

Effect of Edge Quality on Formability of an AA6xxx Aluminum Alloy

H Cestoni¹, D Anderson¹

¹Novelis, Inc., 1950 Vaughn Rd., Kennesaw GA, USA, 30144

hunter.cestoni@novelis.adityabirla.com
david.anderson@novelis.adityabirla.com

Abstract. Edge quality is an important driver of formability of stamped components, especially during stretch flange operations. During these operations the cut edge is directly exposed to primarily tensile loading; therefore, a poor quality edge can lead to significant reductions in formability due to edge cracking. Machining and laser cutting of sheared edges is a costly process. In the present work, the effect of edge quality on formability is investigated with an AA6xxx aluminum alloy. Tensile specimens prepared using various manufacturing methods are compared. Edges are analyzed to determine surface roughness and damage, and these metrics are compared to common tensile testing results to gauge the effect of edge quality on formability.

1. Introduction

The movement to reduce weight in vehicles has increased the use of aluminum alloys in high volume applications, where steel has primarily been used. Some of these applications include complex body panels such as body-sides that require forming large panels to intricate shapes with cut-outs for door openings. Typically material is blanked by a shearing process before the forming process, but shearing can easily result in a damaged edge condition. Edge cracking after shearing is known to affect formability [1] so edge quality can play an important role on the formability of a component.

Le *et al.* [2] focused on the effects of different shearing conditions of an AA6xxx alloy. Different shearing clearances, 5%-40%, were tested and they concluded that clearances above 5% showed a decrease in ductility. So the edge quality for a 5% clearance or less can be thought of as negligible to the materials formability characteristics. Further experiments they performed involved using different cutting angles. Conclusions are made that using cutting angles as tested (10° or 20°) helped increase the ductility of the sheared samples such that changes in formability are not observed until cutting clearances above 10% are practiced. These tests resulted in changes of a materials formability due to different shearing conditions which affect the processed edge quality.

Similar testing was conducted on high strength steels (HSS) by Feistel *et al.* [3]. These tests also focused strongly on the shearing process and different machine settings. As a control, samples produced by milling were used as a comparison. Milled samples experienced higher formability characteristics during tensile tests than the sheared samples. HSS samples were tested with various clearances and sheared using a closed cutting path, where the cutline completely encompasses the part profile or an open cutting path, where the cut is completed in several steps so the sheared edge can extend beyond the edge of the sample providing possible stress relief. Results showed sheared edges reduced the



formability of the test samples compared to the milled sample. For steel, with a closed cutting path, the 10% thickness clearance had improved formability compared to the 5% clearance, but both still experienced reduced performance relative to the milled sample. An open cutting line was used to reduce the edge stress from the shearing process and this showed a decrease in formability as the clearance was increased and an increase over the closed cutting path. Even with this improvement, the formability still did not meet that of the milled specimens.

Studies have been performed Le *et al.* [2] and Feistel *et al.* [3] on different sheared edge formability conditions, but comparisons to other manufacturing techniques is not well observed for aluminum alloys. Since machining and laser cutting can be more costly for high volume applications it would be beneficial to determine a change in formability performance due the manufacturing process. Edge qualities of an AA6xxx aluminum alloy will be observed from several known manufacturing techniques: electrical discharge machining (EDM), laser cutting (LZR), water-jetting (WJ), machining (MAC), and shearing with different clearances. These processes will be used to produce dog-bone samples that will be characterized by mapping the surface roughness on the edge, scanning the profile geometry, and other observations such as subsurface damage of the processed edge. The observation data can characterize the edge quality of each sample and be used to compare with tensile test data to correlate the edge quality with formability.

2. Experimental Methods

Sample Geometry

The material used for this study is an AA6xxx T4 aluminum alloy with a thickness of 2mm. Several ASTM B557 2" dog bone samples [4], are made with the rolling direction aligned with the tensile axis. Different manufacturing techniques: EDM, laser cutting, water-jetting, machining, and shearing with the following single side clearances relative to the thickness: 3%, 6%, 11%, 16%, and 21% are used to make the samples for comparison. Table 1 shows which shearing thickness clearance correlates with the samples throughout this experiment. The shear tooling used supported the sample and the scrap and no shearing angle was used. Tooling was aligned during manufacturing and pinned in placed.

