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Mechanism of fracture in sheet metal cutting processes and its effect on sheared edge stretchability

S F Golovashchenko^{1*}, N Wang¹, S Nasherlahkami¹, N A Reinberg¹, W Zhou¹

¹ Oakland University, 115 Library Drive, Rochester, MI 48309, USA

*golovash@oakland.edu

Abstract. In recent years, implementation of aluminum alloys, the advanced high strength steels and ultra high strength steels (UHSS) is quickly increasing in automotive industry. However, these materials are often sensitive to sheared edge cracking if stretching along the sheared edge occurs in such processes as drawing of panels with blanked windows, stretch flanging and stretch hemming of edges of the panel. This study is dedicated to development of experimental techniques necessary to account for sheared edge condition on material formability as well as reporting the experimental results and general trends. Analysis of the hole punching process indicated that uniformity of the cutting clearance is rather difficult to maintain, especially for UHSS material where cutting forces are substantially higher than for mild steels or aluminum alloys, and stiffness of the tool starts playing critical role. Therefore, the majority of experimental studies were performed as tensile tests of samples sheared along a straight line in a dedicated trim tool where special measures were taken to achieve consistency of the die clearance. Experimental results on sheared edge stretchability of aluminum alloys similar to 6111-T4 and UHSS steel DP980 are reported. The mechanism of fracture propagation in trimming and hole punching processes is discussed in conjunction with sheared edge stretchability. The rather unique mechanism of fracture observed for trimming of UHSS DP980 steel leads to burr breaking at the final stage of the shearing process.

Keywords: Trimming, Punching, Fracture, Sheared Edge Stretchability

1. Introduction

Advanced and ultra-high strength steels (AHSS and UHSS) as well as aluminum alloys (AA) offer impressive combinations of strength and ductility that can reduce the mass and improve the crash-worthiness of sheet-formed automotive parts [1]. The process of stamping parts from sheet metal frequently includes blanking, punching, and trimming operations. A substantial number of research efforts have been dedicated to the analysis of these operations. The common knowledge today is that the clearance between the cutting edges should be maintained at approximately 10% of the sheet metal thickness t , and the cutting edges themselves should be kept sharp. The typical sheared edge on sheet metal has four basic features termed rollover, burnish, fracture, and burr [2].

It should be indicated that for large automotive panels satisfying, optimum cutting condition is often problematic if not impossible due to high cost of accurate alignment of the cutting edges along the perimeter of the trimmed part which can be several meters long. Initially knife-sharp cutting edges usually become duller during the life of the die due to tool wear which requires periodic sharpening of the cutting edges. For AHSS and UHSS steels, wear of cutting edges becomes more critical due to



substantially higher overall strength of the material being sheared and also due to the presence of very hard martensitic particles. In order to avoid slivering problems in trimming of aluminum alloys, the moving cutting edges often belonging to the upper tool are dulled to the radius of approximately 0.1mm as recommended in [3]. Tool wear and dulling of the cutting edges both potentially lead to reduced formability of the sheared edge resulting in splits originating from the sheared edges if the sheared edge undergoes some stretching.

It was already observed in stamping practice of mild steels [2] that loss of formability of the blanks stretched along the sheared edge is associated with the growth of the burr on the sheared edge often reported as a percentage of the thickness of the sheet. For AA6111-T4, which loss of formability was reported by Le *et al.* [4] with increase of the cutting clearance as well as a function of the cutting angle and sheet metal prestrain in forming operations preceding sheet metal trimming. Some loss of formability was observed at even 10% of thickness cutting clearances. AHSS and UHSS are usually less sensitive to the cutting clearance. As reported in [5,6], DP500 and DP600 steel are usually rather forgiving to variation of cutting clearance up 20% of thickness. More recently Nasheralahkami *et al.* [7] studied the effect of clearance and tool wear on generation of burrs.

One of the current issues in stamping of light weight panels is designing the cutting process and shearing tools in a way that material formability is still available for further stretching operations after the sheet metal was sheared, blanked, punched or trimmed. From broadly used concepts of material damage during plastic deformation, it can be assumed that if more damage to the metal is done during shearing, then less formability is available for further forming operations. The amount of damage done to the blank in the shearing process can be measured by the distribution of microhardness in the cross-sections perpendicular to the cutting line. Such studies were performed by numerous researchers: a typical distribution of microhardness for blanking of 5mm thick mild steel was provided by Lange [8] for 1% and 10% cutting clearances. No major difference was observed at maximum hardness level between these two cases. The area of plastic deformation was propagated inside the sheared blank for 0.3-0.58 of sheet metal thickness. The maximum increase in hardness compared to the hardness of the as-received material was approximately a factor of 2.0-2.2. Assuming that the microhardness variation is linear, as described by Pavlina and VanTyne [9], the maximum work hardening can be estimated as the ratio of the flow stress in the deformed zone to the yield stress of the sheet.

