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Evaluation of hole expansion formability of high strength AA7075 alloy under varying temper conditions

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Abstract. There has been a widespread increase in the use of aluminum alloys in automotive industries for meeting ever-growing light-weighting requirements. However, edge formability is a critical manufacturing challenge that restricts their widespread use. Edge formability of sheet metal is determined using a hole expansion test (HET) and is evaluated by the hole expansion ratio (HER). The present study investigates the effect of temper conditions on the edge formability of AA7075 alloy sheets. Hole expansion tests were conducted in different temper such as W-temper (super saturated solid solution followed by water quenching), under aged (UA), and peak aged (PA) conditions. Two different hole preparation techniques, a punching and a drilling process, were used to prepare samples with varying edge conditions. The results demonstrate that the W-temper has the highest edge formability irrespective of hole edge conditions. Researchers have reported that uniaxial stress state prevails at the hole edge during the HET. Consequently, uniaxial tensile tests were conducted on for each temper condition and various tensile properties such as yield stress (YS), ultimate tensile strength (UTS), ratio of yield stress to ultimate tensile strength (YS/UTS) were determined to evaluate edge formability. Furthermore, microstructural and failure analysis of the failed specimens were performed to explain the deformation behavior during the HET.

keywords: Stretch-flangeability; Hole expansion; Aluminium AA7075 alloy; Formability; Heat treatment

1. Introduction

In recent years, aluminum alloys have gained considerable attention in the automotive and aerospace industries for light weighting applications [1, 2, 3, 4]. Among the various aluminum alloys, precipitate hardened aluminum alloys are widely used due to their high strength to weight ratio, good wear and corrosion resistance [1, 5]. However, one of the major technological problem that restricts their widespread usage is their inferior room temperature formability, especially in precipitate hardened conditions [3, 6]. To address these manufacturing challenges, the alloys are



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often formed at elevated temperatures [7]. However, elevated forming temperatures pose significant manufacturing and tooling difficulties, such as reduced die life and poor surface quality of formed components [8]. To circumvent these technological challenges, cold forming technique is currently employed. In this method, the part is subjected to solid solution treatment and then quenched to attain super saturated solid solution (S.S.S) phase and thereafter cold formed [9]. The strength of the formed part is increased by subsequent artificial aging post forming. This process is beneficial as lower forming forces are required, and it improves the die service life and formability[9].

In automotive industries, the formability measurement of sheet metal is a routine task. An accurate formability assessment of sheet metal is very important before the component is subjected to forming operation. Edge formability of sheet material is one of the important formability parameters which is evaluated using the hole expansion test. Typically, the traditional forming limit diagram (FLD) is used to evaluate formability. However, FLD is not suitable for evaluating the edge formability of sheet metal through hole expansion test (HET) data, since HET results are sensitive to hole edge conditions [10, 11, 12]. The test data are used to evaluate a dimensionless parameter called hole expansion ratio (HER), which is defined as the ratio of the change in the hole diameter of the specimen at failure to the initial hole diameter. A higher HER value indicates that the sheet has superior edge formability. A high value of edge formability is desired for sheet materials, especially when forming flanges in complicated shapes. Hole expansion deformation behaviour has been widely studied by various groups [10, 11] and it is well known that the edge formability during HET depends on the punch profile. In the case of conical punch, the hole edge deforms nearly in uniaxial condition [10, 11, 12]. Following this observation, various researchers have correlated the tensile properties like yield strength (YS), uniform elongation (UE) and total elongation (TE) with HER [10]. Majority of these studies were performed on ferrous alloys [10, 11, 12, 13]. Aluminum alloys received less attention in this regard. Despite the importance and potential use of AA7075, only limited studies have been carried out to understand the edge formability, particularly with varying temper conditions. Therefore, the objective of the present study is to investigate the edge formability of AA7075 alloy with varying temper and edge conditions. A systematic approach is used to investigate the influence of temper condition on edge formability of the AA7075 alloy sheet, and results are correlated with uniaxial tensile properties.

2. Materials and methods

2.1. Experimental method

In the present work AA7075 with sheet thickness 2 mm, obtained from Bharat Aerospace, India ¹ was used. The chemical composition of the as-received AA7075 alloy sheets was measured using optical emission spectroscopy (OES) and is listed in Table:1. Square sheets of dimensions $90 \times 90 \text{ mm}^2$ with a center hole of diameter 10 mm were made using drilling and punching process from the as received AA7075 sheets. Two stage drilling of ϕ 5 mm followed by ϕ 10 mm at 630 rpm (lip angle of drill bit 59°) was utilized to prepare drilled edge sample. The punching operation was performed at punch velocity of 10 mm/s. All the heat treatments and aging were performed after specimen preparation. In addition, uniaxial tensile specimens as per the ASTM E8 standard [14] were fabricated using wire cut electric discharge machining (WEDM) process. These sheet specimens (hole expansion and tensile specimens) were solution treated at 480 °C for 2 hours followed by water quenching to obtain S.S.S condition. This treatment is referred

 $^{^{1}}$ Certain commercial equipment, instruments, software or materials are identified to describe a procedure or concept adequately. Such identification is not intended to imply recommendation, endorsement or implication by NIST that the equipment, instruments, software or materials identified are necessarily the best available for the purpose.

