



Comparative study of v-ring indenter configurations in fineblanking in order to derive tool design guidelines

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Abstract

The v-ring indenters and their configurations play a major role in the fineblanking process, directly influencing component quality and characteristics. While past studies regarding residual stresses of blanked components focused mainly on the use of a pair of v-rings, so far no efforts were undertaken to compare different v-ring setups, deducing tool design guidelines and enabling possible cost savings. Therefore, a comparative study of different v-ring indenter setups and their influence on cut surface parameters, surface hardness and induced residual stresses of the produced components was performed. The obtained results indicate a minor influence of blank holder-sided v-rings on the observed component characteristics in comparison to indenters situated on the die leading to recommendations with regard to cost-efficient tool design.

Keywords Fineblanking · Surface hardness · Near-net-shape blanking · Residual stresses

1 Introduction

Shear cutting is a process for the chipless cutting of metallic materials. The process is characterised primarily by its cost-effectiveness for large quantities [1]. As with many separation processes, the formation of the cut surface is an important criterion for the quality of the process in shear cutting [2]. Currently, however, the shear affected zone is increasingly being investigated as an additional quality criterion, since it has a significant influence on the component properties and performance [3]. The factors influencing how the shear affected zone ultimately develops range from the choice of different process parameters to the microstructure of the material at hand [4]. For near-net-shape blanking processes, the final residual stress state in the shear affected

zone is of particular importance, since components manufactured in this way are frequently subject to time-varying loads during operation.

2 State of the art

Fineblanking is one of the near-net-shape blanking processes and, if set up correctly, allows production of components with almost completely clean cut surfaces. Due to the high dimensional accuracy of fineblanked parts and the smoothness of the cut surface, such components can be used directly without the necessity of additional rework processes [5].

The product range for fineblanked parts includes functional and safety components for the automotive, electrical, textile, household appliance and medical industries [6]. A typical application is also the production of gears [7]. As the technology of fineblanking mainly focuses on closed cutting lines, this process is primarily used for blanking and piercing. Fineblanking is characterised by a very small die clearance, which is the horizontal circumferential distance between die and punch u_{rel} , a special preparation of the cutting edges, a v-ring on the blank holder and, if necessary, a v-ring on the die as well as a counter punch, see Fig. 1.

Said v-rings are indenters penetrating and displacing the affected parts of the sheet metal before the actual cutting

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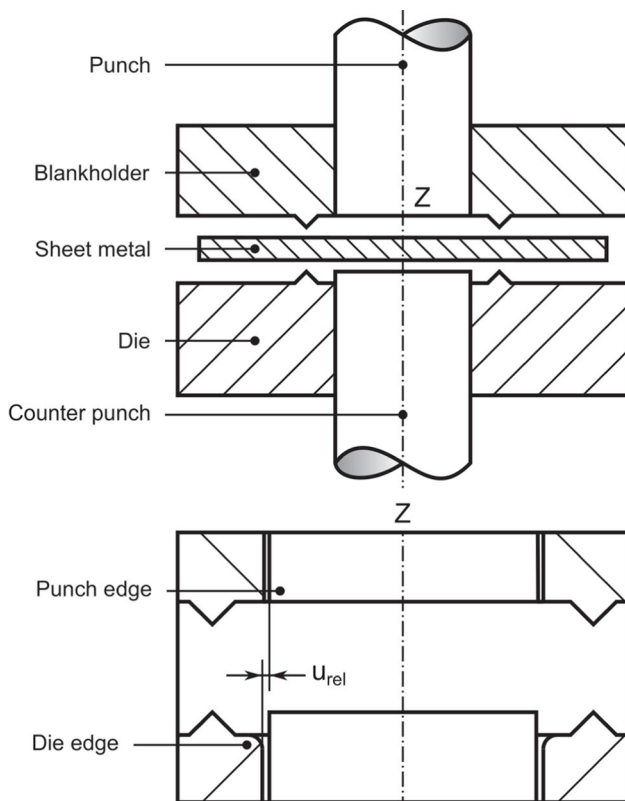


Fig. 1 Schematic of fineblanking (top) and detail (below)

process, influencing the stress state in the material and leading to higher quality cut surfaces, specifically a higher clean cut percentage. Another essential feature of fineblanking is that, during the process, the v-ring force, the punch force and the counter punch force act independently of each other [8].

