Effect of material structure on trimming and sheared edge stretchability of 6xxx aluminum alloys

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Abstract. Wide variety of 6xxx Aluminum alloys is currently being used for manufacturing of lightweight automotive components. Very often each car manufacturer gets its own variation of the 6xxx alloy. Majority of these alloys have very similar yield and tensile strength as well as the stress-strain curve. Therefore, selection of the best alloy for each technical application might be challenging. In this paper, a comparison of performance of three 6xxx alloys in trimming process and sheared edge stretchability for wide variety of cutting clearances is being studied. This performance is compared with postnecking behavior of the same sheets in a standard tensile test. The ability of material to form visible diffuse neck and the cutting tool indentation prior to initiation of fracture shows some correlation for three studied 6xxx Aluminum alloys. The material with more pronounced diffuse neck shows a stronger tendency to form burrs at larger cutting clearances. However, other parameters of the standard tensile, such as yield stress, tensile strength, uniform elongation and even total elongation of these three alloys are very similar. Sheared edge stretchability measured via tensile testing of sheared samples showed that the materials with larger diffuse necking in the tensile test have higher sensitivity of edge stretchability to the cutting clearance. For large cutting clearances, the crack usually propagates almost vertically and leads to a burr formation. It appeared that the grain aspect ratio also influences the trajectory of the crack: for the materials with substantially elongated grains, the crack typically propagates more vertically. For the materials with nearly equiaxial grains, the cracks show stronger tendency to turn towards the lower cutting edge. The reason for such a behaviour is in crack propagation via grain boundaries. The experimental study of nanohardness measured at grains and grain boundaries for one of the studied alloys indicated that the grain boundaries have about 30% lower nanohardness than the material inside the grains.

1. Introduction
The trend towards lightweight automobiles accelerated by recent fuel economy regulations has prompted the automotive industry to increase usage of lightweight materials, such as Advanced and Ultra High Strength Steels (AHSS and UHSS), composites and aluminum alloys. The low density coupled with high mechanical strength gives aluminum alloys a high potential for automotive applications, particularly for exterior body panels, as discussed by Davies in [1]. While the transition from low carbon/HSLA steels to aluminum provides desirable benefits, it may present difficulties in manufacturing processes originally developed for low carbon steels.

Since trimming and hole punching are necessary operations to the manufacturing of almost every sheet metal part, the quality of the sheared surface originating from these shearing processes according to Zhou et al. [2] are among high priority concerns for AHSS as well as for aluminum alloys, as
indicated by Stanton et al. [3]. These concerns include a) early fracture in subsequent operations, where stretching is applied along the sheared surface and b) burrs, which commonly affect exterior panel assembly in hemming operation.

In traditional shearing processes described by Smith [4] as well as in numerous research publications and reference literature, reducing burr formation requires an accurate alignment of the upper and lower shearing edges to within 10% of the material thickness or less. Reference literature often provides very accurate recommendations developed in laboratory environment where cutting parameters are very well controlled. However, in production environment, the clearance between the shearing edges might substantially exceed the existing recommendations due to insufficient stiffness of the trim die and some inaccurate alignment between the upper and lower tools. This issue was very well exemplified by Zhou [5] for trimming of AHSS. The deflection of the punch was also quantified by Senn and Liewald [6] for punching with a slant angle.

The objective of this study is to discuss the effects of cutting parameters on mechanism of sheared edge formation and sheared edge stretchability of three Aluminum alloys commonly used in automotive production and provide recommendations how to select the most suitable alloy for stamping of sheet metal components.

2. Studied aluminum alloys

Three 6xxx aluminum alloys which have similar properties and chemical composition to broadly used 6111-T4 alloy were selected for this experimental study in order to demonstrate the effect of material structure and some difference in chemical composition on sheared edge stretching performance. It should be admitted that each of well-known alloys such as 6111-T4, 6022-T4, 6016-T4, etc. are produced in multiple modifications specifically for each individual customer. These materials also vary from one coil manufacturer to another. The sheets from Alloys 1 and 2 were 0.9mm thick while Alloy 3 sheet was 1mm thick. Comparing chemical composition of selected alloys provided in table 1, it could be indicated that Alloy 1 has visibly higher amount of Cu than Alloy 2 while Alloy 3 has order of magnitude lower amount of copper. Mechanical properties of all three alloys are listed in table 2. The cross-sections of tensile test samples of all three alloys are shown in figure 3.

