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Calibration of a Stress-Triaxiality Based Fracture Criterion for a Recycled Aluminum Alloy

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Abstract

Since application of aluminum recycled product is increasing, more consideration arises about effects of impurities build up by recycling process on mechanical properties of these products. As an illustration, Iron is the most important impurity in aluminum alloys which attend in formation of insoluble brittle phases. This causes an overall decrease in ductility of iron containing aluminum alloys and therefore, realization of the fracture behavior of these alloys is important to prevent their fracture during forming processes. One of the most accepted approaches for prediction of fracture of metals during forming processes is the application of a damage criterion complemented Finite Element Method (FEM) in which the fracture is predicted using variables of the forming process such as imposed equivalent plastic strain and stress-triaxiallity. This work is aimed to calibrate a stress-triaxiallity based damage criterion for Al-1.7Fe-0.9Si-0.5Cu alloy using simulations and experiments. For this purpose, deformation behavior of differently notched tensile specimens of this alloy is simulated using Abaqus 6.13 FEM software. Afterward, the used damage criterion is calibrated by comparing results of simulations with experimental results for fracture of specimens. Results show that the applied FEM method can identically predict the deformation and fracture behavior of notched tensile specimen .Using results of FEM simulation such as local stress-triaxiality and local equivalent strain in different specimen, the damage criterion is calibrated for the used alloy as a dependent of stress-traixiallity.

Keywords: Prediction of Fracture, Damage criterion, Stress-triaxiality, Al-Fe-Si-Cu

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1-Introduction

Aluminum is widely used in different industries not only due to its high corrosion resistance, low density and reasonable mechanical properties but also due to its good recyclability. As an illustration, about 40-90% of different aluminum products are made from recycled alloys [1-2]. However, some concerns shall be considered during application of recycled alloys for production of wrought aluminum products. For instance, recycling process contaminate composition of aluminum alloys by different impurities such as Silicon and Iron. These impurities attend in formation of insoluble needle-like and plate-like inclusions which appear as stress concentration sites and may accelerate fracture of the aluminum alloys during forming process [3-5].

One of the well-known methods for studying fracture behavior of metals during forming is application of an accumulative damage function which associates the imposed damage in each increment of forming to deformation variables such as plastic strain and stress state. Using this damage function, the fracture onset can be predicted by a computational method such as Finite Element (FE) which calculates accumulation of damage during forming process [6-8]. Although different variables of deformation have been applied to develop and calibrate damage functions, experimental studies have shown that the fracture of metal is mainly dependent to strain rate, stress-traxiality and imposed equivalent plastic strain [7-8]. Therefore, considering quasi-static state of deformation, the fracture of metal during metal forming process can be predicted using a stress-traxiality based damage function.

As shown by Bao and Wierzbicki (BW) [8-9], the fracture strain curve of a metal can be drawn in a two dimensional space of stress-triaxiality and equivalent strain neglecting effects of other loading parameters. This curve represents two main fracture mechanisms: “Shear fracture” and “Void growth and coalescence fracture”. In addition, the BW fracture strain curve can be generally fitted in a three rule function as below [9-10]:

$$\varepsilon_f(\eta) = \begin{cases} \frac{c_1}{1+3\eta} & -\frac{1}{3} < \eta < 0 \\ c_1 + (c_2 - c_1)\left(\frac{\eta}{\eta_0}\right)^2 & 0 < \eta < \eta_0 \\ c_2 \frac{\eta_0}{\eta} & \eta > \eta_0 \end{cases} \tag{1}$$

Here, η is the stress-triaxiality parameter which is normal stresses average per unit of von-Misses equivalent stress and η_0, c_1 and c_2 are material constants. In this general damage function, the first rule represent shear fracture mode, the third one represents void growth and coalescence fracture mode and the second one represent the mixed fracture mode. As shown in literature, this three rule damage function can accurately predict fracture of aluminum alloys during forming processes [9-11].