Special fineblanking presses are usually used for fineblanking, whereby the ram generally moves from the bottom to the top. After the punch contacts the sheet metal, the material is first elastically deformed and then blanked. Tearing occurs, but without the decaying oscillation phase characteristic for conventional shear cutting processes [9]. After the cutting process is completed, the blank holder acts as a stripper, removing the metal strip from the punch [10].

The achievable clean cut percentage is strongly dependent on the selected die clearance. In order to produce high clean cut percentages, a smaller die clearance is recommended [11].

The fact that a reduction of the cutting clearance results in a higher clean cut percentage was also confirmed by Spisak et al. [12]. Sahli et al. were also able to confirm, both simultaneously and by experimental investigations, that a reduction in the die clearance leads to an increase in the clean cut percentage [13]. In general a die clearance of 0.5% of the sheets thickness is a basic guideline value, whereby adaptations are to be made depending on the geometry [14]. When

manufacturing components by fineblanking, the die cutting edge is rounded, whereas the cutting edge of the punch remains sharp. In comparison to piercing, where the punch is rounded and the die remains in the sharp-edged state. A combination of a rounded punch cutting edge and a rounded die cutting edge is not recommended to avoid bending as much as possible and to favour pure shearing. The geometry of the die cutting edge can also be done by chamfering, wherein a larger angle with a constant chamfer width leads to a higher die roll on the blanked part [15]. According to, e.g., Thipprakmas et al., the use of a v-ring leads to compressive stresses in the material before and during the cutting process. In addition, the prevention of rotational material flow during blanking causes an increase of the hydrostatic stress state in the shear zone, preventing tearing as well as ensuring higher clean cut percentages [16].

The design guidelines for v-rings in the literature mostly provide for a v-shaped circumferential geometry for the v-ring, whereby for most cases with a sheet thickness up to 4.5 mm a single v-ring on the blank holder is used, with an addition of a second v-ring on the blank holder for sheets with a thickness greater or equal than 4.6 mm [17].

In contrast to the continuous geometry of the conventional v-ring, Mao et al. propose a discontinuous v-ring embodied by individual indenters produced by buildup welding using an electric-spark process. The discontinuous dot indenter achieves comparable stress distributions and material deflections as the conventional v-ring shape. Through an optimisation process, the authors were even able to achieve better results with respect to the clean cut [18].

The distance of the v-ring to the cutting line also influences the die roll, which thus changes the size of the clean cut or the functional area as investigated by Kim [19]. However, the proportion of a completely clean cut surface also depends on the cutting line geometry or component geometry, shown by Fuchiwaki [20]. Although the counter punch plays a minor role with regard to the quality of the cut surface, it has significant influence on the components deflection [21]. In addition to described advantages with regard to the geometry of the components, i.e. high dimensional accuracy and cut surface quality, the fineblanking process influences the microstructure in the shear zone, whereby the respective grains are highly compressed and stretched. The occurring near-surface hardening provides components with special characteristics such as increased wear resistance [22].

The investigation of the residual stresses induced by fineblanking is an active field of study. Cesnik et. al. reported that the burr side of the component near the surface exhibits compressive residual stresses and the die roll side exhibits tensile stresses [23]. Mori et al. showed that conventional cutting of an ultra-high-strength steel (SCM435) with a relative die clearance of 6% produces very high tensile residual

stresses on the cut surfaces. In contrast, very low tensile residual stresses can be expected on conventional steels such as structural steels or high-strength steels [24].

Stahl et al. performed, among others, residual stress measurements on the fineblanked surface of circular cut-outs. The results of the measurements showed compressive residual stresses in both axial and tangential directions [25]. Residual stresses in the sheet thickness direction, which can be influenced by die cutting edge radius, were demonstrated in the tooth root fillet on fineblanked involute gears. Furthermore, high tangential stresses could also be measured in the area of the 30° tangent to the tooth root fillet and at the tooth flank [26].

