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Impact toughness of ternary Al–Zn–Mg alloys in as cast and homogenized condition measured in the temperature range 263–673 K

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Abstract. **Impact toughness of six Al–Zn–Mg ternary alloys are compared with two Al–Zn binary alloys and one CP aluminium metal at eight different temperatures of 263, 268, 273, 300, 373, 473, 573 and 673 K. The effects of alloying and temperature on toughness have been compared and analysed. The influence of alloying is more pronounced than that of temperature in reducing the toughness.**

Keywords. **Toughness; alloy; temperature; aluminium; zinc; magnesium.**

1. Introduction

Al–Zn–Mg alloys constitute an important group among precipitation hardenable aluminium alloys used for aerospace applications (Hatch 1984; Polmear 1995). These have a sloping solvus line in phase diagrams. These alloys possess high strength and adequate stress corrosion resistance (Harendranath *et al* 1974; Prasad and Mallik 1975; Ganguly *et al* 1978; Balasubramanian and Sarkar 1979; Fontana 1987; Rajan *et al* 1992; Smith 1993). Charpy impact toughness is a simple measure of estimating the capability of these alloys to withstand shock and impact loading (Avner 1974; Dieter and Bacon 1988; Reedhill and Reza Abbaschian 1994). It involves testing at a high velocity, of the order of 5 m/s. The sample used is subjected to a triaxial tensile state of stress, high strain rates (10^3 s^{-1}) and localized stress concentration at the notch. It is to be noted that brittleness, ductility and toughness are not fundamental properties of an alloy or a metal (Courtney 1990). It depends on service conditions such as temperature, type of stress and environment (Troiano 1960; Brown 1968; Beechen 1972). The effect of temperature, alloy content and crystal structure on toughness of Al–Zn–Mg ternary alloys is dealt with in the present work. The alloys were used in as cast and homogenized condition purely on the basis of theoretical and academic interest.

2. Experimental

Al–Zn–Mg alloys were obtained by melt casting and air cooling. These were cut into pieces 60 × 15 × 15 mm in size and machined into standard charpy impact test specimens (55 × 10 × 10 mm) with a 45° V-notch 2 mm deep and 0·25 mm root radius. These specimens were then homogenized at 773 K for 10 h to eliminate segregation residual stress and inhomogeneity. Holding time was 2–3 min/mm^2 of section thickness. For 100 mm^2 it will be 3–4 h. Normally ingots are homogenized at 693–793 K for 20–30 h. Since the samples were not ingots and had very small cross-sectional area the above temperature (773 K) and time (10 h) were chosen. Many specimens of six ternary alloys of different compositions were obtained. After homogenizing, the samples were furnace cooled. It gave equilibrium phases of a and q. No natural ageing was possible as no supersaturated solid solution (SSSS) existed after air cooling. Moreover q is not coherent with a. The impact test was carried out at 8 different temperatures of 263, 268, 273, 300, 373, 473, 573 and 673 K. At each temperature two samples were tested. Lower temperatures of 263, 268, 273 K were achieved by using ice and salt mixture and higher temperatures of 373, 473, 573 and 673 K were achieved using an electric furnace. The samples were soaked at each temperature for 2 h to achieve a uniform specimen temperature and then tested for toughness. The experiments were also conducted on commercially pure aluminium and two binary Al–Zn alloys for comparison, with the following six ternary alloys of Al–5Zn–1Mg, Al–5Zn–2Mg, Al–5Zn–3Mg, Al–10Zn–1Mg, Al–10Zn–2Mg and Al–10Zn–3Mg.

