In addition to the gear geometry, the residual stresses, the heat treatment and the surface roughness of the fillet influence the tooth bending strength. For most applications gears get heat treatment after the cutting respectively hobbing process to improve the strength and, therefore, ensure higher fatigue life at unchanging loading conditions. Commonly used heat treatments are case hardening, induction hardening or nitriding. All of these heat treatments

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

Published under licence by IOP Publishing Ltd
processes are applied to improve case properties such as the surface hardness and the residual stress state. Depending on the heat treatment and the additional manufacturing steps, e.g. shot peening and grinding, different hardness and residual stress profiles can be created in the gear teeth. Numerous experimental investigations show an up to 50 % higher fatigue endurance limit caused by residual stresses [3, 4]. In [5], an overview of the influence of residual stresses on different gear failures of case hardened gears such as pitting and tooth root bending is given. Stenico and Krug [6] show the positive effect of high compressive residual stress due to shot-peening or mechanical cleaning on tooth root bending strength. In [7], Höhn proposed a factor \( Y_{RS} \) to consider residual stresses in the calculation method in DIN 3990 [8] and ISO 6336 [9].

As gears are subjected to cyclic loading, the influence of different NNSBPs on the fatigue strength has to be considered in the part design. In [10], the fatigue behavior for edges, cut with a die clearance of 6 %, was investigated for different materials while in [11] the influence of different shear cutting strategies was examined. Both did not investigate NNSBPs, as visible in the comparably high amount of fracture on the cut edge. Nevertheless, it is stated that a high amount of clean shear leads to a higher fatigue strength [11]. In [12] it was found that defects on the shear cut edge are in most cases the limiting factor of the fatigue strength of blanked parts, while this effect is not so severe for mild steels. The beneficial effect of a compressive residual stress state on the fatigue behavior of blanked and coined parts was shown in [13].

The focus in this research work is to gain information about the influence of residual stresses in blanked gears on the load capacity. Tooth root bending fatigue is a typical failure in gears. The goal in the first step was to create a simple geometry as a model of a tooth root. A C-shaped profile with a shear cut edge on one side was chosen. After measuring properties which are known to affect the load bearing capacity, like the hardness [14], the roughness and the residual stress state, fatigue tests are carried out. Finally, an explanation is given for the different behavior.

2. Experimental setup and test equipment

2.1. Material and specimen geometry
S355MC (material number 1.0976 in [15], thickness 6 mm), a micro-alloyed finegrain structural steel common for shear-cut parts was used for the investigations. This steel was chosen because it can be subjected to a stress relief heat treatment to lower the initial residual stresses. At first, the specimen were laser-cut out of the sheet to a size of 100 × 140 mm. Afterwards, the outer contour was milled together with two positioning holes which are later used to ensure a defined position for the shear cutting process. As the milling and laser cutting causes a change in the residual stress state, the material was subjected to a stress relief heat treatment before shear cutting. The final specimen geometry is displayed in figure 1. Further information on the material, including the chemical composition and mechanical properties can be found in [14].
2.2. Shear cutting tool and process parameters
In this paper, five different NNSBPs, as illustrated in figure 2, are investigated. These are fineblanking (FB), precision blanking with blank holder (PB), precision blanking without blank holder (PBwBH), blanking with small die clearance and v-ring (BV), and blanking with small die clearance (B). As it is possible to change from one NNSBP to another by changing the die, the blank holder, or by removing the counter punch, all shear cutting experiments could be carried out in a single tool. Further information on the tool can be found in [14] and [1]. The v-ring geometry was designed according to [16]. Both dies used were manufactured with holes for the positioning pins. These pins were used to locate the specimen with the positioning holes. The die-clearance was 30 $\mu$m (0.5 % of sheet metal thickness) as proposed in [17] and [16]. According to Klocke, for cutting a hole a sharp die edge and a rounded punch should be used while rounding both active element edges should be avoided in order to reduce bending of the part [18]. As a bigger cutting edge radius increases the amount of clean shear but also causes undesired effects like increasing the necessary punch force, the radius should be chosen just big enough so that fracture can be avoided [18]. Therefore, a sharp die edge radius of $<10$ $\mu$m was chosen together with a punch edge radius of 200 $\mu$m. The latter is slightly smaller than the 250 $\mu$m radius used by Hörmann, with which he achieved a smooth cut surface for the same material [1]. Additionally, a cutting velocity of 50 mm s$^{-1}$, a blank holder force of 200 kN, a v-ring force of 450 kN, and a counter punch force 200 kN were set. These are the same process parameters as in [14] to ensure comparability.

2.3. Roughness testing
The roughness of the specimen was measured by a VHK-150 laser scanning confocal microscope manufactured by the company Keyence Corporation, Osaka (Japan). This microscope offers a high accuracy and makes it possible to measure a comparably big area. At least four specimen of each configuration were measured with eleven lines in tangential direction on each specimen.