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to as W Temper condition. Thereafter, these sheets were artificially aged at 120 °C for 1 hour and 24 hours to obtain under aged (UA) and peak aged (PA) conditions, respectively. Fig. 1 shows the heat treatment cycle followed for obtaining various temper conditions. Tensile tests were performed using a Zwick/Roell 100 kN machine. Specimens were tested with a nominal strain rate of 0.001 s^{-1} . All the experiments were repeated three times to ensure repeatability of test data.

Table 1: Chemical composition of as-received AA7075 alloy sheet.

Elements	Zn	Mg	Cu	Cr	Ni	Si	Ti	Fe	Al
Contents (%)	6.02	1.3	1.43	1.4	1.3	1.43	1.43	1.43	balance



Figure 1: Heat treatment cycle followed for obtaining various temper conditions used for both sheet and uniaxial tensile specimens.

2.2. Hole expansion test

Standard hole expansion tests (HET) were performed on the heat treated specimens using a conical punch with a cone angle of 60° . HET was conducted as per the ISO 16630 2009 standard [15] (Fig.2). A blank holding force of 65 kN was applied in order to prevent drawing in of the sheet specimens. The test was continuously monitored with the help of a camera with an external light source. The test was stopped once through-thickness cracks appeared. The hole expansion ratio (HER) value was calculated using equation (1).

$$HER(\%) = \frac{D_f - D_i}{D_i} \times 100\tag{1}$$

where, D_f and D_i refers to the final and initial diameter of the central hole. D_i is calculated using the average value of four diameters measured at angles of 45°. IOP Conf. Series: Materials Science and Engineering 1238 (2022) 012038 doi:10.1088/1757-899X/1238/1/012038



Figure 2: Experimental setup used for hole expansion deformation process.

3. Results and discussion

3.1. Correlating: HER with tensile properties

The shape of the HET specimen before and after the hole expansion deformation process is shown in Fig.3(a,b) respectively. The values of HER in different temper conditions are tabulated in Table 2. It is observed that the HER values significantly varied with hole edge and temper condition. Maximum HER was obtained in W-temper, followed by UA and PA for both the edge conditions [16].However, the drilled edge was found to exhibit higher HER compared to the punched edge. The dependence of HER with the hole edge can be attributed to difference in the surface roughness for the two edges, which is discussed in Section 3.2. It is known that, the hole edge in HET deforms in uniaxial tensile deformation conditions [10, 11]. Therefore, to better understand the edge formability characteristics of this alloy, HER values are correlated with the uniaxial tensile properties of the sheet with varying temper conditions.



Figure 3: A typical HET specimen (a) before deformation, (b) after deformation (arrows in the insert figure showing the through thickness crack).

Condition	HER values $(\%)$		
	Punched edge	Drilled edge	
W-Temper	36.08 ± 1.35	43.52 ± 2.26	
UA	20.74 ± 1.37	24.25 ± 1.86	
PA	14.20 ± 2.69	18.62 ± 1.42	

Table 2: Evaluated HER values for AA7075 sheet in different temper and hole edge conditions.

Fig.4 shows the stress strain response of AA7075 alloy in different temper conditions. As the aging proceeds from solutionized (W-Temper) to PA condition, significant changes in the deformation behaviour are observed. Servated deformation behavior is observed in the W-temper condition. This is characteristic of occurrence of Portevin–Le Chatelier effect (PLC) [3, 17]. In the W-temper condition, solute elements present in the aluminum matrix, interact with the dislocations during plastic deformation resulting in the servated flow behavior. However, when the material is subjected to artificial aging, the solute elements precipitate out of the aluminum matrix. The depletion of solute elements in the aluminum matrix, is manifested by the suppression of serrated flow behavior in UA and PA condition. During deformation, dislocations interact with the precipitates, and this interaction is responsible for the increase in strength levels in the aged condition. The tensile properties obtained in different temper conditions are tabulated in Table 3. The yield strength (YS) and ultimate strength (UTS) significantly increased upon aging. It is also important to note that the strain hardening capacity of the material significantly decreased as the alloy is subjected to increased aging treatment. In case of W-temper condition, the ratio of yield strength to ultimate tensile strength (YS/UTS) is 0.42 whereas, as the material is aged the ratio of yield strength to ultimate tensile strength (YS/UTS) increased from 0.66 to 0.85 for UA and PA respectively, indicating significant loss in the ductility. This is evident from considerable decrease in uniform elongation (UE) and total elongation (TE) values obtained in UA and PA compared to W-temper condition.