In addition, the residual stresses of fineblanked gears could be used to generate higher fatigue strengths with respect to the tooth root bending strength [27]. Investigations done by Stahl on blanked disks showed that a sharp-edged cutting punch and a rounded die cause higher compressive residual stresses in the tangential direction on the fineblanked surface than an inverted cutting edge preparation of punch and die. Further tests showed that the use of a v-ring on the die and blank holder leads to increased compressive residual stresses in the tangential direction measured on the cut surface. The axial residual stresses, on the other hand, are reduced only to a small extent. The influence of the blank holder in combination with a v-ring on the measured residual stress state is substantial and significantly increases the compressive residual stresses in the tangential and axial directions [28]. In this context it is important to stress that the calculated influencing of the quality characteristics and to this extent the functional characteristics, e.g. tooth root breakage capacity, provide enormous opportunities. As the produced components already possess the necessary qualities, following production and refinishing steps may be reduced in extent or even completely economised.

3 Problem formulation and solution approach

As outlined in the previous section fineblanking and investigations of different process parameters are active research subjects. Of particular interest are component related studies in the field of gear manufacturing. This is due to the different advantages of fineblanked components, e.g. high dimensional accuracy and surface hardness as well as the induction of compressive residual stresses, which have a positive effect on critical properties like wear resistance and tooth root bending strength.

The aim of the present work is to provide a comparative study of different v-ring indenter setups with special regard to near-surface hardness and induced residual stresses, advancing the general understanding of the production process and enabling the deduction of statements regarding

tool design. Therefore specific quality characteristics of the produced specimens, i.e. cut surface characteristics, surface hardness and residual stresses, were measured and examined. In the following the observed values were investigated with regard to the qualitative and quantitative influence of different v-ring setups.

4 Experimental setup and test equipment

4.1 Material

The steel grade S355MC (material number 1.0976) according to DIN EN 10149-2 and a sheet thickness of 6 mm was used as the test material, with the surface of the material free of mill scale [29]. The delivered sheets were separated by laser cutting into squares with dimensions of 100 mm × 100 mm. Subsequently, the heat-affected zone was removed by milling, resulting in a final dimension of the blanks of 88 mm × 88 mm. Thereupon, the specimens were stress relieved in order to achieve the lowest possible initial stress state. In accordance with DIN EN 10149-1, care was taken not to exceed the temperature of 580°C, above which a reduction in the strength values occurs [30]. After the stress relieve was completed, the specimens were cleaned.

4.2 Shear cutting tool and process parameters

A triple-acting Feintool ‘HFA 3200 plus’ fineblanking press, with a total pressing force of up to 3200 kN, was used for the cutting tests with different v-ring configurations. The tool body allows the active elements to be replaced. All tests were carried out with the following identical press parameters. The cutting speed was 50 mm / s, the blank holder force and the counter punch force were calculated according to [31] to 450 kN and 200 kN, respectively. For the investigations, circular disks with a nominal diameter of 60 mm were chosen as the specimen, therefore the circular punch geometry was set to 59.94 mm to achieve a relative die clearance of 0.5%. For the design of the v-rings, the recommendations of [17] were used, as illustrated in Fig. 2.

The cutting edges of the punch, remained in the sharp-edged state ($r_s < 40\mu\text{m}$), whereas a radius of $200\mu\text{m}$ was applied to the die-side cutting edge. In order to be able to investigate the influence of the use of v-ring in fineblanking, the active elements shown in Table 1 were manufactured for the different fineblanking tests. As can be seen, a total of four different configurations were used for the studies. The code FB represents a conventional tool setup, with v-rings in both blank holder and die and acts as a baseline for following comparisons. The configuration FB_{OVR} denotes a tool setup without any indenters, while FB_{VRBH} and FB_{VRD} are configurations with the v-ring on either the blank holder or the die, respectively.