This work is aimed to calibrate the BW damage function for a recycled aluminum alloy containing high concentration of Fe and Si. For this purpose, tensile tests of differently notched specimens from this alloy are compared with their FEM simulation counterparts. Compiling results of simulation and experiments, fracture strain vs. stress-triaxiality curve for used material can be drawn and it can be compared with other aluminum alloys.

2- Simulation procedure and Experiments

Deformation behavior of differently notched tensile specimens from the used alloy are simulated by Abaqus 6.13 FEM software using 3D dynamic explicit FEM model based on Lagrangian formulation. Figure 1 shows the geometry of specimens and related dimensions. The thickness of all specimen are considered as 3 mm. Specimens are meshed by the C3D10M tetrahedral elements which consist of 4 nodes. The mesh size is 1.7 mm for un-notched surfaces and 0.5 mm for notched surfaces of specimen. Voce relation is used for extrapolation of flow stress vs. plastic strain curve since this relation can identically predict the flow stress of aluminum alloys subjected to extensive plastic strain [12]. For extrapolation of Voce relation, the saturation flow stress is considered equal to 200 MPa as reported by Reihanian et al. [13].

The chemical composition of used aluminum alloy is evaluated by optical emission spectrometry as Al-1.7Fe-0.9Si-0.5Cu. Scanning Electron Microscope (SEM) is applied to study microstructure of used alloy. Tensile specimens are annealed at 753°K for 45 minutes before tests. Tensile tests are achieved at ambient temperature using strain rate of 0.001 S^{-1}.

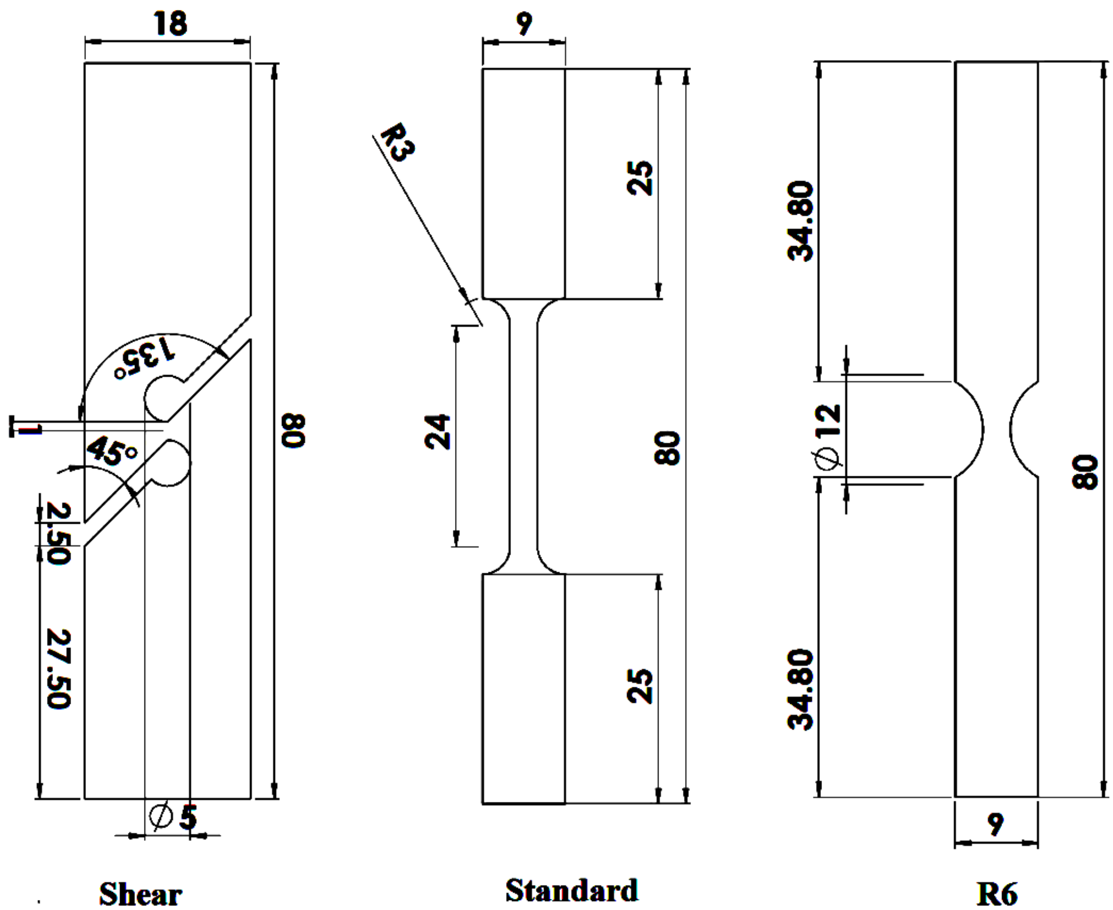
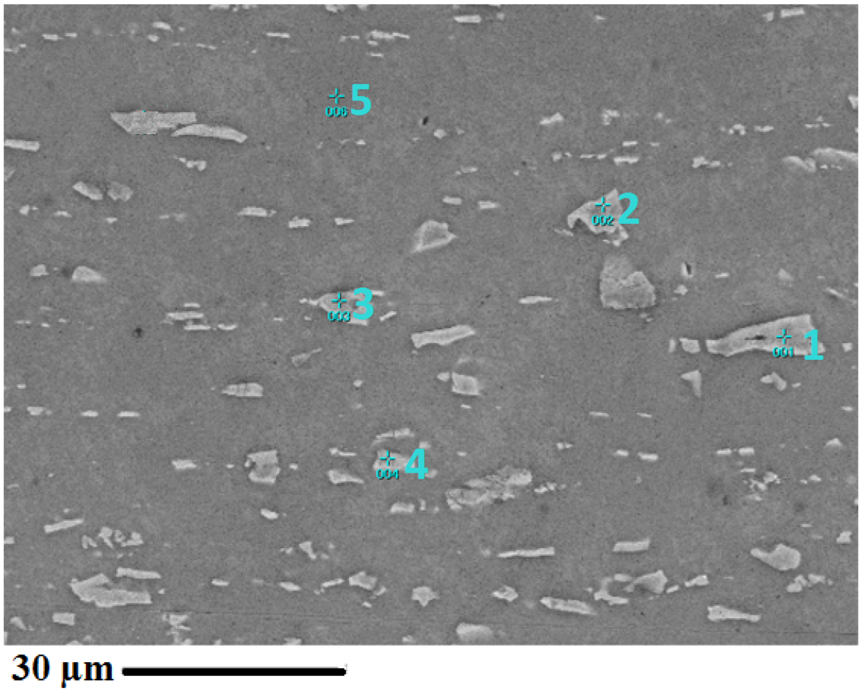