No major difference was observed for these two conditions in shear resistance calculated as a ratio of maximum cutting force and area of sheared cross-section: the shear resistance was slightly higher for a smaller clearance. A small difference in shear resistance for a variety of clearances was also observed by multiple other researchers for a variety of other materials. In general, it indicates that the average level of plastic deformation in sheet metal along the sheared surface is approximately the same assuming that the area of the sheared surface does not change significantly.

Johnson and Slater [10] also used similar methodology comparing microhardness distribution in blanked 9.5mm thick plate samples for sharp and dull shearing edges of the blanking die. The maximum hardness observed in both cases was similar. However, the depth of plastic deformation for the dull tool was larger. Hilditch and Hodgson [11] performed microhardness measurement for AA6111 and mild steel for different levels of tool penetration for 5% cutting clearance. It was observed that the overall trends of hardness was similar for both materials. The hardness of central line between the cutting edges was increasing with the growth of penetration of the cutting edges into the blank.

A number of analytical models of the cutting processes were developed based upon the simplifying assumption that the shear strain is constant within the cutting clearance and equal to the ratio of penetration and cutting clearance. A review of these models is discussed by Klingenberg and Singh [12]. The major assumption was that the strains can be estimated based upon the shear angle which could be

estimated as a ratio of the burnish zone and the cutting clearance. The displacement of the points of the blank was considered vertical. This model confirms that the strains increase with increasing of the cutting edges penetration. However, if one imagines that the cutting clearance is reduced factor of 10 (as described by Lange [8]), the strain level should increase factor of ten and be reflected in the material work hardening. Experimental studies of the shear strains based upon microstructural observations was performed by Wu *et al* [13] for variety of steels.

Material flow characterization in shearing processes using square grids was performed by Swift [14] for a variety of materials using shearing bars of rectangular cross-section for various cutting clearances. Using gridding technology, Golovashchenko [15] analyzed the strain distribution in AA6111-T4 plate sheared with 2% and 10% clearances. Based upon grid analysis as well as by reviewing the hardness distribution, it could be indicated that plastic deformations propagate substantially outside the cutting clearance. However, the increase of measured strains with increased penetration of the cutting edges can be interpreted as an increase of sheared surface damage with the increase of burnished area of the sheared edge.

In this study, the emphasis will be made on the mechanism of sheet metal fracture during trimming and its effect on sheared edge stretchability. Since the trimming process more often is followed by sheared edge stretching in stretch flanging and stretch hemming, compared to blanking and hole punching, the major emphasis in this paper is made on sheared edge stretchability after trimming.

2. Mechanism of fracture

The schematic of the trimming process is illustrated in Figure 1a. Unlike in blanking or hole punching processes (illustrated in Figure 1b), in trimming, the scrap can freely rotate driven by the upper shearing edge of the die. An ideal separation mechanism described in a number of early publications on shearing and blanking reviewed in [10] as well as in more recent reference literature [16] is in propagation of two cracks moving from steady and moving cutting edges of the die. If both cracks meet, a fairly smooth sheared surface is formed from the sharp cutting edges indenting into the blank. This mechanism is possible for blanking operations when the sheared portion of metal has a closed perimeter for cutting with rather small clearance and when no bending of the sheared material takes place. As was indicated by Golovashchenko in [17], such a cutting mechanism is possible for automotive sheet if the clearance is about 2%. Such cutting conditions are unrealistic for large automotive panels because of the risk of damaging the die if the clearance becomes negative. In the automotive industry, bending of scrap is often the factor which shifts fracture from the “classic two-crack meet each other” mechanism to a mechanism of single crack propagation from the moving cutting edge of the tool.

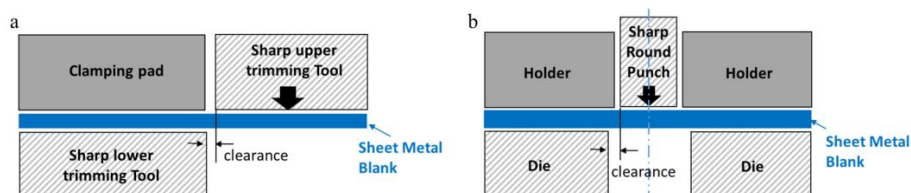


Figure 1. (a) Trimming process; (b) punching process of round hole.