3. Results

The Rockwell hardness values at room temperature are shown in table 1 for all the compositions. Figure 1 shows the energy absorbed at various temperatures for all the nine compositions. It is obvious from the figure that

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energy absorbed gradually decreases as testing temperature decreases. The drop is neither very sudden nor very sharp. At any given temperature commercial purity aluminium possesses the highest toughness and Al–10Zn–3Mg the lowest toughness. As the alloy content increases toughness decreases at all temperatures. At 673 K, commercial purity aluminium has a toughness of 40·4 J while Al–10Zn–3Mg has 13·1 J, a drop of about 30 J due to alloying. At 263 K, the respective values are 29·7 J and 11·7 J, a drop of only 18 J. For Al–10Zn–3Mg ternary alloy as temperature of testing changes from 673 K to 263 K impact toughness changes from 13·1 to 11·7 J, a decrease of 1·4 J. The respective values for commercial purity aluminium are 40·4 J, 29·7 J and 10·7 J. The effect of alloying is more pronounced than that of temperature. Binary Al–Zn alloys come intermediate between ternary alloys (maximum alloying) and commercially pure aluminium (zero alloying). The fracture surfaces were fibrous, dull and grey indicating the ductile behaviour of the specimens. Some of the specimens did not even break into two pieces. Most of them were bent. This is also corroborated by the (toughness values) energy absorbed in each test as shown in figure 1.

Table 1. Hardness values at room temperature for the nine compositions.

Material	Hardness (R_H)
Al	10
Al–5Zn	13
Al–10Zn	15
Al–5Zn–1Mg	16
Al–5Zn–2Mg	24
Al–5Zn–3Mg	28
Al–10Zn–1Mg	20
Al–10Zn–2Mg	30
Al–10Zn–3Mg	35

4. Discussion

The ductility of an alloy or a metal is explained with the following equation (Cottrell 1958)

$$(t_i D^{1/2} + K')K' = G g_s b,$$

where t_i is the resistance of the lattice to dislocation movement, D the grain size, K' a parameter related to the release of dislocation from a pile up, g_s the effective surface energy including the energy of plastic deformation, b the ratio of shear stress to normal stress (it is equal to 1 for torsion, 1/2 for tension and 1/3 for a notch) and G the shear modulus. This equation is valid for different strain rates which will influence t_i.