Table 1. Sheared samples clearance schedule

Sample ID	Shearing Thickness Clearance (%) [Clearance = $100 \cdot (\text{gap}/t)$]
SA	21
SB	16
SC	11
SD	6
SE	3

Edge Characterization

To compare the edge quality of each process, images of the edge faces are captured with a Keyence VHX-5000 digital microscope. With the VH-Z100R\W\T lens and 200X zoom the desired images were produced. Using the Keyence software a 3D depth composition was created to capture the variations in the surface texture. Each image displays a detailed view of the edge condition and incurred surface damage can be seen.

Surface roughness is measured using a Nanofocus usurf confocal microscope, and the topography results are reported according to ISO 25178. Six locations, three on each edge, are measured and the roughness values from all six locations are averaged with the standard deviations computed. For the sheared samples, roughness measurements are taken to include the burnish zone and also without the burnish zone. These average values are compared between the different sample types.

Each different sample is sectioned transversely in three different locations, then mounted and polished. These are viewed with the digital microscope to observe the sub-surface characteristics of the specimens resulting from the various manufacturing methods.

Tensile Testing

Tensile testing is performed on a MTS frame with 300kN load cell and the digital image correlation (DIC) method is used to measure the strains of each specimen. For the DIC, two 4-megapixel cameras fixed with 50mm lenses are attached to the tensile frame and calibrated to a target deviation less than 0.050 pixels. A stochastic pattern is applied to each specimen with a matte white base coat misted with matte black paint. Each specimen, 5 samples for each manufacturing process, is pulled at a crosshead speed of 0.05 mm/s to create an initial quasi-static strain rate of 0.001s^{-1} , until fracture occurs, and GOM Correlate computes the strain for each image set using a 50mm gage length to calculate the global elongation. The digital microscope is used on the broken samples to measure the area reduction using a similar method discussed in [5], which provides a more local elongation pattern. The values from each sample are averaged and standard deviations are computed to compare results between each manufacturing process.

3. Results

Roughness values help elaborate on the detailed images captured from the microscope. Figure 1 shows the average maximum pit height (Sv) for each manufacturing method, which could be important to the formability because this depth being cut into the material can cause high stress concentrations. Other roughness measurements (i.e arithmetic mean height Sa) show the same pattern between the different manufacturing methods as the Sv values. Water-jetting Sv measures 65% higher than the 21% shear clearance sample (SA), and machining is 90% lower than laser cutting, which is the next lowest measurement. Roughness measurements from the five shearing clearances refer to Table 1; only show small differences between successive clearances with a 20% increase from the tightest clearance (SE) to the largest clearance (SA)

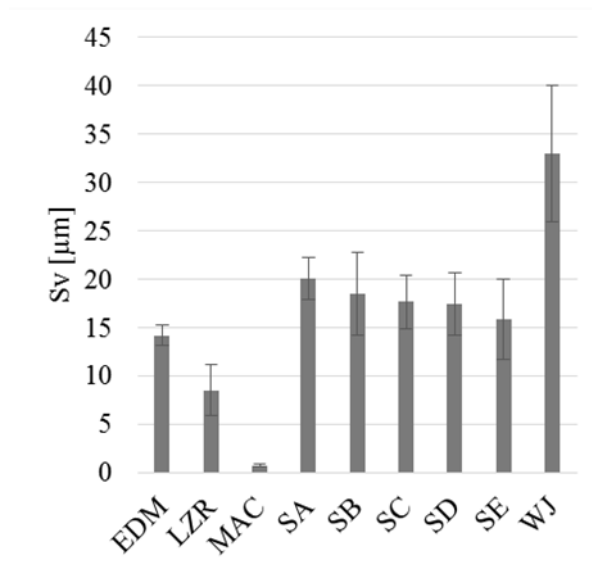


Figure 1. Roughness Sv values of manufactured edges.

The images in Figure 2 show the edge details from the different preparation methods. Machined (MAC) and EDM samples display the most consistent pattern of surface irregularities over the entire area, and laser cutting (LZR) and water-jetting (WJ) appear to be the most inconsistent, and has what

appears to be cuts at various depths into the width of the sample. Between the different shear samples, there are slight variations in appearance, where the burnish zone shows more variation in the SA and SE specimens and there is evidence of some burnishing of peaks in the fracture zone of the SE sample. None of the sheared samples had burrs.

