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# Analysis of sheared edge formability of aluminum

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ABSTRACT

Edge quality produced by shearing processes often leads to reduced material formability which was observed in multiple studies and summarized in the reference literature. The intention to make the sheared edge performance more predictable has motivated development of several experimental techniques such as the hole expansion test and the half dogbone tensile test. The paper presents a detailed review of published results for both of these techniques and illustrates very limited research dedicated to sheared edge performance of aluminum alloys. The experimental study, performed on a broadly used aluminum alloy, 6111-T4, illustrated the effects of cutting clearance on longitudinal, transverse and diagonal orientations of the trim line relative to the rolling direction. For all sheet orientations, increasing the cutting clearance resulted in a substantial reduction in material stretchability along the sheared surface. However, for all investigated conditions a cutting clearance of 5% of material thickness resulted in stretching performance similar to the standard tensile test. In this case the sheared edge does not affect the stretching behavior of tested material. The analysis of material prestrain on sheared surface stretchability for a variety of combinations of minor and major strains indicated that for the widely accepted industry standard gap of 10% of the material thickness, the prestrain has significant effects on stretchability which only gets stronger with increased thinning of the sheet in the prestraining process. For an extended clearance of 40%, the effect of prestrain was less visible indicating that the sheared edge has a stronger effect on these cutting conditions than prestrain.

Analysis of the effect of the cutting angle on stretchability indicated that higher elongations were observed with cutting angles of 10° and 20° for broadly used 10% clearance compared to orthogonal cutting with an identical clearance.

The results of half dogbone tensile tests were compared with the results of hole expansion tests performed on the same sheet material. This comparison indicated that a substantial amount of localization occurs in the hole expansion test and leads to a much higher hole expansion ratio for small cutting clearances compared to the total elongations observed in tensile tests. However, the local strains measured in the area adjacent to fracture in the tensile test were above the hole expansion ratio.

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## 1. Introduction

The trend toward 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. Early fracture in stamping operations where stretching is applied along the sheared surface represents a significant problem, as it was pointed by Smith (1990).

The edge of sheet metal blanks, initially produced by blanking, can be subject to various metal forming operations. The edge could be on the interior window of a sheet metal blank, subject to drawing with a relief window, or on the periphery of the blank. Subsequently it undergoes operations such as stretch flanging, stretch bending as well as drawing with a concave external edge. An increasing attention is paid to the experimental studies of stretching performance of sheared surface through the hole expansion test reviewed by Hance et al. (2013) for AHSS and disclosed by Stanton et al. (2011) for aluminum alloys. According to JFST1001-1996 standard "Method of hole expanding test" published by the Japan Iron and Steel Federation and International Standard ISO16630-2009 "Metallic materials – Sheet and strip – Hole expanding test" the hole expanding test consists of two steps: (a) punching a hole of 10 mm in diameter with 12% radial clearance between the punch and the die; (b) forcing a conical expanding tool into a pre-punched hole until any one crack extends through the test piece thickness of the metallic sheet.

It should be admitted that even though this standardized test creates stretching along the perimeter of pierced hole, it is different from the hole flanging operation. According to Avitzur (1983), in flanging, the edge of the hole is bent 90° to the parent material,

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while in hole expansion test defined by JFST Standard (1996) the material is expanded by a 60° punch which should be large enough, so the metal is not expected to be fully flanged.

According to JFST1001-1996 and ISO16630-2009, the hole expansion ratio, $\lambda$, is calculated based upon measuring the initial diameter of the hole before the test, $D_o$, and the final diameter of the hole at the end of the test, $D_h$, in two perpendicular locations from the following formula:

$$\lambda = \frac{D_h - D_o}{D_o} \times 100$$

ISO16630-2009 Standard had very similar testing conditions to JFST1001-1996, but added possible deviations for the following critical parameters: (a) clearance between the punch and the die in the piercing tool, (b) conical punch angle, and (c) die entry radius in the hole expansion tool were defined.

The hole expansion test is taken much more broadly in the research literature than it is defined in both JFS and ISO standards. For example, Stanton et al. (2011) employed both conical punch and flat punch for three 5xxx alloys and nine 6xxx alloys using punching method of hole fabrication as well as drilling and reaming method. Many other researchers, such as Chintamani and Sriram (2006), studied a broader range of clearances than 12% defined by JFST1001 (1996) or 11–13% range defined by ISO16630-2009.

Empirical formulas predicting the hole expansion ratio were published by Comstock et al. (2006) for nineteen ferritic, ferritic stainless, and austenitic stainless steels. Similarly, Stanton et al. (2011) developed empirical formulas to calculate hole expansion ratio for twelve 6xxx and 5xxx aluminum alloys. The method employed by Stanton et al. (2011) was based upon the approach developed by McEwan et al. (2009) to incorporate the hole expansion test results into the Forming Limit Diagram (FLD) assuming that the material in hole expansion test is deformed in uniaxial tension on the FLD. However, this approach did not take into account the punching process parameters which critically affect the hole expansion ratio assuming only optimal cutting clearance conditions.