In this study, the mechanism of fracture during trimming was analyzed by using a partial trimming process where the stroke of the press was interrupted before the final separation of the scrap and part sides. Typically, the smallest acceptable cutting clearance in trimming operation can be 5%. The development of fracture in aluminum sheet belonging to 6111-T4 family is illustrated in Figure 2a where the process was stopped before the major crack propagated from the upper cutting edge to the lower. Looking at the cross-sections of the part side (Figure 2b) and scrap side (Figure 2c) after trimming was

completed and analyzing the distortions of grain structure, it is quite obvious that majority of heavily deformed metal stays on the scrap side.

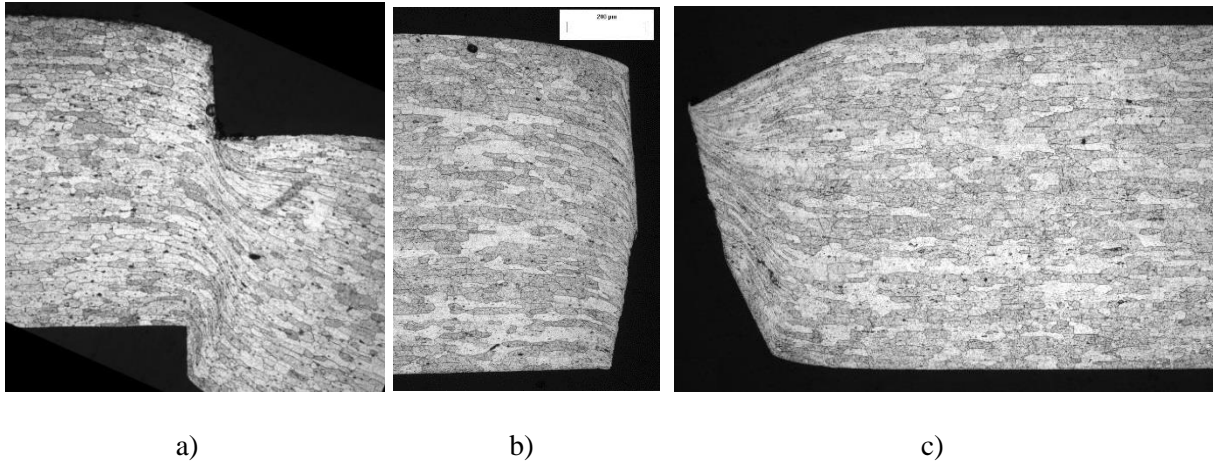


Figure 2. Cross-sections of 1mm thick aluminum sample (a) during trimming process with 5% cutting clearance; b) part side and c) scrap side after the trimming process was completed.

This asymmetric behavior is the result of bending down of the scrap during trimming process. Reviewing the grain structure of the partially sheared sample in Figure 2a, it could be observed that the shear angle γ varies substantially along the height of the sample. Fairly deep indentation of the upper cutting edge of the trim die into the blank at the moment of separation (Figure 2b) of approximately 48% of the thickness leads to large strain of the sheared edge. Reducing the indentation to 30%, as shown in Figure 2a leads to visibly smaller strains. From this perspective, increasing the height of burnish zone is the factor contributing to the overall increase of the strain on the sheared edge. However, the trajectory of the crack is also highly critical: if the crack would propagate vertically, heavily deformed material adjacent to the lower shearing edge would be retained on the part side.

Experimental results on trimming the sample with 20% cutting clearance from the same material is illustrated in Figure 3. In this case, fracture propagates almost vertically from the upper cutting edge to the free surface at the bottom of the sample rather than to the area of indentation of the lower cutting edge. It should be noted that fracture does not propagate instantly. At the end of the separation process the burr has additional stretching until it fractures. Even though material undergoes rather substantial plastic deformation in the area of upper cutting edge indentation, the deformation process at this stage occurs with rather substantial contact pressure applied to the tool. The area of the tip of the burr undergoes plastic deformation on the free surface of the blank. Towards the end of the separation process, it is deformed as in a plane strain tensile test. Therefore, the material has very substantial damage at the tip of the burr.