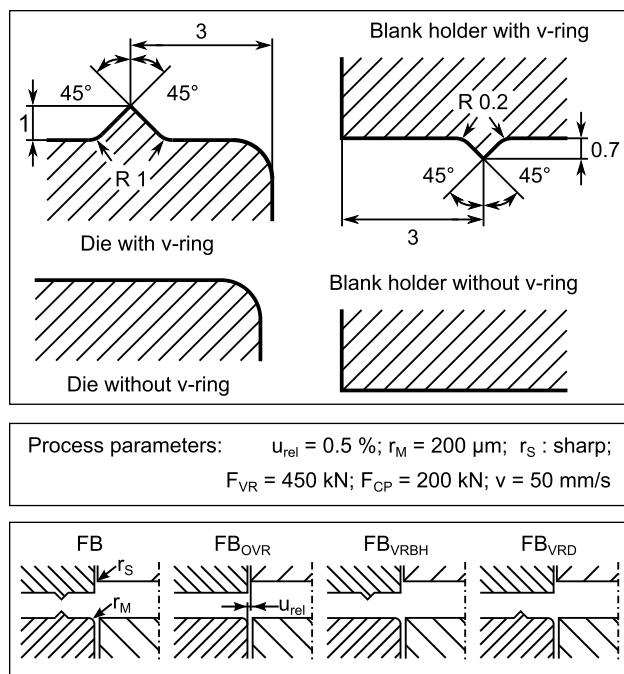


Fig. 2 V-ring geometries and process parameters

Table 1 Overview of test configurations

Active element	FB	FB _{OVR}	FB _{VRBH}	FB _{VRD}
Punch	✓	✓	✓	✓
Blank holder with v-ring	✓		✓	
Blank holder without v-ring		✓		✓
Die with v-ring	✓			✓
Die without v-ring		✓	✓	
Counter punch	✓	✓	✓	✓

4.3 Measurement equipment

4.3.1 Tactile surface measurement

The characterisation of the cut surface of the manufactured parts was carried out on a MarSurf XC20 profile measuring station, which achieves a resolution of less than $0.5\mu\text{m}$ with a probe arm length of 350 mm. Before the linear scanning of the surface, a zenith search was performed to ensure the perpendicularity of the measuring section to the component surface. Four measurements were carried out for each of the three specimens ($n = 12$) per single v-ring configuration investigated.

4.3.2 Hardness testing

A Vickers hardness test, within the small load range (HV 0.2), and in accordance with DIN EN ISO 6507-1 was set up

[32]. The surface hardness measurements of the specimens were carried out on an AMH-43 microhardness tester from LECO Instrumente GmbH, whereby a nominal test load of 1.961 N was applied. All testing was done on surfaces in radial direction of the original specimen, with special care taken to ensure the perpendicularity of the measurement plane with respect to the outer contour of the cut component, as illustrated in Fig. 3. The necessary cutting of the specimens was carried out with very low feed rates and sufficient cooling, in order to prevent excessive heating, and was followed by a polishing of the to be measured surfaces.

A second Vickers hardness test with a test load larger than 49.03 N (HV 5) was performed on an INNOVATEST NEXUS 8100. The hardness measurements were performed on the x-ray diffractometer specimen in axial direction as illustrated in Fig. 4, in order to assess the influence of the residual stresses on the hardness tests. The preparation of the respective specimens is detailed in the following subsection.

4.3.3 X-ray diffractometer

The tangential and axial surface residual stresses were measured with a Seifert XRD 3003 PTS System with $\text{Cr-K}\alpha$ radiation. The 1-mm collimator has 10-mm distance between collimator and specimen surface. The residual stresses were evaluated with the $\sin^2\psi$ -method. In order to be able to measure the specimens on the cut surface, they were cut due to limited space of the diffractometer. A 10-mm-high part was cut off for the measurement as shown in Fig. 4. The cutting was performed with a cutting disk with sufficient cooling, therefore influences of the heat on the residual stresses can be ruled out.

5 Results

5.1 Cut surface characteristics

The cut surface parameters, i.e. die roll and clean cut, are given in relation to the sheets thickness, while absolute values are used for the burr height. The results shown are mean

