A REVIEW OF PARAMETERS AFFECTING DUCTILE FRACTURE OF ALUMINUM ALLOY

Savan P. Makwana

M.E.CAD/CAM, Mechanical Engineering, A.D. Patel Institute of Technology, Gujarat, India

ABSTRACT

This paper reviews mechanical properties of two types of cast aluminium components made in sand mould and cast iron mould. And also experimental data and numerical simulations of smooth and notched tensile tests on four different aluminum alloys are used to investigate the effect on ductile fracture. The ductile fracture of alloys may be described by macroscopic models which indicate that the tensile fracture strain should scale with the yield strength for a constant microstructure. An important failure mechanism in ductile metals and their alloys is by growth and coalescence of microscopic voids. Using a combined experimental–numerical approach, the plasticity and fracture properties of the components are characterized in terms of the true stress–strain curve and the ductile fracture locus. It is found that the sand-moulding component is of higher yield resistance and lower ductility than the metal-moulding one. The importance of non-proportional loading paths on the predicted ductility of the aluminum alloys used in this investigation. The fracture strain of Al alloys scales linearly with the yield strength, the detailed relationship depending on aspects of the microstructure relevant to the fracture process. The decrease in fracture strain with increasing yield strength identifies a yield strength that, if achievable, would have a zero fracture strain. This could be a useful parameter when considering the optimization of alloy composition, microstructure, heat treatment or processing for the best combination of strength and fracture resistance reveals that there exist two competing failure mechanisms, Meanwhile, the fractographic study reveals that there exist two competing failure mechanisms: the internal necking of the matrix at high positive stress triaxialities and void sheeting due to shear at negative stress triaxialities.

Keyword: Ductile fracture, sand mould, cast iron mould, aluminum , numerical approach

---

1. INTRODUCTION

Sand and metal are two types of mould media commonly used in casting manufacturing processes. Because of superior heat dissipation ability, metal moulds are able to rapidly solidify cast alloys and thus to refine dendrite cells. Cast components made in metal moulds usually exhibit higher ductility than in sand moulds. The improvement of mechanical properties of aluminium castings by increasing solidification rates was reported in the literature.

Ca´ceres et al. (1995) and Wang (2003) obtained a wide range of solidification rates in one single cast thick plate by attaching a large cast iron chill at one end. Tensile tests were performed on round bars prepared at different distances from the chill. It was shown that the specimen machined at the chilled end was of the largest elongation to fracture. Shabestari and Moemeni (2004) evaluated four different types of moulds made of graphite, copper, cast iron, and sand, respectively. It appears that the graphite mould produces the casting of the highest ductility. Mae (2007) presented the material ductility was characterized through round bar tensile tests. A previous study reveals that cast aluminium components are of significantly higher resistance to fracture under shear than under tension. Hence, it would be interesting to study effects of solidification rates on fracture properties under compression and shear. Results from previous experimental studies have revealed a nearly linear relationship between the tensile failure strain and the initial yield stress of various aluminum alloys (Liu et al., 2011; Lloyd, 2003). Similar results have also been reported in recent studies for the aluminum alloys considered in the present work (Pedersen et al., 2015; Westermann et al., 2014) and for 6xxx aluminum alloys (Hannard et al., 2016). In the present study, the scaling of the failure strain with the initial yield stress of the material is investigated by micromechanical simulations. A large experimental database is available from previous studies on various aluminum alloys (Pedersen et al., 2015; Westermann et al., 2014), which serves as the background material for this numerical study.

1.1 Specimen preparation

The tensile tests on round bars are commonly used to calibrate plasticity and fracture properties of materials. The round bar tensile tests characterize the ductility of the cast components under tension. Fracture properties under compression and shear are determined from biaxial loading tests on butterfly specimens. The butterfly specimen is of double curvature in the gauge section and thus there is a smooth transition from the shoulder region to the gauge section. The stress concentration on the boundary of the gauge section is diminished. At the same time, the central region of the gauge section is of the minimal thickness 1.0 mm, which is one third of the thickness of the shoulder region. This design ensures that a macroscopic crack would first occur at the centre of the gauge section. The geometrical dimensions of the butterfly specimen are given in Fig.1.