The results of sheared edge stretchability study measured by the tensile test of the sheared strip according to the methodology described by Le *et al.* [4] are illustrated in Figure 4. Formation of the burr on the sheared edge leads to a substantial drop in sheared edge stretchability.

Illustrated cross-sections of aluminum samples are very convenient for study of the areas of plastic deformation and evolution of strains during the trimming process due to fairly large size of grains which are typically an order of magnitude larger than steel grains. Very similar trends occur in steels. For example Smith [2] illustrated the drastic loss in sheared edge formability as a function of the burr height for mild steel. Since mild steels are very formable, stretching of the tip of the burr at the final stage of the process is very likely the reason for this phenomenon. Similar trend was observed by the authors for DP500 and DP600 steels as well as for three aluminum alloys. Two major mechanisms of fracture are observed during sheared edge stretchability study: a) for trimming conditions resulting in no-burr on the sheared edge, fracture initiates in the form of multiple cross-hatched lines throughout the fracture surface

of the sheared edge (Figure 5a) and b) for trimming conditions leading to formation of burrs, the typical fracture mechanism is through multiple crack initiation from the tip of the burr (Figure 5b) which was subjected to substantial stretching in plane strain conditions.

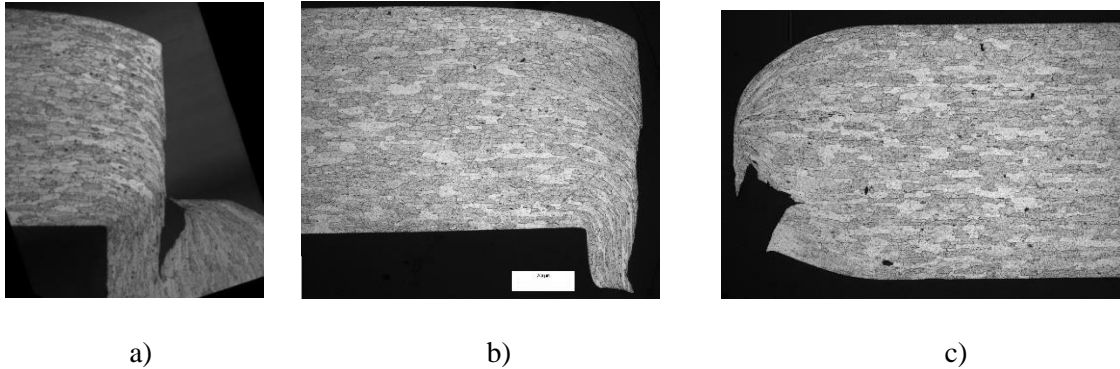


Figure 3. Cross-sections of 1mm thick aluminum sample (a) during trimming process with 20% cutting clearance; b) part side and c) scrap side after the trimming process was completed.

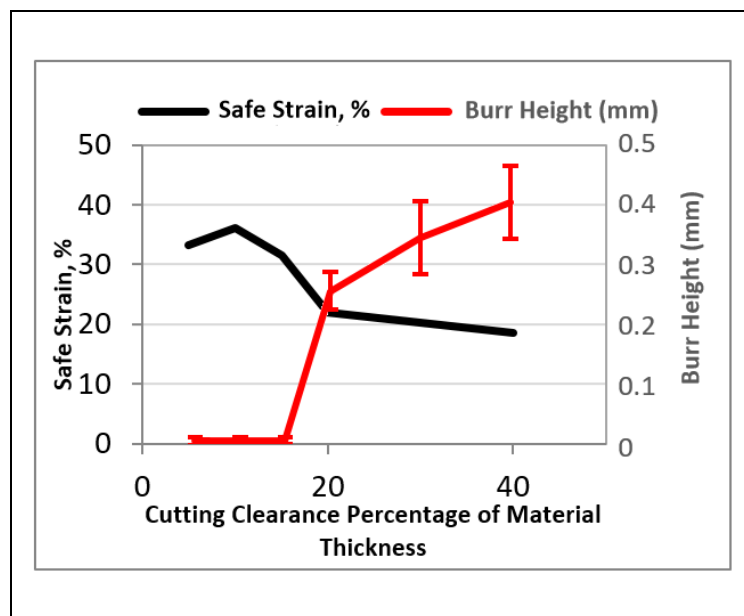


Figure 4. Results of 6111-T4 sheared edge stretchability study and burr height of the sheared edge for various cutting clearances.