| Table 1. Chemical composition of studied Aluminum Alloys. |
|-------------------------------------------------------------|
| Chemical Composition, % Weight                             |
| Si  Fe  Cu  Mn  Mg  Cr  Ni  Zn  Ti                        |
| Alloy 1  0.63  0.25  0.72  0.19  0.74  0.02  0.01  0.01  0.04 |
| Alloy 2  0.77  0.22  0.52  0.15  0.58  0.01  0.01  0.04  0.05 |
| Alloy 3  0.80  0.14  0.06  0.08  0.61  0.03  -  0.01  0.03 |

| Table 2. Mechanical properties of Aluminum Alloys. |
|---------------------------------------------------|
| Yield Stress, MPa | Tensile Strength, MPa | Total Elongation, % |
|--------------------|------------------------|---------------------|
| Longitudinal:      |                        |                     |
| Alloy 1             | 142.5                  | 283.4               | 24.8                |
| Alloy 2             | 135.2                  | 263.2               | 24.9                |
| Alloy 3             | 140.4                  | 255.2               | 26.1                |
| Transverse:         |                        |                     |
| Alloy 1             | 141.9                  | 282.2               | 26.6                |
| Alloy 2             | 129.4                  | 259.1               | 27.3                |
| Alloy 3             | 132.8                  | 240.6               | 27.2                |
The grain structure of Alloys 1 and 2 is much more elongated than for Alloy 3. Along the thickness direction the grain size of all three alloys was approximately 15…20 micrometers. In the longitudinal direction, the grain size for Alloys 1 and 2 was 40…50 micrometers, while for Alloy 3, the grains had about the same dimension as in the thickness direction.

3. Experimental methodology

Trimming process is illustrated in figure 1. The trimming die was designed and fabricated on a die shoe in order to achieve a proper stiffness of the tool and parallelism of the upper and lower portions of the die. The cutting inserts were fabricated from flat plates of the tool steel D2 heat treated to HRC60…62. The cutting clearance was adjusted by insertion of the proper set of shims behind the lower insert. The cutting clearances were varied in the range between 5% and 40% of the sheet metal thickness. The experiments were performed on 50kN MTS Q50 testing machine. The trim die was installed in the testing machine, and testing was performed in a compression mode. The selection of the equipment was motivated by the necessity to be able to stop the process at different phases of cutting in order to understand the formation and propagation of cracks. The cutting speed was selected at a higher level of MTS machine speed capabilities of 3mm/sec. Strips of studied Al alloys were clamped to the lower portion of the trim die with the plate using four M12 bolts. Accuracy of the strip positioning was achieved by machining the pocket on the lower portion of the die.

After trimming tests, the sheared samples were cross-sectioned and mounted in a cylindrical block later filled with epoxy. The samples were ground, polished and etched for further microstructure observations. The samples for tensile testing of sheared edges were prepared as strips with parallel edges. The tested specimen had the following dimensions: 104 mm of length, 12.7 mm of width, and thickness of Alloys 1 and 2 were 0.9mm while thickness of Alloy 3 sheet was 1mm. The sheared edge was left as is after cutting. The opposite edge was metal finished to eliminate the effect of plastic deformation on this side of the sample. Samples were tested to check the failure modes: the satisfactory criterion was to achieve traditional necking behavior observed in a standard tensile tests.

In order to compare the material deformation in the shearing test and tensile test, standard tests of all three studied alloys were performed. The comparison of shearing and tensile testing is of qualitative nature.

![Figure 1. Schematic of trimming process.](image)

In order to understand the difference in properties in grains and grain boundaries potentially leading to understanding of the fracture mechanisms, Nano Test Platform was used to perform nanohardness measurements of grains and grain boundaries for studied Alloys. Specimens were cut, mounted, polished and etched to reveal the grain structure. This work is currently in progress. Therefore, the data only for Alloy 3 is reported in this manuscript. For indentation measurements, the indenter was forced into the surface under an increasing load. After reaching a pre-determined maximum value, the load was removed, and the penetration depth decreased due to elastic recovery of the deformed material. The depth and load are recorded continuously, which allowed both hardness and Young’s modulus
data to be derived. A 3-faceted Berkovich diamond indenter was used for these experiments. The maximum load in each case was 5 mN. The dwell period at this load was 60 s. Contact areas are determined automatically from the depth of penetration vs. load data. Using such a small load allowed us to characterize the grains and grain boundaries separately. Experiments were performed in a grid of 3x100 indentations. The distance between indentations was set as 60 µm, and the distance between the rows of indentations was 100 µm. Three rows of indentations are illustrated in figure 2. Further analysis was performed using the optical microscope to separate results for the grains and grain boundaries. It was rather clear where the indentation took place. During processing of the results, hardness values were averaged separately for the grains and grain boundaries.