Figure 1: Geometry and dimensions of tensile specimens.

3- Results and discussion

Figure 2 shows SEM microstructure of the used alloy and chemical composition of different points. As shown here, plate-like and needle-like second phase particles sized between 1-10 μm can be seen in the microstructure of used alloy. In addition, these particles mainly consist of Al, Fe and Si elements. Figure 3 compares the results of simulation and experiment for load-displacement curve of R6 specimen. As can be seen, the results of simulation and experiment are similar to each other. This similarity is also observed for “Standard” and “Shear” specimens and indicates the validity of simulation results. The fracture displacements of three tensile specimens are illustrated in Table 1.



	Concentration of Element (Wt%)			
Indicated point Number	Cu	Al	Fe	Si
1	2.6	51.9	38.5	5
2	3.8	55.4	33.2	5.7
3	2.2	57.9	33.3	4.5
4	1.1	62.9	31.8	2.7
5	0.15	98.1	0.1	0.9

Figure 2: SEM microstructure of the used alloy and chemical composition of different points.

Table 1: Fracture displacements of three tensile specimens.

Specimen	Standard	Shear	R6
Displacement at fracture (ΔL_f) (mm)	4.27	3.00	1.62

Figure 4 illustrates variation of stress-triaxiality by displacement for different specimens. As can be seen, the average stress-triaxiality for “Standard”, “Shear” and R6 specimen is 0.38, 0.02 and 0.54, respectively. Figure 5 compares the contours of plastic strain at fracture displacement (ΔL_f) for different specimens. As can be seen, the fracture strain for “Standard”, “Shear” and R6 specimen is 0.89, 0.75 and 0.65, respectively. By substitution of simulation results in Eq. 1, η_0, c_1 and c_2 for the used alloy are calculated as 0.395, 0.74 and 0.89, respectively. Using these constant parameters, the fracture strain vs. stress-triaxiality curve for the used alloy is drawn as presented in Figure 6.

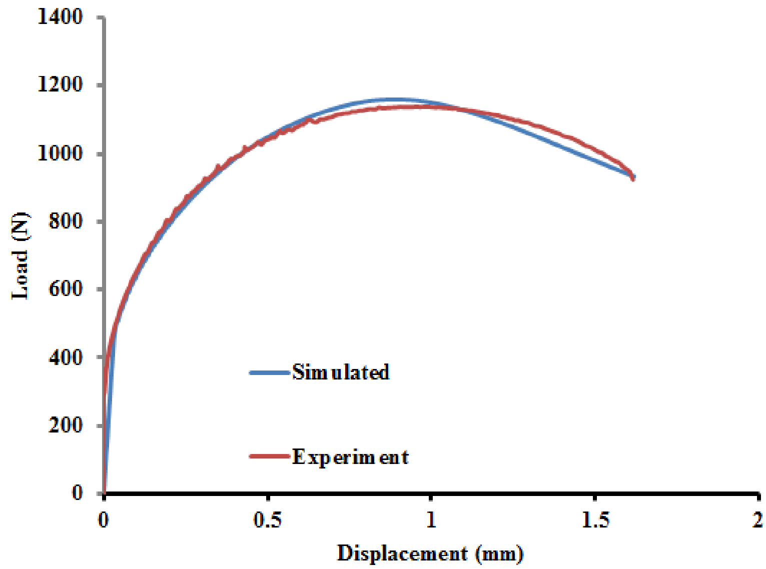


Figure 3: Experimental and simulation results for load-displacement of R6 tensile test.

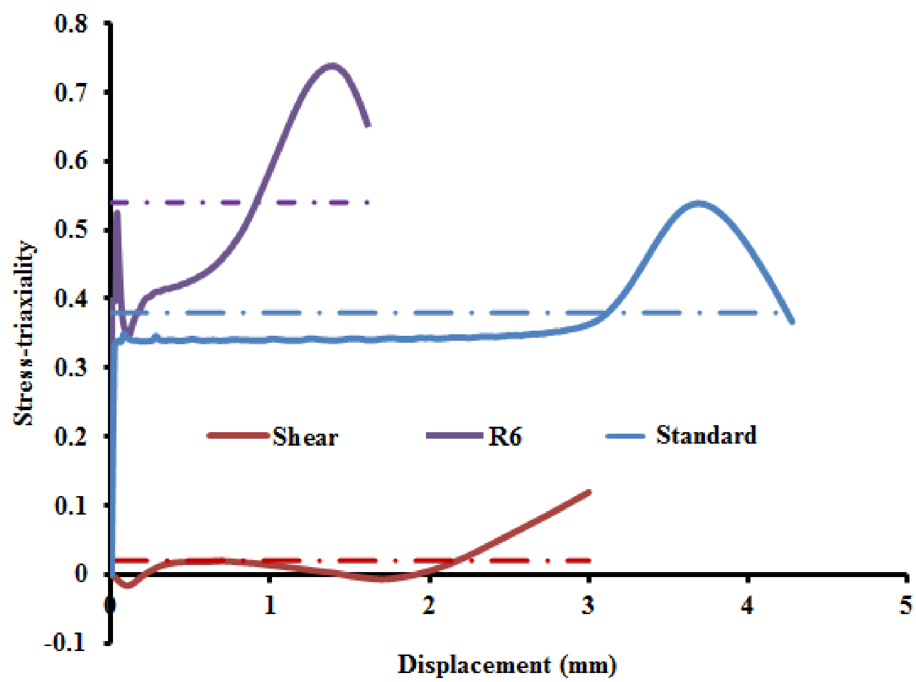


Figure 4: Variation of stress-triaxiality by displacement for different specimens.