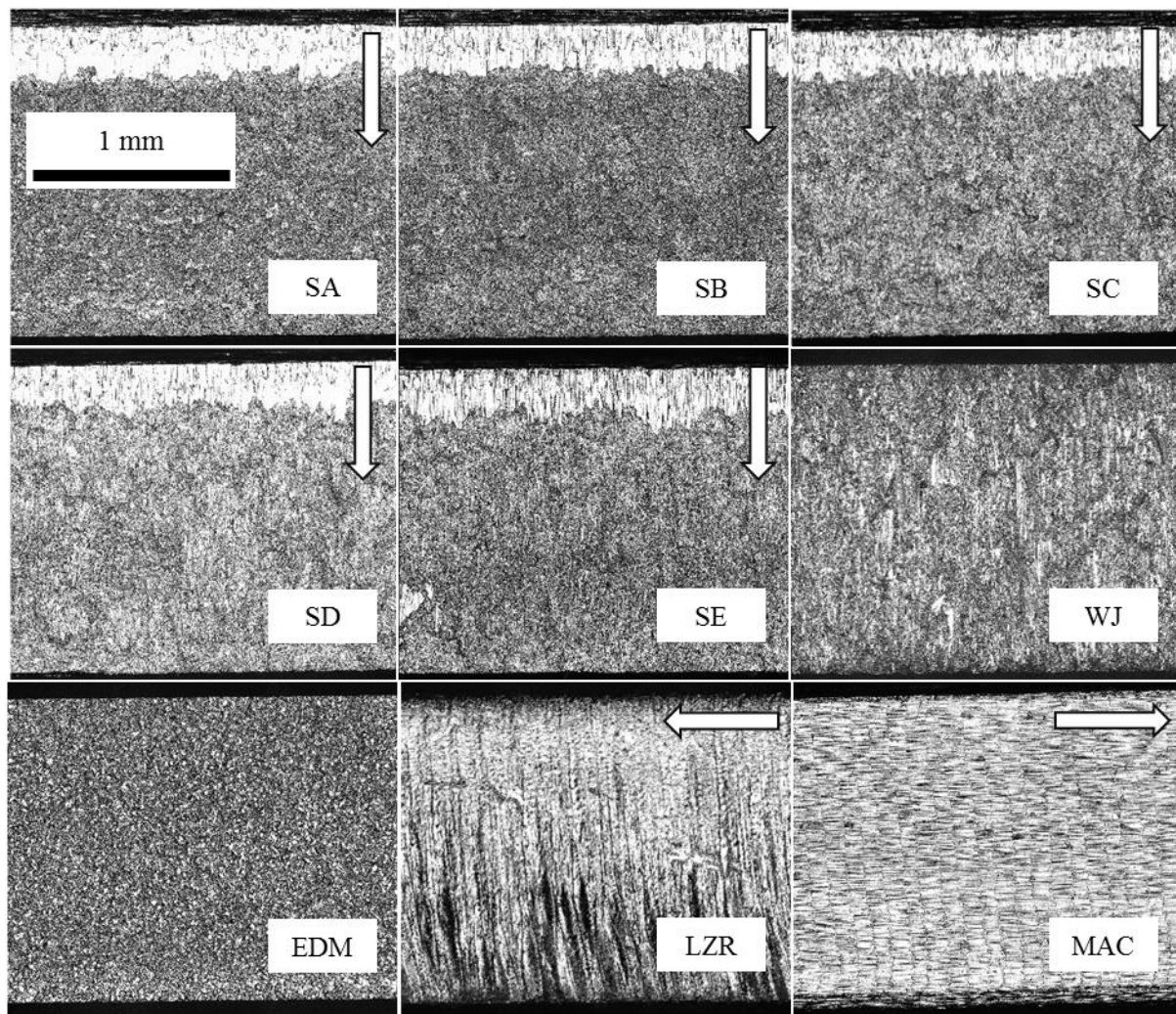


Figure 2. Digital microscope processed edge images, 200X zoom. Arrows indicate shearing or cutting direction if known

Studying the cross-section of each sample shows how the manufacturing process affects the material structure beneath the surface. Water-jetting measured the highest surface roughness, but the profile of this roughness has less acute pits than the sheared samples seen in Figure 3. These sharp points present in the sheared specimens could be susceptible to higher stress concentrations. Alloy particles of Iron containing intermetallics in the sheared samples exhibit signs of internal deformation, Figure 4, appearing to flow in the same direction as the shear path. This characteristic is not seen in any of the cut samples making these processes preferred over shearing for formability performance. More damage is found in the sheared samples by prevalent decohesion around hard particles which are additional potential areas for material fracture.