![Image of Alloy 3 sample](image)

**Figure 2.** The view of Alloy 3 sample under the optical microscope with rows of indentations shown with red circles.

### 4. Results

Sheared edge formation typically starts during the initial stage of plastic deformation of the sheet metal blank being trimmed. The mechanisms of separation of three alloys during trimming were compared to localization and fracture of these materials during tensile tests: up to the neck formation all three alloys deformed similarly to the same level of strain corresponding to uniform elongation. The cross-sections of samples after the standard tensile testing are illustrated in figure 3. After the neck formation, alloy 1 and especially alloy 2 deform to much larger strains than alloy 3.

Behavior of three alloys during the phase of cutting edges indentation into the blank is very similar. However, after the crack initiation, especially for larger cutting clearances, the behavior of these materials differs substantially. As a result of the indentation of the upper tool prior to crack initiation, the material at the bottom of the blank gets extruded below the lower cutting edge which certainly work hardens material in this area. Initiation of the crack in trimming with 30% cutting clearance starts after approximately 37% of thickness indentation of the cutting tool into the sheet metal thickness in alloys 1 and 2 and after about 28% of a thickness for alloy 3. However, after fracture initiation, the separation process requires visibly larger punch displacement for Alloys 1 and 2 than for Alloy 3. The parallel comparison can be made with the tensile test behavior of these three materials: Alloy 3 has substantially smaller reduction in area in the tensile test than Alloys 1 and 2.

![Cross-sections](image)

**Figure 3.** Cross-sections of tensile tested standard tensile samples in the direction of tension: a) Alloy 1; b) Alloy 2; and c) Alloy 3.
It should be noted that the shape of the grains also makes a substantial difference in the separation mechanism. Based upon the observed deformed microstructure of the samples from all three alloys, it can be indicated that fracture propagates mostly along the grain boundaries. Alloys 1 and 2 have rather elongated grains while alloy 3 has rather equiaxial grains. As a result, the cracks propagating along the grain boundaries, get major direction along the longer side of the grain for Alloys 1 and 2. For Alloy 3, the crack has a tendency to turn towards the lower cutting edge. Based on this consideration, cracks in Alloys 1 and 2 after initiating from the upper cutting tool propagate more vertically, while for Alloy 3, cracks can turn easier towards the lower tool (figure 4). Depending on the final stage of the separation process, the extruded portion of the blank may stay on the scrap side or on the part side where it forms the burr (figure 4). It was observed by Golovashchenko et. al [7] that the crack initially propagating at a small angle to vertical direction from the upper shearing edge of Alloy 3 sample, at the final stage of trimming process turns its direction towards the lower shearing edge leaving no burr on the part side. Similar mechanism of fracture was observed by Choi et al. [8] for trimming of UHSS DP980. Propagation of the cracks along the grain boundaries makes the process of fracture more random from sample to sample even though the preferential direction of fracture dictated by the stress state certainly defines the major trend.

Figure 4. Mechanism separation where crack propagates from the upper cutting edge to the lower cutting edge (left); from the upper cutting edge almost vertically to the free bottom surface of the blank forming a substantial burr (middle); from the upper cutting edge towards the free surface of the blank and then turning towards the lower cutting edge leaving already extruded burr on the scrap side.

Mechanism of separation with 40% cutting clearance is shown in figure 5. In general, it corresponds to the mechanism of burr formation. However, from comparison of the grain structure for Alloys 1 and Alloy 3, it can be seen that the deformed structure in the burr area obtained more deformation in Alloy 1 than in Alloy 3. During the experimental work, it was rather difficult to capture partial shearing of Alloy 3 because it separates very fast from the moment the initial crack was initiated from the upper cutting edge. This mechanism reflects on formability of sheared samples when stretching is applied to the sheared sample using the tensile test methodology described by Le et. al [9].