In Chintamani and Sriram (2006), hole expansion test was performed for DP500, BH210 and DQSK steels with variation of the die clearances ranging from 5% to 55% of the material thickness. The parameters of the sheared surface such as burnished area, fracture depth, burr height and hole expansion ratio were studied as a function of the die clearance. The general trend was the hole expansion ratio slightly increased with the growth of the clearance from 5% to 10–15% clearance and then decreased (by approximately a factor of 2.5–3) with the cutting clearance opening to 55%.

In the experimental study reported by Konieczny and Henderson (2007), sheared surface parameters and hole expansion ratio were studied for HSLA 340, DP590, TRIP780, DP780 and DP980 steels for cutting clearances in the range between 1.1% and 20% compared to the hole expansion ratio for reamed edge finish and for laser cutting. In general, the trend indicated that reamed edge provided the best performance of the edge followed by the laser cutting results. The effect of cutting clearance on hole expansion ratio varied from one material to another and differed significantly from the results reported by Chintamani and Sriram (2006) being either stable in the whole range of clearances (HSLA340), stable and then increased (DP780, TRIP780 and DP980), or decreased and then increased (DP590). For the last case, a hemispherical punch instead of a conical punch was employed in the experiment which indicates that the shape of the expanding punch might significantly affect the outcome of the test.

Very detailed analysis of hole expansion results was performed in Chiriac (2010). A comparison (Chiriac, 2010) between hole expansion ratio values obtained in different conditions indicated that the hole expansion ratio produced by a conical punch was nearly a factor of 1.5 higher than the hole expansion ratio from a flat bottom punch, since, according to Chiriac (2010), the strain path at the hole edge for conical punch hole expansion was more in uniaxial compression than the strain path for flat punch hole expansion where the test conditions of the edge were closer to uniaxial tension. A detailed analysis of strain path in hole expansion test with the conical punch and with the flat punch conducted by Levy and Van Tyne (2008) indicated that more stretching occurs if the flat punch is employed. Based on this analysis, Levy and Van Type called the hole expansion test with the conical punch as hole extrusion while the process with flat bottom punch was called hole expansion. These comparisons again indicate that the shape of the expanding punch is a very important factor which may affect the experimental results.

An important observation was made by Chiriac (2010) by measuring strains of individual grids around the perimeter of the expanded hole. The major strains of each grid element were tangent to the hole edge, and the average strains were in good correlation with the hole expansion ratio while the maximum and minimum major strains were significantly different. For different versions of DP780 steel, the ratio of maximum observed major elongation to minimum observed major elongation of individual ellipses ranged from 1.83 to 3.56. The SEM results reported in Chiriac (2010) indicated multiple strain localizations and, therefore, provided experimental evidence that the hole expansion ratio is the averaged value between the localized and non-localized areas of material deformation. It should be emphasized that the criterion how failure is defined might affect the results on hole expansion ratio. The definition of failure in JFST1001-1996 standard "Method of hole expanding test" published by the Japan Iron and Steel Federation and International Standard ISO16630-2009 "Metallic materials – Sheet and strip – Hole expanding test" is that one crack should propagate through the thickness of the testpiece. The definition of failure in published research literature on Hole Expansion Test varies. Konieczny and Henderson (2007) followed the JFST1001-1996 standard stopping the test when the crack propagated through the thickness. Comstock et al. (2006) stopped the test when a visible crack was observed which probably happened earlier than the crack propagated through the thickness. Stanton et al. (2011) were using the drop in penetration force technique which might lead to a different result than the crack propagation through the thickness.

Analytical results and experimental data on hole expansion described by Atkins et al. (1998) indicated multiple necks and cracks along the perimeter of the hole. An experimental study by Arndt et al. (2001) was dedicated to the hole expansion study of aluminum sheet using hydraulic bulging approach using an undersheet of very ductile mild steel. A hole expansion experiment was done using pure aluminum sheet which had low strain to the initiation of necking, but high strain to fracture. The choice of this material by Arndt et al. (2001) enabled rather detailed study of a number of necks along the perimeter of the hole. For the ratio of the hole diameter to thickness of the sheet equal to 10, five to six necks were observed which was in accord with study performed by Atkins et al. (1998). These results correlate with observations by Chiriac (2010) and serve as an evidence providing possible explanation why the hole expansion ratio is substantially larger than the total elongation in the tensile test where only one neck usually occurs. Localization of strains is unacceptable for production stamping process; therefore, including these multiple areas in the sheared edge stretching prediction leads to overestimation of elongations which sheared edge might safely sustain without fracture.

Theoretical analysis of hole expansion test employing Finite Element Method was performed in Sartkulvanich et al. (2010) based upon 2D simulation, taking into account the shape and strain distribution from the hole piercing process. A simplified approach to

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