Figure 3. Edge roughness comparison details. 21% shear (SA) to Water-Jetting (WJ) showing acute surface pits on SA sample compared to the smooth undulations of WJ. Insets shown at 1000x original magnification.

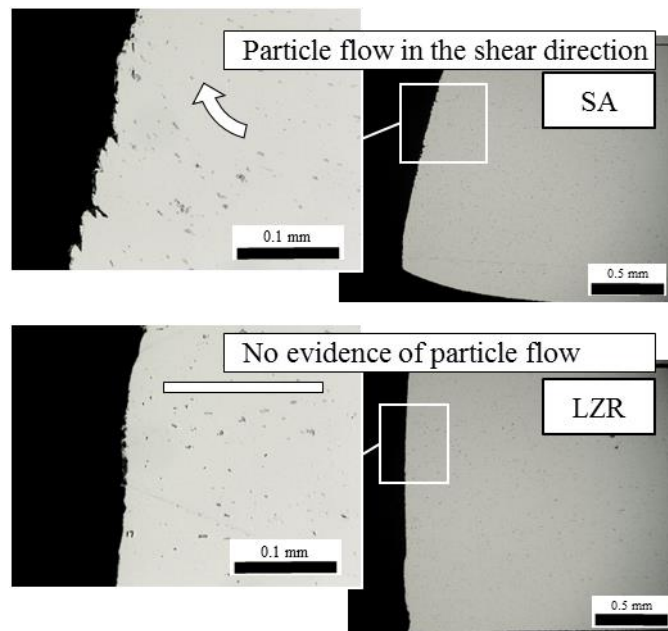


Figure 4. Iron particles displaying a flow pattern in SA samples and no evidence in a laser cut sample. Insets shown at 1000x original magnification.

Tensile testing revealed a difference of elongations between the processes. The columns in Figure 5 show that all the sheared samples fractured between a 23- 24% elongation and the cutting methods all fractured between a 24-25% elongations. Maximum elongation is achieved by the laser process and the minimum elongation from the SA shear conditions. The sheared sample elongations vary with the different clearances. Both the largest clearance, SA, and the smallest clearance, SE, (21% and 3% respectively) have the lowest elongations with sample SB and SC (16% and 11% clearances respectively) have the larger elongations of the sheared samples.

Reduction in area percentage is plotted in Figure 5, and this reduction measurement is an observation of the local formability at the fracture point. Similar to the elongation data, laser cutting has the highest area reduction value, and the tightest shearing clearance, SE, has the lowest reduction. The method used for the reduction area views the sample perpendicular to tensile direction and does not account for an out-of-plane fracture edge. So for the SA samples, which fractured at a greater angle out of plane, the

reduction in area is measured to be greater than it actually is, hence why this trend does not match that of the elongation data. Typically, there is a correlation between the elongation and the reduction in area data, but with the measuring method used; large errors are likely to happen due to the irregular profile of the fracture surfaces and the rounding of the edges from the shearing process. This makes it difficult to compare reduction in area results between the manufacturing processes.

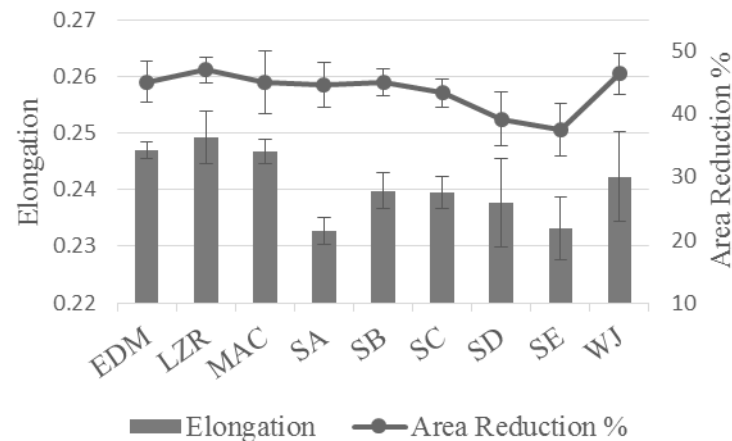


Figure 5. Elongation tensile data and area reduction.