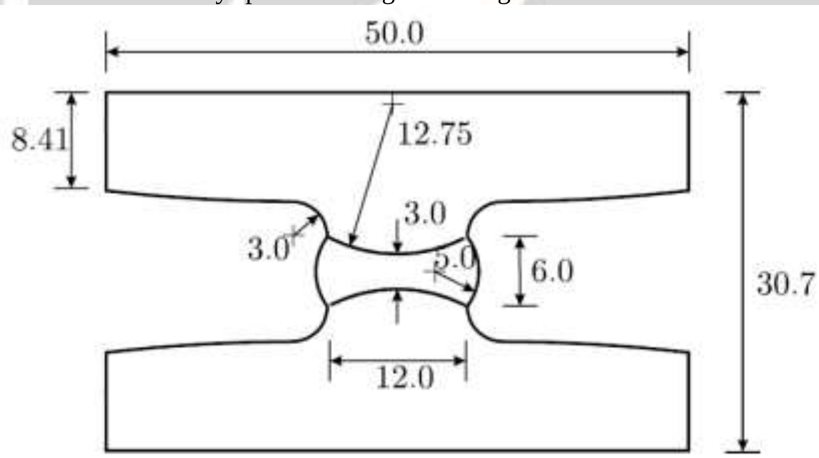


Figure 1 Geometrical dimensions

1.2 Fracture in 6000 series alloys

To examine the fracture behaviour of aged 6000 series alloys, 1 mm sheet samples of AA6111-T4 (nominally Al–0.7wt.%Mg–0.7wt.%Si–0.7wt.%Cu–0.2wt.%Mn0.2wt.%Fe) were aged for various times in the temperature range 100–180 ^{o}C, tensile tested at room temperature and the yield strength and fracture strain (taken as the reduction in area at fracture, RA%) measured. The resulting variation in RA with yield strength is shown in Fig. 2.

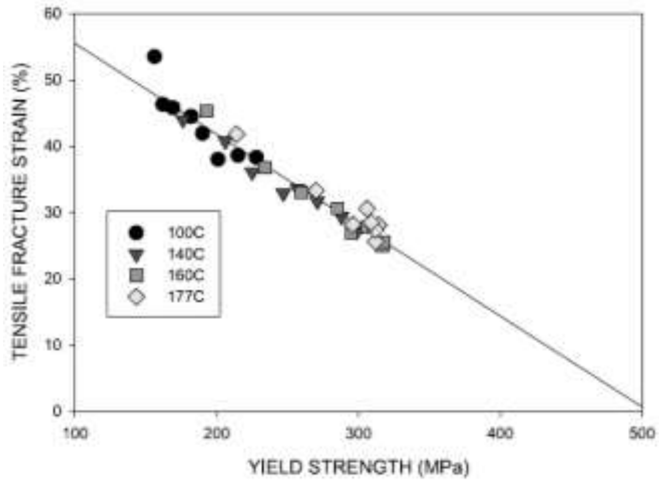
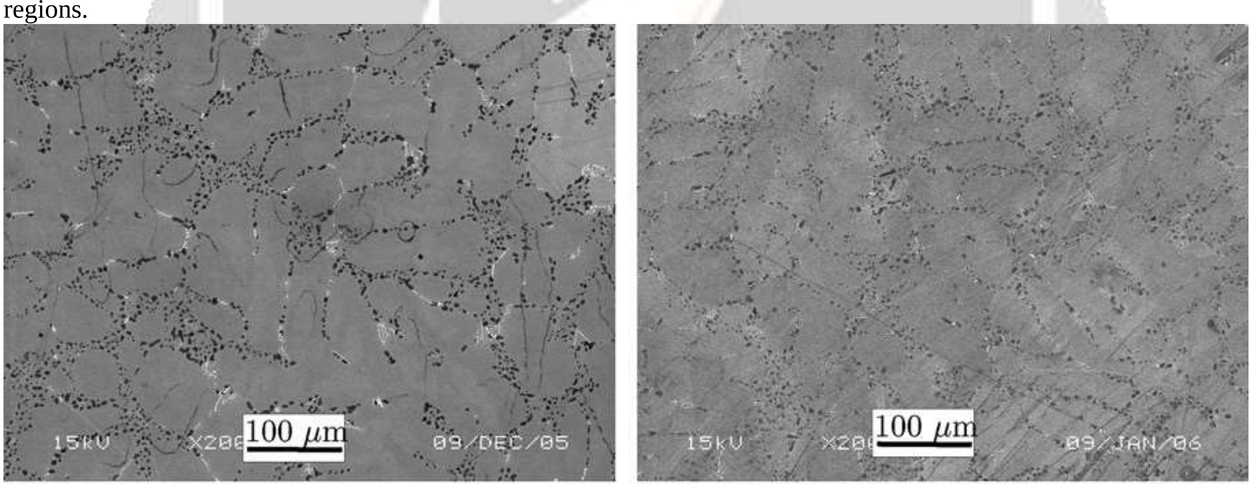