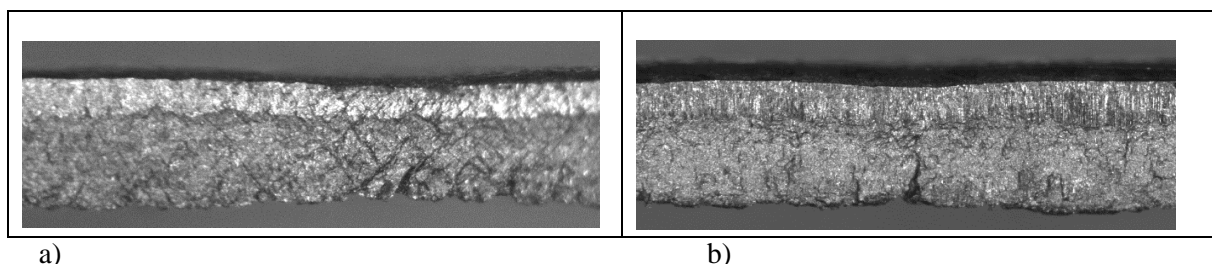


Figure 5. Mechanisms of fracture observed during stretching of sheared edge in tensile testing of trimmed strips: a) for cutting conditions with no burr; b) for cutting conditions with substantial burr.

The role of the burrs in initiation of fracture during stretching was further analyzed in order to clarify what feature of the burr plays the most substantial role in fracture initiation. On one hand, the burrs have rather substantial deformation due to material extrusion into the cutting clearance followed by additional stretching during the final separation stage. On the other hand, burrs have variable heights and cross-sections; therefore, areas with smaller cross-section might create concentration of stresses during a tensile test. In order to distinguish between these two mechanisms, aluminum sheared strips were subjected to heat treatment, as described in detail by Wang and Golovashchenko [18], which removed the effect of cold work, but left the geometry of the burr with variable cross-section in place. The results of the tensile testing of as-sheared compared to sheared and heat treated samples provided substantial increase in elongation of the sample up to the failure mode of necking which clarified that cold work is the most important reason why fracture originates on the tip of the burr.

Analysis of mechanisms of fracture of the sheared edge was also performed for Ultra High Strength Steel (UHSS) DP980. In general, this steel showed less tendency to form burrs. For small cutting clearances, the fracture mechanism during trimming was very similar to the mechanism observed for the aluminum samples in Figure 2. However, as rather unusual mechanism of separation was observed for large cutting clearances. It should be admitted that cutting forces as well as loads applied to the cutting edges are much larger for UHSS than for aluminum and mild steel and tend to open the cutting clearance. Therefore, special measures should be undertaken to prevent cutting tools from deflecting.

The unusual mechanism of fracture during trimming observed for 40% cutting clearance for DP980 steel sheet 1.4mm thick is shown in Figure 6b. The overall mechanism of blank deformation before initiation of fracture (Figure 6a) was very similar to the mechanisms observed for aluminum, mild steel, DP500 and DP600 steels. However, instead of propagating vertically from the upper shearing edge to the free surface at the bottom of the blank, the crack turned near the lower surface of the deformed blank and resulted in separation mechanism, leaving the burr on the scrap side. In general, this mechanism of fracture is more favorable from a sheared edge stretchability: it removes the area of the blank which was subjected to large plastic deformation and forms a cavity at the bottom of the sheared surface.

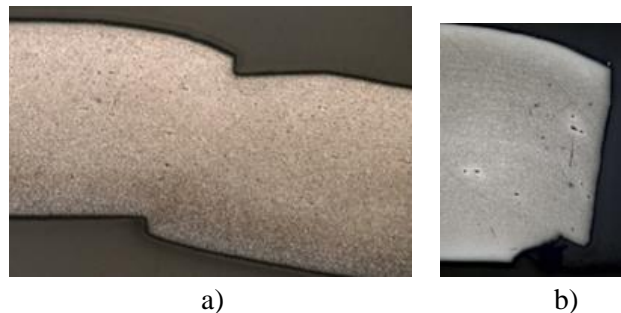


Figure 6. Cross-sections of samples of DP980 1.4mm thick sheet after trimming with 40% cutting clearance: a) partial shearing right before initiation of fracture; b) part side of the sheared edge.

Even though the burr is broken off on the sheared edge, the failure mode of the sample during stretching is very similar to the case illustrated in Figure 5b: the crack initiates from the area at the bottom of the sheared edge where typically the burr would be. Capturing the exact mechanism of crack propagation has not been possible yet. It should be noted that the crack propagates very quickly, and capturing fracture propagation is rather difficult.