4. Discussion

Surface roughness created during various manufacturing techniques does not appear to have a drastic effect on the tensile formability of the investigated AA6xxx alloy. Comparing the elongation data with the surface roughness measurements does not show matching trends. Water-jetting produced the highest surface roughness, but these samples show better elongation and area reduction compared to all of the sheared samples that measured roughness values about 40% lower. The machined edge measured roughness values 94% lower than an EDM edge, but both of these have similar elongation results.

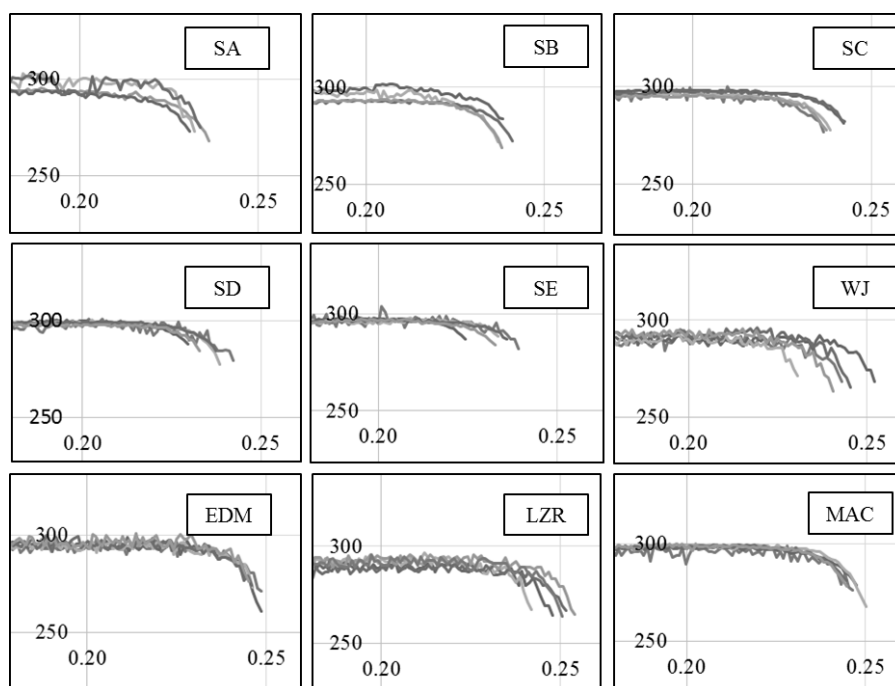


Figure 6. Stress-Strain curves near fracture point

The consistency of the surface pattern seems to affect the predictability of the elongation before fracture. This is evident from the stress-strain curves in Figure 6. Water-jet produced samples have the largest deviation, shown both in the stress-strain data and the error bars in Figure 5. The images of water-jetting and laser cutting have terrain variations across the edge surface and these have the higher deviations of elongation to fracture, while machining and EDM samples have the lowest deviations, and their edge patterns are the most consistent.

Each shearing process rolled the edges of the samples over, and every increase in clearance made this rollover more prominent, seen in Figure 7. Evidence of material deformation below the edge of the sheared samples can be seen in the pattern of the hard particles. Shown in Figure 4 at 1000x, these particles appear to follow a flow pattern that moves toward the direction of the shearing process, as one would expect. Some of these particles near the edges have fractured and there are signs of damage to the alloy caused by this particle cracking and decohesion seen in Figure 8. This region of internal deformation can reduce the formability performance of the material, which explains why the sheared samples resulted in lower overall elongation than the water-jetting process that had higher surface roughness values. The other processes (EDM, MAC, LZR, and WJ) did not have evidence of this type of particle flow or fractures. Results from Sao *et al.* [6] shows that the EDM process does not induce enough stress on an aluminum alloy to create surface cracks so it would not be likely to cause internal material damage such as the shearing processes.