Figure 2 Variation in fracture strain with aging in AA6111

2. MICROSCOPIC OBSERVATIONS

This section presents metallographic and fractographic examinations of the two types of the cast aluminium components. In order to evaluate effects of mould media, variation in fracture strain with aging in AA6111 microstructure of the castings, dozens of small cylinders were prepared and polished for microscopic observation and measurement. Two selected SEM graphs are displayed in Fig. 3 showing typical aluminium-rich dendrites separated by eutectic regions. The Secondary Dendrite Arm Spacing (SDAS) was measured to describe the microstructure. The average values of the SDAS are 60 lm and 40 lm, respectively, for the sand-moulding and the metal-moulding components. The increase in the cooling rate refines dendrite cells and silicon particles in eutectic regions.



(a) Sand-molding (b) Metal-molding

Figure 3 Microscopic structures of the sand-moulding and the metal-moulding components.

2.1 Fractographic analysis

To better understand the failure mechanism of the castings under various loading conditions, the fracture surface of each specimen was examined with a scanning electronic microscope. Some of the SEM pictures are selectively presented in the paper. Fig. 4 shows the fractographs of the unnotched round bars. A number of small dimples, which is a typical characteristic of the ductile fracture, can be easily recognized. The fracture surfaces also exhibit many, smooth, flat areas separated by bright ridges. The flat areas are cleaved silicon particles. Studies have found that the fracture of cast aluminium alloys is often initiated by the cracking of silicon particles, e.g. see Dighe et al. (2002) and Wang (2003).