Until burrs are formed on the sheared edge of Alloy 3, it has very limited sensitivity to the cutting clearance. Even after burrs are formed at 40% clearance, its negative effect on edge stretchability for Alloy 3 is much weaker than for Alloys 1 and 2. The reason for this phenomenon is that fracture for Alloy 3 propagates much more abruptly than for Alloys 1 and 2. As a result, the damage of the tip of the burr for Alloy 3 is much smaller than for Alloys 1 and 2. Therefore, it takes longer for Alloy 3 to initiate fracture from the tip of the burr during edge stretchability testing than for Alloys 1 and 2.

As a result of much slower crack propagation in Alloys 1 and 2 during trimming, the tip of the burr in these alloys gets substantially larger strain than in Alloy 3. Moreover, if during the initial stage of shearing, extrusion of the area of the future burr goes with some level of compression, at the final stage of the shearing process, the tip of the burr is deformed in the condition similar to plane strain tension, which is much more damaging for the material. Even though, the strain level in the area of indentation of the upper and lower cutting edges in the sheet metal at the beginning of the cutting process is larger, these strains are occurring under substantial amount of compression. The
deformation of the tip of the burr at the final stage of the cutting process with large cutting clearance represents the worst condition.

![Figure 5](image1)

**Figure 5.** Mechanism of separation of blanks trimmed with 40% clearance from Alloy 1 (left) and Alloy 3 (right).

![Figure 6](image2)

**Figure 6.** Burr height and sheared edge stretchability as a function of the cutting clearance.

The mechanism of turning the crack towards lower cutting edge is occurring for Alloy 1 only for the clearance of 5% among the observed cases. For all larger clearances for Alloy 1, the crack propagates almost vertically. For Alloy 2, the crack propagates towards the lower cutting edge up to
15% clearance, while for larger clearances the mechanism of vertical crack propagation and burr formation prevails. For Alloy 3, the mechanism of crack propagation to the lower edge prevails up to 30% clearance with the exception of 15% case. These fracture propagation trajectories reflect on burr height observed on the trimmed samples of each alloy shown in the form of the graphs of burr height for each alloy for the range of cutting clearances in figure 6.

Figure 7. Alloy 3 sample nanohardness measurements at grains and grain boundaries.

Analysis of nano-indentation results showed that average hardness value of the grains is approximately 1.7 times higher than the average hardness value of the grain boundaries, as it is illustrated in figure 7. Even though the hardness measurements provide very limited information for the analysis of deformation process of the structure including grains and grain boundaries, it provides certain hint why fracture tends to occur along grain boundaries. Further analysis is certainly needed to clarify the observed mechanism of fracture through the grain boundaries. However, it should be noted that this mechanism explains some variability in the sheared edge shape along the perimeter of the trimming line: the grain size and shape varies significantly which dictates the variations in the trajectory of crack propagation.

5. Discussion
Measurements of elongations as a result of stretching of samples along orthogonally trimmed sheared surfaces indicated that the increase of the cutting clearance above 5% for Alloy 1 and above 15% for Alloy 2 usually leads to reduced elongations of trimmed samples. The effect of cutting clearance on sheared edge stretching performance for Alloy 3 is significantly less pronounced than for Alloys 1 and 2, which makes Alloy 3 very attractive for exterior panel automotive applications where significant stretching of sheared edge can be anticipated.

The major factor leading to generation of burrs and reduced formability from sheared edge in the new stamping dies is an excessive clearance which may be a result of inaccurate alignment of the upper and lower trim dies or as a result of flexing of the die driven by the cutting forces and insufficient stiffness of the trim die.

Performed experimental study of sheared edge stretchability of three aluminum alloys with very similar mechanical properties revealed that the response of different alloys to trimming in identical cutting conditions varies substantially. Developed experimental procedures of identifying sensitivity of sheet metal to specific cutting conditions may serve as a method of selecting more appropriate alloy for specific needs and applications, especially when substantial stretching of sheared edge occurs in post-trimming operations such as flanging and hemming.
Comparison of behavior of three aluminum alloys during tensile testing and during trimming process revealed visible correlation between material ability to form the local neck and the tendency to form burrs during trimming process.

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