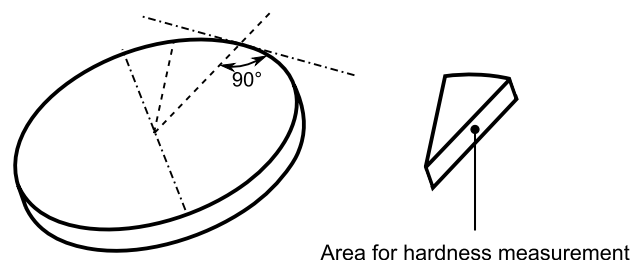


Fig. 3 Schematic illustration of hardness specimens

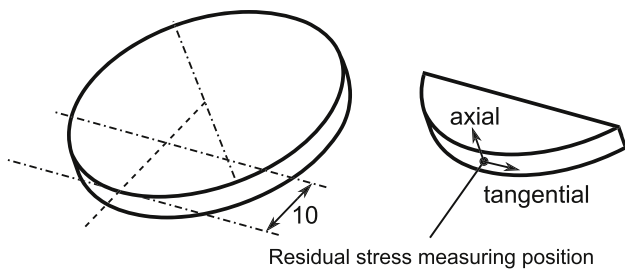


Fig. 4 Schematic illustration of x-ray diffractometer specimens

values from four measurements for each of the three specimens per indenter configuration as depicted in Fig. 5.

In the comparison of the four configurations, a maximum clean cut of 94.2% and a minimum die roll of 5.8% is achieved. It can be seen that the components manufactured without the aid of a v-ring, 'FB_{OVR}', have the highest die roll and consequently also the lowest clean cut percentage. Compared to that, the parts cut with only one v-ring, 'FB_{VRBH}', on the blank holder show a slightly reduced die roll and a slightly increased clean cut percentage. The cut surface characteristics of the parts produced using two v-rings 'FB', with only 5.9% edge indentation and 94.1% clean cut percentage, are comparable to the specimens with only one v-ring on the die 'FB_{VRD}', whereby the observable difference has to be interpreted as a measurement inaccuracy. The achieved angle of the clean cut of the different v-ring configurations is the same with the exception of the 'FB_{VRBH}' variant, where a very small deviation of 0.1% can be observed. The measured burr heights range between 28μm and 53μm and show in general very small values. The results obtained show the highest clean cut percentage and the lowest edge indentation for the conventional 'FB' process and the 'FB_{VRD}' setup and the lowest clean cut percentage and the highest edge indentation for the 'FB_{OVR}' variant. This fact is in agreement with the simulated results from [16], but it necessary to mention that the experimentally produced specimens do not show any tears in contrast to the simulated geometries from [16]. Otherwise the results show no clear indication of significant influence of the indenter setup on the shear angle. With regard to the measured burr heights, the magnitudes are small, within a similar scope across the different configurations. Here it is important to note that since process-related the sheet metal components may fall on the burr and consequently alter the height, therefore influencing later measurements.

5.2 Hardness

The results of the hardness measurements are plotted across the sheets thickness, with the different coloured graphs denoting different distances to the cut surface. Two general trends are observable, as can be seen in Fig. 6, as in