2.4. Surface geometry measurement
To investigate the influence of bending on the fatigue results, the specimen surface was measured with the optical surface scanning device ATOS II 400 by the company GOM GmbH (Germany). To identify the height deviation, a plane was fitted to the rectangular part of the clamping surfaces. All measurements were carried out on the burr side of the specimen to avoid an error caused by the die roll. To be able to describe the surface for an analysis with the Finite Element Method (FEM), a cone was fitted to the whole part with the exception of the distinct imprint caused by the contact between sheet metal and die close to the cutting edge. All surface fittings were carried out in GOM Inspect V8 with a Gauss algorithm.
2.5. Residual stress analysis
The residual stress state was measured by X-ray diffraction. The description of the measurement can be found in [14]. The residual stress state was determined at the surface of the critical cross section and up to depths of circa 0.3 mm. Here, the specimen geometry without positioning holes as presented in [14] was chosen, which has the same critical cross-section as the specimen shown in figure 1. This allows to compare the results in this paper to earlier work.

2.6. Fatigue testing
The focus in this research work is to gain information about the influence of residual stresses in blanked gears. Tooth root breakage is a typical failure in gears. The calculation of the tooth bending strength is described in ISO 6336-3 [19]. The nominal stress numbers (bending) in the calculation are described in ISO 6336-5 [20]. The allowable nominal stress depends on the material, the quality of the material and the heat treatment. The nominal stress numbers are determined by testing reference gears with a pulsating test rig. The fatigue tests in this paper were carried out with a servo-hydraulic pulsating test rig (Instron 8872). The test rig consists of a load cell, a specially designed specimen holder and the C-shaped profile. To prevent the specimen from slipping the contact pressure was chosen accordingly to the load. Also contact pattern tests were carried out to assure slipping is prevented. The specimen was clamped offset in such way that the force application point increases bending stresses in the critical cross section. The fatigue strength was determined on two load stages of 19 kN and 16 kN in the limited lifetime. The test frequency was 50 Hz with tensile swelling loads in sine form where the load stage defines the upper load amplitude, the lower amplitude is chosen zero (\(\sigma_{sch} = 2\sigma_a, R = 0\)). This procedure corresponds to reference tests for the tooth root bending strength in ISO 6336-5 [20].

For each variant of the NNSBPs a reduced S-N curve in the limited lifetime was determined. The tests were performed at two load stages with at least three runs for each load stage. The low cycle fatigue was determined for 50 % failure probability. The \(k\)-factor is calculated with \(k = -\log(N_1/N_2)/\log(F_1/F_2)\) which relates the load to the number of cycles. For steel, \(k = 5\) is usually determined for notched specimen and \(k = 15\) for unnotched specimens [21].

3. Results
3.1. Fatigue behavior
The results of the pulsator tests for the limited lifetime are shown in figure 3 in addition with the slopes, defined by the \(k\)-factor. In this paper only the limited life range was investigated.

As displayed in figure 1, the crack is initiated at the surface of the critical plane and grows within a few load cycles to the middle of the depth. Afterwards, ductile fracture accompanied by a high degree of plastic deformation is observed. For the high load, FB parts show the best results, followed by those manufactured by BV, PB and PBwBH. A different behavior is observed for the low load. Here, the parts manufactured by PBwBH show the best results, followed by those made by FB, PB, BV and B. The lines are not parallel but can be divided in three groups. The processes with a v-ring (FB, BV) show a similar slope and those with a blank holder (PB, B) are almost parallel. Only PBwBH stands out.

3.2. Surface roughness
For FB, a surface roughness of \(Ra = 1.9 \pm 0.21\ \mu m\) was measured, \(Ra = 0.96 \pm 0.17\ \mu m\) for PB, \(Ra = 0.84 \pm 0.24\ \mu m\) for PBwBH, \(Ra = 1.4 \pm 0.21\ \mu m\) for BV, and \(Ra = 1.5 \pm 0.26\ \mu m\) for B. Here, \(Ra\) varies in a comparably small range between 0.84 and 1.9 \(\mu m\) where the FB show the highest roughness and the ones manufactured by PBwBH the smallest. Due to the opposing trend of the fatigue tests and the small range of the roughness difference, the roughness does not seem to be the characteristic responsible for the different fatigue behavior.
3.3. Residual stresses
The measured residual stresses in tangential and axial direction in the depth normal to the specimen surface is shown in figure 4. The residual stress profile of B is shown in [14]. Close to the surface, all processes show compressive residual stresses in axial direction which change to tensile stresses between 0.07 mm (BV) and 0.14 mm PB. Only for PBwBH this change is not observed. The tangential residual stresses are negative on the surface and change to a tensile stress state between 0.03 mm (BV) and 0.08 mm PB. Again, PBwBH shows a different behavior, where the cut surface shows a tangential tensile stress state. The residual stress state is able to explain the different results between FB and BV on the one side, and PB and B on the other side. In both cases, the surface geometry, the hardness and the roughness are comparable, while higher compressive residual stresses lead to a higher number of cycles to failure. Still, the residual stress state alone is not able to compare the three different groups to each other regarding their lifetime.
3.4. Specimen bending