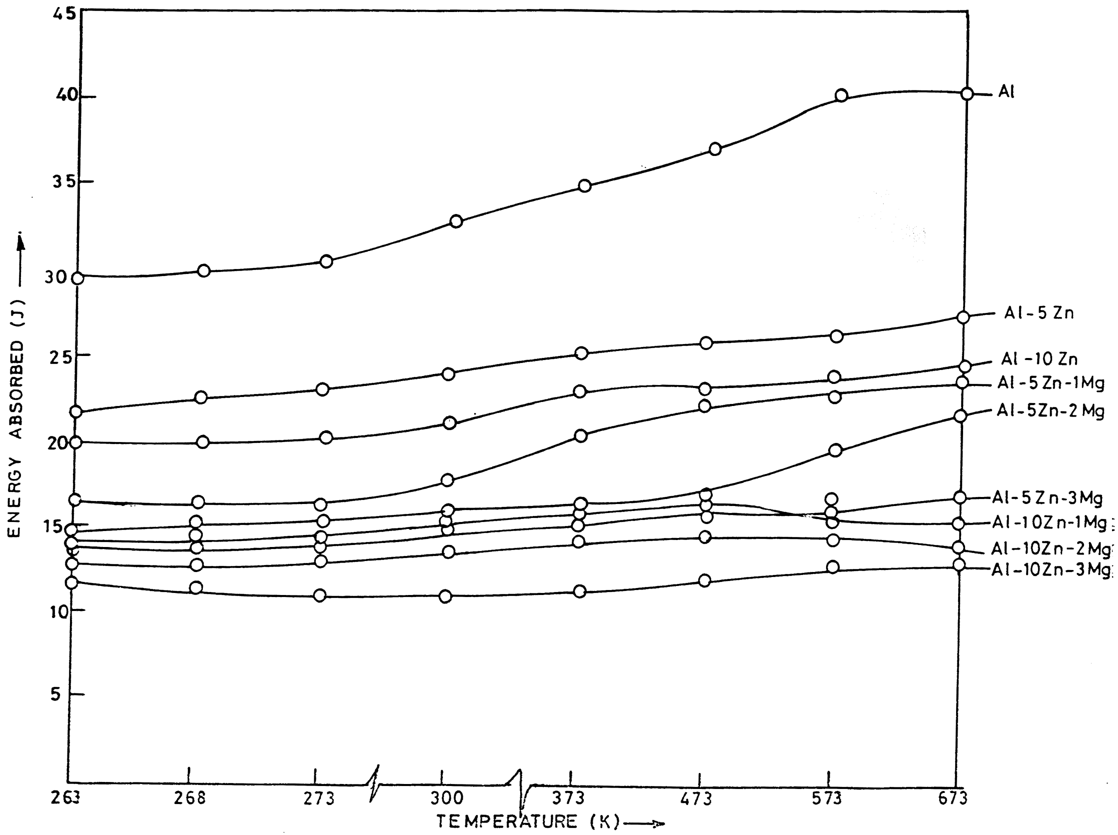

Figure 1. Variation of energy absorbed against temperature.

The above equation expresses the limiting condition for propagation of cracks from a pile up of glissile dislocations. If the LHS < RHS microcrack will form but no growth occurs. If LHS > RHS a propagating crack will grow when shear stress is equal to yield stress. If K' is high the alloy is more prone to brittle fracture, as the dislocations get locked up. The number of mobile dislocations at the tip of crack is important as also the number of available slip systems.

The number of mobile dislocations is very less in BCC metals and only three slip systems are available in HCP metals. In FCC metals and alloys neither of the above condition exists. Consequently these FCC metals and alloys are not ordinarily prone to brittle fracture. Toughness is reasonably high at all the temperatures used for testing in the present case and all the 9 compositions tested possess FCC crystal structure. The influence of crystal structure and temperature are minimal in the present case in lowering the toughness but the effect of alloying is very pronounced. Solid solution strengthening occurs due to alloying and dislocation movement is hampered as a result. Mobile dislocations are locked up. This reduces the toughness. That is why the heavily alloyed Al–10Zn–3Mg alloy has the lowest toughness among the nine compositions tested. Some precipitates may also have formed which again affects the movement of dislocations. The effect is not expected to be very significant since the samples are not naturally or artificially precipitation hardened but were tested in as cast and homogenized condition. It is well established that at temperature below solvus temperature equilibrium microstructure consists of $a + q$ where q is $MgZn_2$ in ternary alloys. At higher temperatures (473, 573, and 673 K), above the solvus temperature the equilibrium microstructure is a only. But the effect on toughness by dual phase and single phase microstructure is as expected. Equilibrium precipitate 'q' is not coherent with a and also number, size and distance between precipitates should be optimum for effective strengthening of the alloy (peak hardness) and consequent reduction of toughness, appreciably.

Irrespective of when and where the measurement is done, at a given temperature, toughness remains the same because of the amount of microconstituents. As temperature of testing increases volume of second phase decreases and above the solvus line volume of second phase is zero. As a result toughness increases with increase in temperature albeit marginally, due to microstructure (a or $a + q$) consisting of different proportions of a and q.

The increase in toughness due to the influence of microstructure is not dominant compared to the effect of increase in temperature for a particular alloy. At higher temperatures number of dislocations released are more. Therefore temperature is more influential as can be seen from the factor K' and t_i in Cottrell's equation. Both of them are less at higher temperatures.

5. Conclusions

The following conclusions were arrived at based on the present work:

(I) As the temperature of testing decreases impact toughness decreases for all the nine compositions but very insignificantly.

(II) As the alloy content increases toughness decreases at a constant temperature. The least value of toughness is obtained for the heavily alloyed Al–10Zn–3Mg system (13·1 J) and the highest value is obtained for commercial purity aluminium (zero alloying) (40·4 J) at 673 K.

(III) No DBTT occurs in all the nine compositions due to the crystal structure being FCC even though individually, Al is FCC, and Zn and Mg are HCP.

(IV) The effect of alloy content in decreasing toughness is more pronounced than that of decrease in tem perature.

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