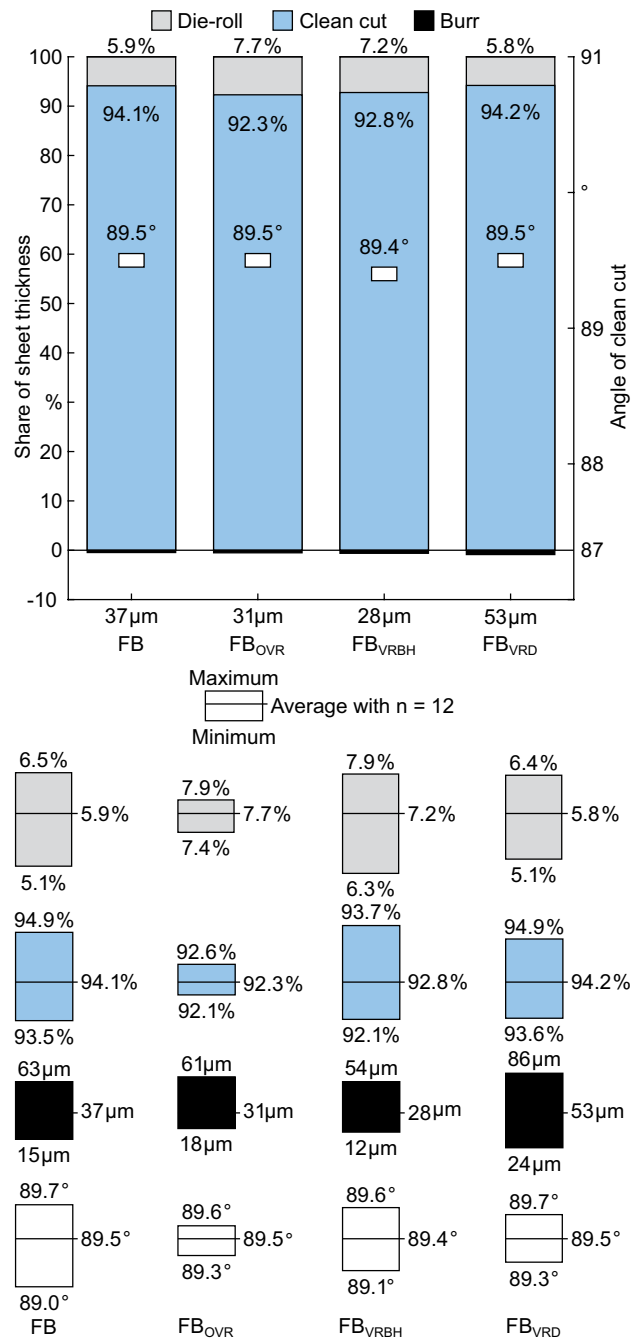


Fig. 5 Cut surface parameters

y-direction, across the sheets thickness, the hardness values steadily increase from the die roll side until they reach a maximum near the burr side, forming a sort of lens shape. The total hardness in negative x-direction, i.e. radial material depth, decreases, whereby a bisection of the maximum value from edge to centre of the specimen is observable. The behaviour in y-direction is due to the fact that the highest plastic deformation and grain distortions occur at the burr respectively burr side. Whereas the hardness progression in

x-direction is due to the near-surface influence of the fine-blanking process.

The hardness curves generated by fineblanking for the considered v-ring configurations differ only at individual locations, which can be attributed to possible measurement inaccuracies. In this context it is important to note that the measurements closest to the surface, at $x = -0.125$ mm, a noticeable decrease in hardness for the 'FB' and 'FB_{OVR}' setups is observable in the edge zone around $y = -5.5$ mm. It is difficult to attribute any significance to this phenomenon, as said measurements lie within the edge zone of the specimen, whereby different effects, e.g. carbides, voids or the support of the surrounding material, may influence values.

A clear trend with regard to the influence of the use of v-rings on the hardness distribution cannot be observed. Accordingly, it is shown that the use of a v-ring, conventional or single indenter setup, does not result in any advantages in terms of higher or more favourable total hardening or hardness distribution compared with fineblanking without v-rings. Figure 7 shows the polished specimens with indentation marks after the HV0.2 hardness measurements for the four different fineblanking configurations.

It is important to note that additional tests were undertaken to assess the correlation of the obtained hardness results and the induced residual stresses, which may be influenced by the specimen preparation, including the specimen geometry. Vickers hardness measurements were carried out on the X-ray diffractometer specimens, specifically the same

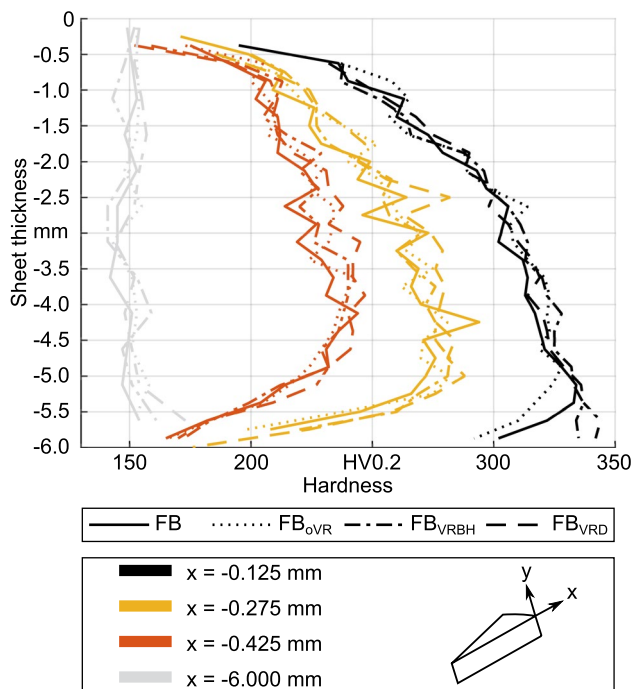


Fig. 6 Surface hardness measurements

positions as used for residual stress measurements, i.e. on the cut surface as shown in Fig. 4. Said measurements reveal no influence on the hardness values with a mean value of 363 HV5, a maximum value of 364 HV5 for the conventional setup, FB, and a minimum value of 339 HV5 recorded for the configuration without any v-ring indenters, 'FB_{OVR}'. These figures lie within a similar range of values and single outliers may be attributed to the measuring process itself, as described before.