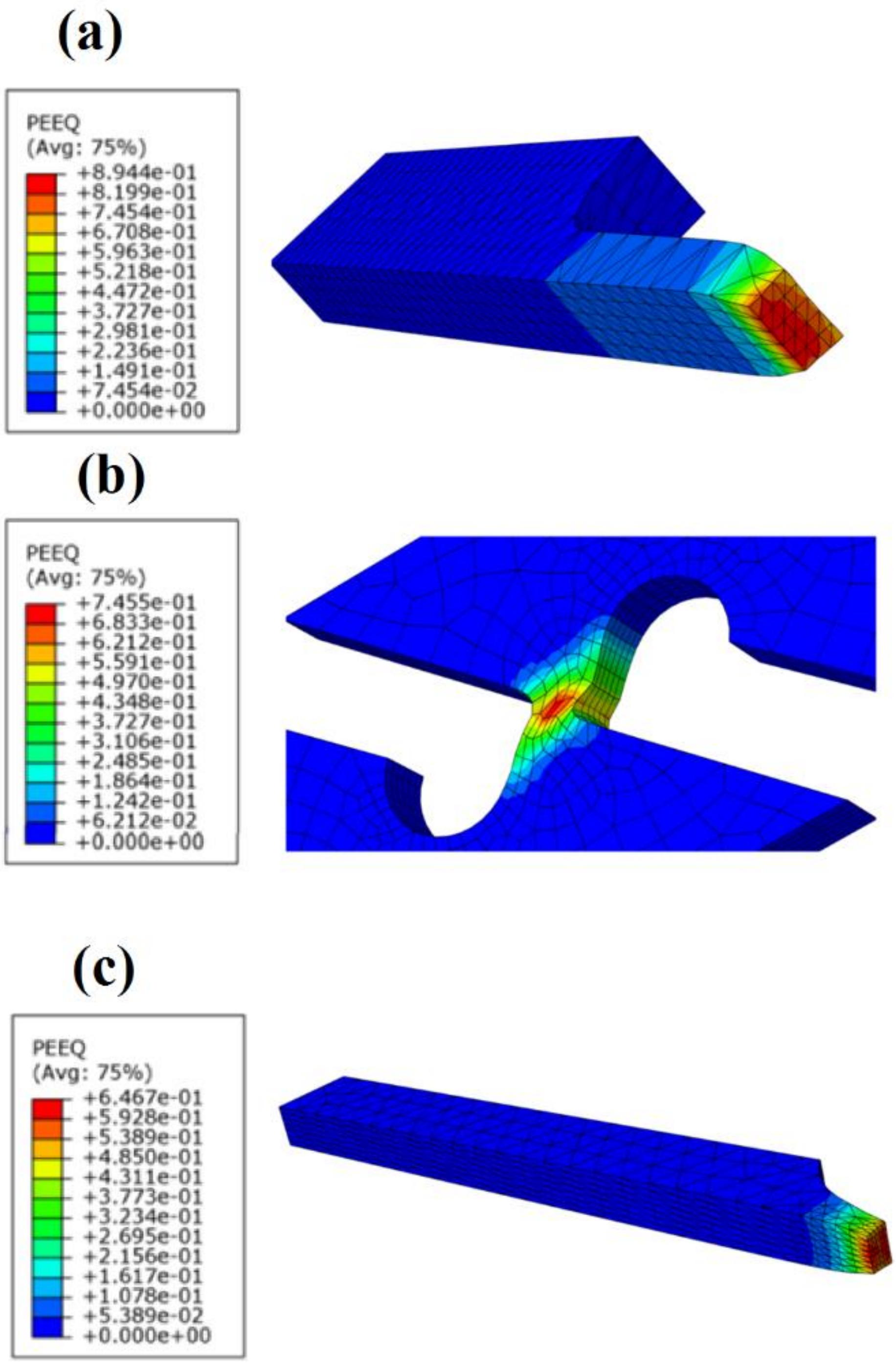


Figure 5: Distribution of equivalent plastic strain at ΔL_f for: (a) Standard, (b) shear and (c) R6.