Usually, a blank holder is used to prevent bending of the sheet metal strip. To identify the influence of the usage of a blank holder or a v-ring on this, the height deviation from a plane is presented in figure 5. It can be observed that the part produced by PBwBH shows a significant deviation, i.e. it is heavily bend. PB and B show a lower bending which is only visible close to the cutting line. The parts produced with a v-ring are almost flat, with the exception of the imprint caused by the v-ring. This corresponds well with the fatigue behavior of the parts.

3.5. Finite Element Simulations

In the fatigue testing machine, the specimen have to be gripped by two clamping jaws in order to subject the specimen to the test load. If the specimen is bend, this means the jaws bend it straight again. To identify the effect of this gripping on the stress field, a FEM model was built in Abaqus Explicit 2018. Only the load induced by the clamping without the pulsator load was investigated. As the deviation from the plane is the highest for the specimen manufactured by PBwBH, this process was chosen exemplary. The geometry was identified by fitting a cone to the sheet metal as described above. The result is displayed in figure 6. The biggest error of this fit is close to the inner edge where the die causes a distinct imprint on the sheet metal. This error was reduced by modelling the geometry of the cut-surface with lines and a radius as illustrated in figure 6.

While the sheet metal was modelled as an elastically deformable body (C3D8R elements, typical Young’s modulus and Poisson’s ratio as published [14]), the clamping jaws were modelled...
Figure 7. The resulting von Mises stress (left), the stress in x-direction (middle), and regions subjected to hydrostatic pressure or tension (right) calculated by the FEM model.

as rigid bodies. To reduce the computation time, the symmetry of the setup was used. This lower clamp is fixed in space, only the rotation of the center of the jaw around the y-axis was allowed. The upper clamp is able to move along the y-direction and is also able to rotate around the y-axis. This clamp is loaded with a force of 190 kN, the force induced by the screws in the real clamping jaw. The coefficient of friction was chosen to be 0.3, a comparably high value which represents the rough surface of the clamp. Due to the assumptions, this model should be regarded as a qualitative approach for identification of the influence of the jaws. The result of the calculation is displayed in figure 7.

While the notch root shows a comparably high von Mises stress, this stress is overlaid by compressive hydrostatic stresses. It is also visible, that the stress in x-direction, the tangential direction in the notch root, opposes the tensile residual stress state of the cut surface and the stress applied by the fatigue testing machine, which acts in positive x-direction. This results in the excellent fatigue behavior of the parts manufactured by PBwBH. However, tensile stresses are induced on the upper side of the specimen. Additionally, the parts show a big die-roll height, the smallest clean shear height and the cut surface angle furthest from $90^\circ$ (see [14] for the cut surface characteristics). This seems to be responsible for the small number of cycles to failure for the higher testing force. Furthermore, this indicates that the bending of the specimen is responsible for the different slopes of the lines in figure 3. FB and BV show a similar bending and similar slopes, as well as PB and B. From here, the residual stresses close to the surface have to be considered. The specimen manufactured by BV show a lower number of cycles to failure compared to FB. Also, the residual stress in tangential direction is significantly lower while a similar stress in axial direction was measured. The same effect can be observed when comparing the residual stress state for PB with the residual stresses for B published in [14].

4. Conclusion
In this paper, the fatigue strength of specimen manufactured by five different Near-Net-Shape Blanking processes has been investigated. It was observed, that for a high testing force, the fineblanked parts show the highest cycles to failure, followed by blanking with small die clearance and v-ring, precision blanking, blanking with small die clearance, and precision blanking without blank holder. For the low testing force, precision blanking without blank holder showed the best results, followed by fineblanking, precision blanking, blanking with small die clearance and v-ring, and blanking with small die clearance. Furthermore, the slope of the connecting lines show similarities between fineblanking and blanking with small die clearance and v-ring as well as between precision blanking and blanking with small die clearance. Precision blanking without blank holder stood out with a completely different slope. This effect corresponds well with the bending of the specimen. By carrying out FEM simulations, it was shown that the clamping jaws of the fatigue testing machine induce compressive stresses which are responsible for the different slopes. By measuring the depth distribution of the residual stresses, the different cycles to failure
for the parts with a similar bending could be explained. As expected, compressive residual stresses close to the surface lead to a higher fatigue strength. That the residual stresses are responsible for the different cycles to failure was confirmed by comparing the results to those published in [14], where almost similar cut surface characteristics and hardness distributions were measured for the parts manufactured by the different NNSBPs.