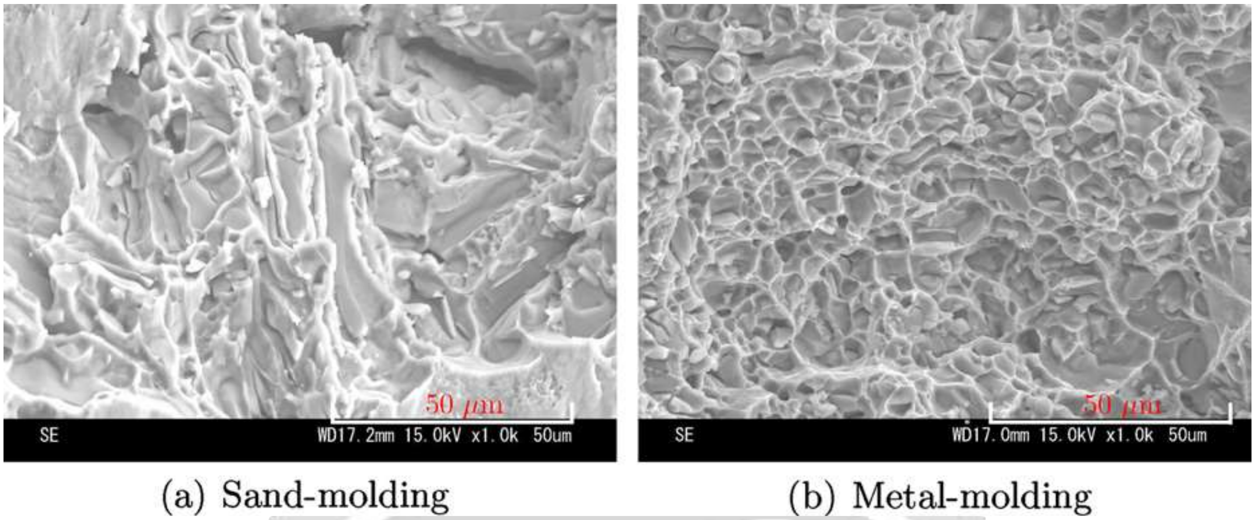


Figure 4 Fractographs of the combined tension and shear tests on the butterfly specimens

2.2 True stress–strain curves

The difference in the load–displacement response between the sand-moulding and the metal-moulding castings can be clearly attributed to the distinction in plasticity properties. Fig.5 illustrates the true stress–strain curves calibrated for the two types of the cast components. It appears that the sand-moulding component is of higher yield resistance and hardening rate than the metal-moulding one. This finding is consistent with the experimental data obtained by Wang (2003). An inverse engineering approach was used to determine the true stress–strain curves. Two-dimensional, axi-symmetrical and three-dimensional finite element models were developed, respectively, for the round bars and the butterfly specimens with ABAQUS/Standard.

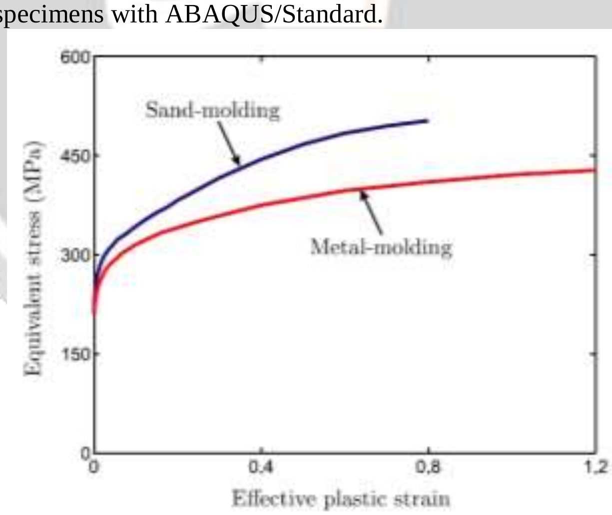


Figure 5 The true stress–strain curves for the sand-moulding and the metal-moulding cast aluminium components

3. NON-HEAT TREATABLE ALLOYS

The results from the AA6111 experiments demonstrate that the fracture strain does scale linearly with the yield strength, and the relationship is dependent on the particular heat treatment. The commercial non-heat treatable Al alloys are microstructurally very similar, achieving their range of strengths mainly by solute compositional variations, but they will have a variation in grain sizes, dispersion particle and constituent particle contents. In spite of these differences the fracture strain scales quite well with the yield strength. This demonstrates that the influence of microstructural features such as constituent particle content has to be considered in the context of the strength of the alloy.