As can be seen in Figure 6, the fracture strain of Al-1.7Fe-0.9Si-0.5Cu is very close to two other aluminum alloys ones when the stress-triaxiality is less than 0.2. This domain is where the shear fracture is predominant fracture mechanism. This implies that presence of second phase particles has negligible effect on occurrence of shear fracture in aluminum alloys. Despite this, the fracture strain of Al-1.7Fe-0.9Si-0.5Cu is less than other aluminum alloys ones when the stress-triaxiality is greater than 0.2. This domain is where the void growth and coalescence fracture mechanism becomes predominant. The lower fracture strain of Al-1.7Fe-0.9Si-0.5Cu is more obvious when the stress-triaxiality is greater than 0.4-0.5. Here, the fracture takes place purely due to void growth and coalescence mechanism. In addition, when the stress-triaxiality is greater than 0.5, the highest fracture strain is related to 1050H14 alloy which is containing relatively negligible concentration of second phase particle in comparison of 6061O and Al-1.7Fe-0.9Si-0.5Cu alloys. This illustrates more activity of void growth and coalescence fracture mechanism in alloys containing second phase particles [14]. In addition, the lower fracture strain of Al-1.7Fe-0.9Si-0.5Cu in comparison of 6061O can be attributed to brittleness of Fe/Si containing second phase particles which accelerates overall fracture of the alloy [14].

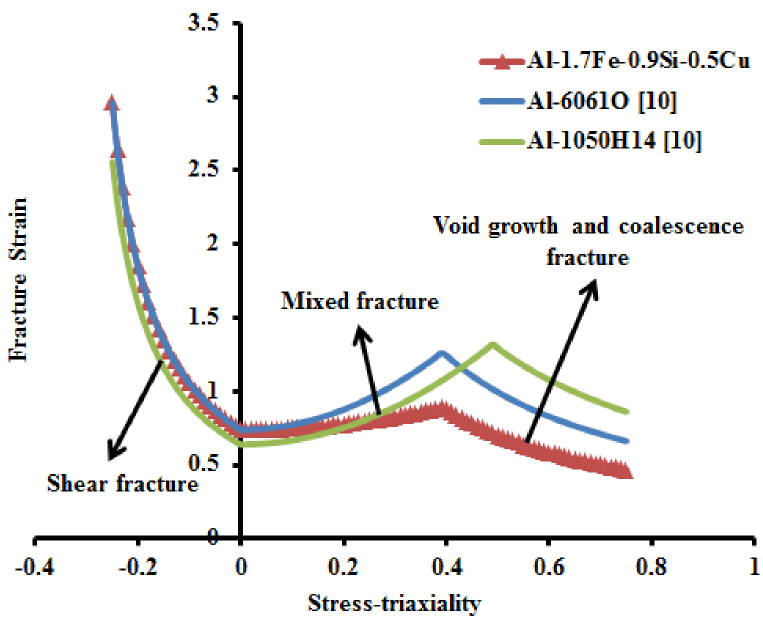


Figure 6: Comparison of fracture strain vs. stress-triaxiality curve for different aluminum alloys.

5- Conclusions

Considering what told above, results of this work can be briefly presented as below:

1- Fracture strain vs. stress-triaxiality curve for Al-1.7Fe-0.9Si-0.5 Cu alloy is drawn using BW damage function.

2- When the stress-triaxiality is less than 0.2, the fracture strain of Al-1.7Fe-0.9Si-0.5 Cu is very close to other aluminum alloys ones. This implies negligible effect of second phase particles on shear fracture mechanism of aluminum alloys.

3- For stress-triaxialities greater than 0.2, the fracture strain of Al-1.7Fe-0.9Si-0.5 is lower than other aluminum alloys ones attributed to presence of brittle second phase particles which accelerate void growth and coalescence fracture mechanism.

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