Even though in many publications, hole expansion is considered to be the major sheared edge stretchability test due to its acceptance in International standard [19], analysis of mechanism of fracture of DP980 sheet in punching 10 mm in diameter hole has revealed a totally different mechanism of burr formation compared to trimming operation, opposite to the trends previously observed for variety of steels in [4] and for dual phase steels by Golovashchenko and Ilinich [5] for trimming of dual phase

steels and for punching of similar materials in Sriram *et al.* [20]. In previous studies, trimming processes showed much more tendency to form burrs due to the scrap rotation rather than punching process of small diameter hole where the slug is very stiff against bending. It should be indicated that for punching of DP980, the burrs were observed even for 5% average radial cutting clearance. Emphasizing the average clearance is important because in punching processes the tendency for non-uniform clearances is much more pronounced than for trimming. The diagram in Figure 7a illustrates the map of burr height along the perimeter of the punched hole. The height of the burr zone was also rather non-uniform which is very likely due to rather substantial differences in actual cutting clearance even though the experimental tool was built on a die shoe with four guiding columns. During the hole expansion process using the conical die illustrated in Figure 7b, the fracture of sheared edge was rather non-uniform. There was some correlation between the location of burrs and the location of initial cracks on North and East sides of the sample illustrated in Figure 7c. It should be admitted that for such rather small clearances, the crack initiation occurred from the burr side. However, the geometric specifics of the hole expansion test might also play a certain role: the circumferential strain of the burr side of the sample during hole expansion is visibly larger than for the burr side of the sample, since the burr side is required to be at the top based upon International Standard [19].

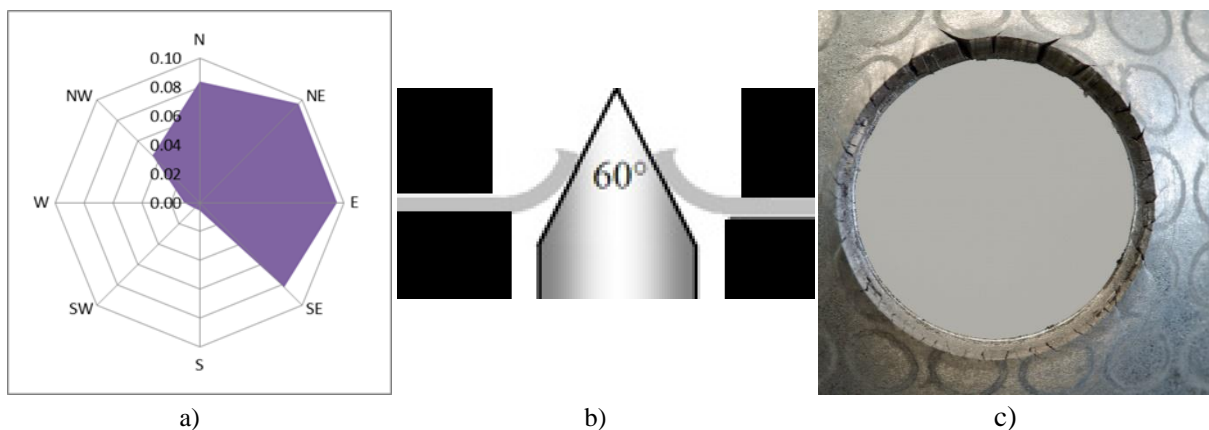


Figure 7. Results of punching and hole expansion of the punched hole: a) distribution of the burr height for punching of 10mm diameter hole with average clearance of 5% shown in mm; b) schematic of the hole expansion process; c) sample of DP980 steel after hole expansion: cracks initiate from the burr side.

The tendency to form the burrs in punching is also continued for a broad range of cutting clearances. Therefore, considering the hole expansion process as a test for trimmed edge stretchability may lead to rather substantial inaccuracies. Overall the major outcome of this study is an understanding that it is necessary to have a good correlation between testing and production conditions in order to make predictions regarding edge stretchability in production conditions.

3. Conclusions

- The current experimental study has revealed that the mechanism of shearing and possible burr formation plays very important role for sheared edge stretchability;
- Cutting clearance is certainly not the only parameter which is critical for sheared edge condition;
- Shearing of higher strength dual phase materials may have rather different fracture behaviour, as it was illustrated for DP980. For these materials the absence of burrs does not guarantee good edge stretchability.

Acknowledgments

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