5.3 Residual stresses

The residual stresses, shown in Fig. 8, in the axial direction are plotted in dark blue, the residual stresses in the tangential direction in light blue. The lowest axial compressive, in tangential direction even tensile, stresses were observed for the setup without v-rings, 'FB_{OVR}'. The 'FB_{VRBH}' configuration produces, compared to the previous configuration, both larger axial and tangential compressive stresses. The results obtained for the conventional configuration 'FB' and the single indenter setup 'FB_{VRD}' show the highest compressive stresses, with respect

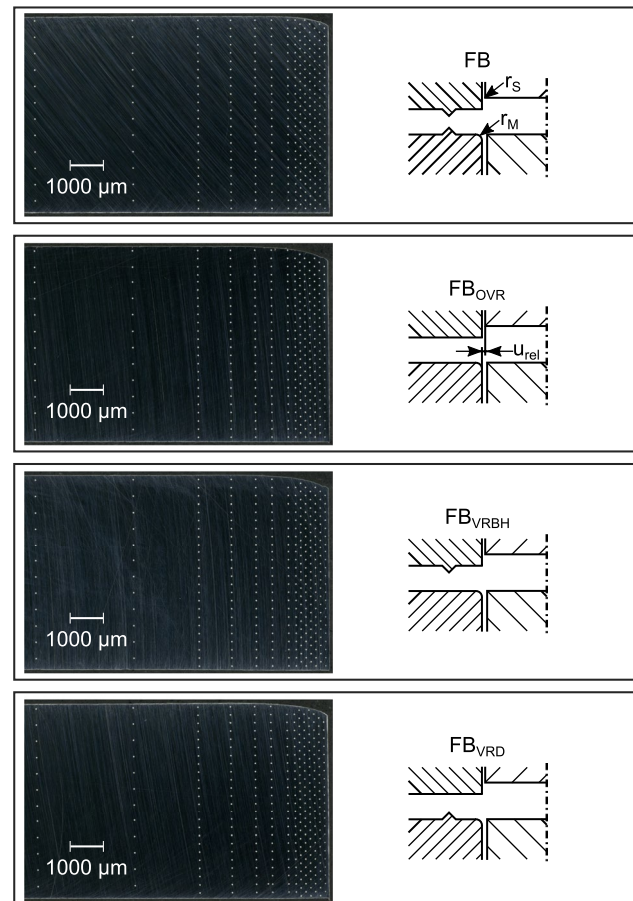


Fig. 7 Polished specimens of the four different fineblanking configurations with indentation marks after the hardness measurements