4. CONCLUSIONS

The present paper reviewed the parameters affecting the fracture ductility of aluminium alloy. the mechanical properties of the two types of the cast aluminium components were compared using the combined experimental–numerical approach. The castings were made in sand moulds and cast iron moulds, respectively. A comparison was made to investigate the effect of the solidification rate on the plasticity and ductility. The fracture surface of the is examined using a scanning electron microscope. Two distinct fracture patterns are observed. In the tensile tests, fracture first occurs at large silicon particles by the cleavage mechanism. Cracks grow along grain boundaries leading to the complete failure of the round bars. Also The fracture strain of Al alloys scales linearly with the yield strength, the detailed relationship depending on aspects of the microstructure relevant to the fracture process. Tensile fracture occurs as a result of void nucleation, growth and coalescence, all of which can occur simultaneously in different regions of the sample.

6. REFERENCES

[1]. H. Mae et al., 2007. Comparison of ductile fracture properties of aluminium castings: Sand mould vs. metal mould International Journal of Solids and Structures 45 (2008) 1430–1444.
[2]. Bao, Y., Wierzbicki, T., 2004. A comparative study on various ductile crack formation criteria. Journal of Engineering Materials and
Technology 126 (3), 314–324.
[3]. Ca´ceres, C.H., Davidson, C.J., Griffiths, J.R., 1995. The deformation and fracture behaviour of an Al–Si–Mg casting alloy. Materials Science and Engineering A 197, 171–179.
[4]. Wang, Q.G., 2003. Microstructural effects on the tensile and fracture behavior of aluminium casting alloys A356/357. Metallurgical and Materials Transactions A 34, 2887–2899.
[5]. Leupp, J., Epprecht, W., 1977. Ductile intergranular fracture of an aluminium cast alloy. Scripta Metallurgica 11, 13–15.
[6]. Liu, G. , Scudino, S. , Li, R. , Kühn, U. , Sun, J. , Eckert, J. , 2011. Coupling effect of primary voids and secondary voids on the ductile fracture of heat-treatable aluminium alloys. Mech. Mater. 43 (10), 556–566
[7]. Papasidero, J. , Doquet, V. , Mohr, D. , 2015. Ductile fracture of aluminium 2024-t351 under proportional and non-proportional multi-axial loading: Bao-wierzbicki results revisited. Int. J. Solids Struct 69–70, 459–474 .
[8]. Hannard, F. , Pardoen, T. , Maire, E. , Le Bourlot, C. , Mokso, R. , Simar, A. ,2016. Char- acterization and micromechanical modelling of microstructural heterogeneity effects on ductile fracture of 6xxx aluminium alloys. Acta Mater. 103, 558–572 .
[9]. Westermann, I. , Pedersen, K.O. , Furu, T. , Børvik, T. , Hopperstad, O.S. , 2014. Effects of particles and solutes on strength, work-hardening and ductile fracture of alu- minium alloys. Mech. Mater. 79, 58–72 .
[10]. Chandra, N. , Li, H. , Shet, C. , Ghonem, H. , 2002. Some issues in the application of cohesive zone models for metal-ceramic interfaces. Int. J. Solids Struct. 39 (10), 2827–2855 .
[11]. Johnson, G.R., Cook, W.H., 1985. Fracture characteristics of three metals subjected to various strains, strain rates, temperatures and pressures. Engineering Fracture Mechanics 21 (1), 31–48
[12]. Mae, H., Teng, X., Bai, Y., Wierzbicki, T., 2007. Calibration of ductile fracture properties of a cast aluminium alloy. Materials Science and Engineering A 459 (1–2), 156–166
[13]. Powell, G.W., 1994. The fractography of casting alloys. Materials Characterization 33, 275–293.
[14]. Teng, X., Mae, H., Bai, Y., Wierzbicki, T., submitted for publication. Statistical analysis of ductile fracture properties of a cast aluminium alloy.
[15]. Wierzbicki, T., Bao, Y., Lee, Y.-W., Bai, Y., 2005a. Calibration and evaluation of seven fracture models. International Journal of Mechanical Sciences 47 (4–5), 719–743.