Figure 4: Stress-strain response of AA7075 alloy in different temper conditions.

Temper condition	YS (MPa)	UTS (MPa)	YS/UTS	UE	TE
W-Temper	182.91 ± 2.07	492.08 ± 3.27	0.37 ± 0.001	0.13 ± 0.003	0.17 ± 0.002
UA	394.65 ± 3.44	591.10 ± 3.43	0.66 ± 0.002	0.11 ± 0.003	0.15 ± 0.001
РА	549.29 ± 2.57	641.27 ± 2.58	0.85 ± 0.0005	0.07 ± 0.004	0.13 ± 0.002

Table 3: Uniaxial tensile properties of AA7075 alloy in various temper conditions.

Fig.5(a-e) presents plots of variation of HER with tensile properties (YS, UTS, YS/UTS, UE, TE) (Table. 3). It is observed that irrespective of tensile properties, the HER values for drilled edge are higher than those obtained from the punched edge tests. HER values are largest for the W-temper followed by UA and PA temper condition as evident from Fig.5(a-e). These figures also show that the HER values continued to decrease with aging. HER values ultimately decreased by 60.6% and 57.2% from corresponding values for the W-temper condition for drilled edge and punched edge hole tests respectively for the PA condition. As observed from Fig.5a and Fig.5b, there exists a negative correlation between HER and YS and UTS. In the W-Temper condition, the material exhibits the least values of both YS and UTS. However, as the aging continues from UA to PA condition, both the YS and UTS values considerably increase, thereby decreasing the HER values. To further understand, we plotted the HER variation with the YS/UTS ratio. In the W-Temper condition, the ratio of YS/UTS is 0.37, which increases to 0.66 and 0.85 in UA and PA temper conditions respectively. The increase in the ratio of YS/UTS indicates the decrease in material formability, which is also manifested by lower HER values as shown in Fig.5c. Similar negative correlation between HER and YS and UTS values were reported by Paul et al. [18] for wide grades of automotive steels. HER values were found to be positively correlated with UE and TE for both the hole edge conditions, as shown in Fig.5d and Fig.5e. The correlation is limited to the given edge condition. Varying the edge condition during sample preparation could lead to a different correlation, which is a limitation when attempting to correlate the HER with the uniaxial behavior.

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Figure 5: Variation of HER with (a) Yield strength (YS), (b) Ultimate tensile strength (UTS), (c) Yield stress to Ultimate tensile strength ratio (YS/UTS), (d) Uniform elongation (UE) (e) Total elongation (TE) in different temper and edge conditions.

3.2. Effect of edge condition

Fig.6a shows a schematic of HET specimen position during hole edge preparation using punching and drilling process. The measured average surface roughness (Sa) for drilled and punched hole is 1858 ± 35 nm and 2981 ± 27 nm respectively. It is well established that edge preparation technique plays a critical role in HER values obtained in HET [10, 11]. During the hole edge preparation method, significant plastic deformation takes place near the hole edge. As a result,

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initial micro-cracks are generated due to punching and drilling process which is shown in Fig.6b and Fig.6c. These initial micro-cracks serve as crack initiation sites during HET. It is important to note that during punching, the initial micro-cracks are aligned along the through thickness direction whereas, in the drilling process, the initial micro-cracks are mostly in transverse direction. During HET the through thickness micro-cracks tend to open up easily, resulting in lower values of HER in punched specimens. On the other hand, the transverse direction micro-cracks for the drilled edge conditions provide some resistance to the crack progression. Consequently, higher HER values are obtained for the drilled edge conditions.



(b) Punched edge

(c) Drilled edge

Figure 6: (a) Schematic of specimen preparation and orientation (punching and drilling is done along the "z" axis. Arrow represent drill axis). SEM micrographs showing the presence of micro-cracks in the HET specimens (b) Punched edge (c) Drilled edge

4. Conclusions

The objective of the present study was to investigate the effect of temper condition on the edge formability of aluminum alloy AA7075 sheets using hole expansion tests. From this study, the following are major findings.

1. HER was found to be sensitive to the hole preparation method and temper conditions.

- 2. W-temper condition was found to be a promising method for improving the edge formability of AA7075 alloy.
- 3. HER correlate well with the tensile properties. HER is inversely proportional to YS and UTS and directly proportional to UE and TE.
- 4. Through-thickness micro-cracks formed during punching tend to open up easily during HET resulting in lower HER values. On the other hand, transverse micro-cracks are seen to form along the plane of the sheets during drilling. These cracks appear to delay the eventual failure during HET resulting in higher HER values for drilled hole specimens.

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