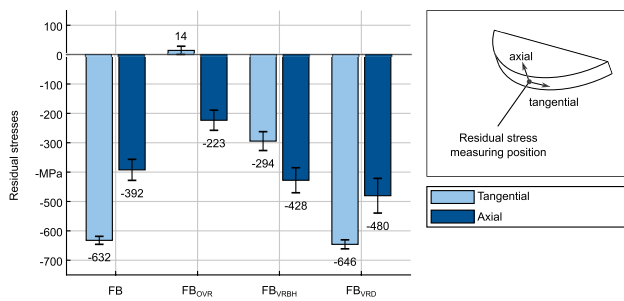


Fig. 8 Residual stresses of specimens

to both absolute values and the relation of axial and tangential compressive stresses, wherein the deviations of both configurations are small. The results show a strong influence of the v-ring on the tangential residual stresses, as indicated by the difference from the configuration ‘FB_{OVR}’ compared to ones with v-rings. It is also evident from the comparison of the single indenter setups ‘FB_{VRBH}’ and ‘FB_{VRD}’ that a v-ring situated on the die causes significantly higher compressive residual stresses in the tangential direction and moderately increased compressive residual stresses in the axial direction, than a blank holder-sided indenter. This difference between the single indenter configurations ‘FB_{VRBH}’ and ‘FB_{VRD}’ is mostly related to the difference in geometry of both v-rings, whereby the larger, die-sided v-ring is more effective, as indicated by the results. Another factor may also be attributed to the fact that in the case of the v-ring situated on the die, the punch exerts the punch force in a manner that assists with better indentation of the material. In contrast to this, the indentation direction in the case of the blank holder including the v-ring lies in the direction of the cutting force and indentation is not assisted. The most interesting observation is the fact that the use of two v-rings, i.e. configuration ‘FB’, does not achieve any further increase in the residual compressive stresses. Compared to the values obtained with the single die-sided indenter setup ‘FB_{VRD}’, the results are very similar, which reflects the decisive role of the v-ring situated on the die.

In general the results are in good accordance with previous works, e.g. the work of Thipprakmas [16], whereby the use of v-rings counteracts a rotation of the material flow, resulting in increased hydrostatic compressive stresses during blanking. Referencing Stahl [28], higher tangential compressive stresses during the cutting process result in a higher compressive residual stress state in the tangential direction after springback has occurred in the blanked component. The measurements obtained show that a v-ring on the die is sufficient to produce an equivalent residual compressive stress state compared with that using an additional v-ring on the blank holder. It is theorised that under certain circumstances, an enlarged v-ring on the blank holder further increases the residual compressive stress, but also requiring the v-ring to be pressed in deeper, which may be limited by the v-ring force generated by the fineblanking press.

Furthermore, a suitable cross-sectional area of the v-ring on the die namely a variation, which is larger and possibly more obtuse, could be conducive to higher possible residual compressive stresses in the finished cutout. Further investigations are necessary to confirm these hypotheses.

6 Conclusion

In this study the effects of different v-ring configurations on certain component characteristics, specifically the cut surface parameters, surface hardness and residual stresses, were investigated. Therefore a total of four indenter configurations were prepared, with a double v-ring setup on both blank holder and die representing the conventional approach, two assemblies with single v-rings situated on either blank holder or die and a process without v-rings. The produced specimens were prepared and measured in accordance with common test standards. The surface hardness values indicate no particular influence of the v-ring on either the absolute values or the shape of the hardness distribution across the sheets thickness. Additional examinations also showed no particular influence of the residual stresses on the hardness values.

The comparison of the measured surface parameters shows similar results, with marginal differences of die roll, clean cut percentage and shear angle, wherein the configuration without v-ring indenters exhibits the smallest clean shear values.

In the case of the residual stresses, obtained through x-ray diffractometry, major differences in the both quality and quantity of the measurements were identified. The conventional two-indenter setup does not provide any significant benefits in comparison to the die-sided v-ring. In the case of the v-ring situated on the blank holder marginally lower values of compressive residual stresses were obtained, largely due to the smaller geometry of the indenter, and therefore the lower effectiveness. As before the configuration without any v-ring produced the most deviating results, in the case of the measured residual stresses even tensile residual stress in tangential direction of the specimen. The principal conclusion that can be drawn from the obtained results is that a single indenter situated in the die produces nearly same results as the conventional double v-ring setup in both die and blank holder. Based on this observation, a possible reduction of production costs due to lower tool manufacturing expenses is possible, whereby results may change depending on the specific component. Said cost reductions are reflected in the saving of material, necessary for the indenters as well as production costs. The laborious machining steps, including the hardening and machining of said hardened v-ring, can be omitted for the v-ring situated on the blank holder. The elimination of unnecessary tool elements, in this case the blank holder-sided v-ring, also helps with the simplification of the design process in the case of specific problems, reducing the number of to be considered parameters. It must be noted, of course, that this statement regarding

cost savings is valid with regard to the initial tooling, as in terms of a complete assessment of the financial benefits of each setup, maintenance costs also have to be considered.

Author contribution All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Anian Nürnberger, Daniel Müller and Lukas Martinitz. The first draft of the manuscript was written by Anian Nürnberger and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability Not applicable

Code availability Not applicable

Declarations

Ethics approval Not applicable

Consent to participate Not applicable

Conflict of interest The authors declare no competing interests.

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