Acknowledgments
This work is funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) - VO 1487/30-1; STA 1198/13-1, and is part of the DFG-priority program SPP2013.

References
[1] Hörmann F 2008 Einfluss der Prozessparameter auf einstufige Scherschneidverfahren zum Ausschneiden mit endkonturnaher Form Dissertation Technische Universität München
[2] Manopulo N 2011 An ALE based FE formulation for the 3D simulation of the fineblanking process Ph.D. thesis ETH Zurich
[3] Hirsch T 1983 FVA 15 II: Kugelstrahlen. Untersuchungen zur Zahnfußfestigkeit kugelgestrahelter Zahnräder
[4] Benedetti M, Fontanari V, Höhn B R, Oster P and Tobie T 2002 International Journal of Fatigue vol 24 chap Influence of shot peening on bending tooth fatigue limit of case hardened gears, pp 1127–1136
[5] Güntner C, Tobie T and Stahl K 2017 AGMA 2017 Fall Technical Meeting (Columbus, Ohio, USA) chap Influences of the residual stress condition on the load carrying capacity of case hardened gears, pp 328–344
[6] Stenico A and Krug T 2004 Eigenspannungen Zahnfuß FVA-Nr. 369/I+II - Heft 145: Eigenspannungseinfluss auf die Zahnfußtragfähigkeit kleinmoduliger Zahnräder
[7] Höhn B R, Tobie T, Stenico A and Lombardo S 2009 The Proceedings of the JSME international conference on motion and power transmissions vol 2009 chap Influence of Residual Stresses on Tooth Root Bending Strength of Case Hardened Gears, pp 333–337
[8] DIN 3990 1987 Calculation of load capacity of cylindrical gears
[9] ISO 6336 2006 Calculation of load capacity of spur and helical gears.
[10] Meurling F, Melander A, Linder J and Larsson M 2001 Scandinavian Journal of Metallurgy vol 30 chap The influence of mechanical and laser cutting on the fatigue strengths of carbon and stainless steel sheets, pp 309–319 URL https://onlinelibrary.wiley.com/doi/abs/10.1034/j.1600-0692.2001.300506.x
[11] Paetzold I, Dittmann F, Feistle M, Golle R, Haefele P, Hoffmann H and Volk W 2017 Journal of Physics: Conference Series vol 896 chap Influence of shear cutting parameters on the fatigue behavior of a dual-phase steel, p 012107 URL http://stacks.iop.org/1742-6596/896/i=1/a=012107
[12] Lara A, Picas I and Casellas D 2013 Journal of Materials Processing Technology vol 213 chap Effect of the cutting process on the fatigue behaviour of press hardened and high strength dual phase steels, pp 1908 – 1919 URL http://www.sciencedirect.com/science/article/pii/S0924013613001519
[13] Yasutomi T, Yonemura S, Yoshida T, Mizumura M and Hiwatashi S 2017 Journal of Physics: Conference Series vol 896 (IOP Publishing) chap Blanking Method with Aid of Scrap to Reduce Tensile Residual Stress on Sheared Edge, p 012098 URL https://iopscience.iop.org/article/10.1088/1742-6596/896/1/012098
[14] Stahl J, Müller D, Tobie T, Golle R, Volk W and Stahl K 2018 Production Engineering chap Stress in parts manufactured by near-net-shape-blanking URL https://doi.org/10.1007/s11740-018-0865-5
[15] DIN EN 10149-2 1995 Hot rolled flat products made of high yield strength steels for cold forming
[16] VDI 3345 1980 Fine blanking
[17] Schmidt R, Hellmann M, Burkhard R, Rademacher P, Höfel P, Birzer F and Hoffmann H 2007 Cold forming and Fineblanking 2nd ed (München Wien: Carl Hanser Verlag) ISBN 978-3-446413504
[18] Klocke F 2013 Sheet Metal Separation (Berlin, Heidelberg: Springer Berlin Heidelberg) pp 407–456 ISBN 978-3-642-36772-4 URL https://doi.org/10.1007/978-3-642-36772-4_5
[19] ISO 6336-3 2006 Calculation of load capacity of spur and helical gears: Calculation of tooth bending strength
[20] ISO 6336-5 2003 Calculation of load capacity of spur and helical gears: Strength and quality of materials
[21] Einbock S 2018 Statistics of Metal Fatigue in Engineering: Planning and Analysis of Metal Fatigue Tests (Books on Demand) ISBN 97837352889016