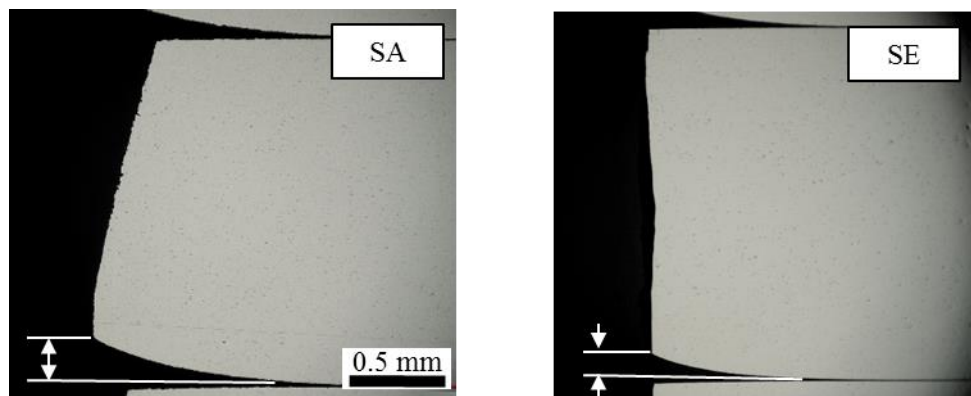


Figure 7. Larger edge rollover of SA samples compared to SE samples

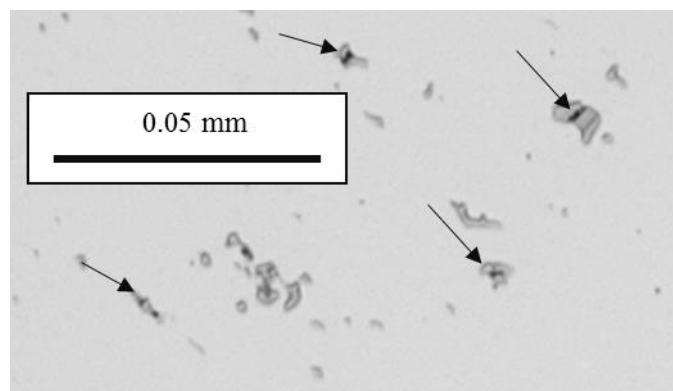


Figure 8. Hard particle cracking from SA shear sample.

The results in [2] concluded that shearing clearances over 5% reduced the elongation of the specimen. For their tests, half dog-bone samples of 0.9mm thick AA6xxx material. This differs from the full dog-bone 2mm thick specimens used for this experiment, which concluded more of a bell-shaped response

where 11% and 16% clearance had the higher elongations and clearances below or higher than those have lower elongations.

Results from steel samples in [3] found that as shear clearances increased the elongation improved, starting at 2% up to 20%. Samples in this experiments use a milled edge and a manipulated sheared edge on the other side, similar to the half dog-bone.

5. Future Work

To further study the effects, SEM images of the fracture surfaces to observe the type of failure (ductile, shear) can be performed and the further use of the DIC data to determine failure initiation is ongoing. Some other considerations could be scaling the sample size, such as reducing it to a ASTM B557 1" sample that may be more sensitive to the edge quality or using half dog-bone samples and 0.9mm thick sheet could produce data that can be better compared to that found by Le et al [2]. Additional testing that more closely mimics actual forming conditions may also prove more revealing in terms of the effects of edge preparation method as a function of formability. This work is currently ongoing.

6. Conclusions

As the industry grows more into using aluminum alloys, and weight reduction is becoming more critical, this kind of study can help the manufacturer's further push material capabilities for forming components. At present there does not seem to be an easily quantifiable method (e.g. surface roughness) to predict the reduction in elongation as a function of edge condition, but the material damage due to the manufacturing process and process conditions can have a greater effect. Methods like laser cutting or water-jetting would be best, but these may not be the most cost effective, especially for large volume production. There is evidence from this work and others that show various shearing conditions such as clearance and cutting angle can affect edge formability. Initial work spent to optimize the shearing parameters to minimize the edge roll over and surface cracking for blanking can help improve the material formability.

References

- [1] Hu XH, Sun X, Golovashchenko SF 2014 *Computational Materials Science* **85** 409-419
- [2] Le Q, deVries J, Golovashchenko S, Bonnen J 2014 *Journal of materials processing technology* **214** 876-891
- [3] Feistle M, Golle R, Volk W 2016 *Procedia CIRP* **41** 1078-1083
- [4] ASTM International 2015 *B557 - Test Methods for Tension Testing Wrought and Cast Aluminum and Magnesium Alloy Products*
- [5] Larour P, Freudenthaler J, Weissbock T 2017 *IDDRG 2017*
- [6] Rao PS, Ramji K, Satyanarayana B 2016 *Alexandria Engineering Journal* **55** 1077-1084