RESISTANCE TO FRACTURE OF AlZnMgCu HIGH STRENGTH ALLOYS - The effect of chemical composition and microstructure -

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Several Al alloys of AlZnMgCu type had been designed in order to meet the specification requirements regarding strength and fracture toughness for heavy duty structures, with the content of Zn ranged between 6.0 and 8.8 and of Mg ranged between 2.15 and 3.6.

The best combination of strength ($R_{p0,2}$=645 MPa, R_m=670 MPa) and fracture toughness (K_{Ic}=41.4 MPa·$\sqrt{m}$) properties of high strength alloy AlZnMgCu had been achieved by 7.2% Zn and 2.2% Mg and limited amount of Fe content (0.12%), obtained after two steps precipitation regime (100°C/5h + 160°C/5h). Ductile microstructure for this alloy is a result of fine grained second phase particles, corresponded to low Fe content and applied heat treatment.

INTRODUCTION

Materials of complex specified properties, such as strength, ductility, fracture resistance, stress corrosion cracking resistance, are required for the application in structures operating under heavy service loadings (aircrafts and rocket industry) with prescribed high level of safety margin.

Aluminum alloys, due to convenient strength-to-density ratio, have found extensive application in heavy duty structures. This is the case with AlZnMgCu alloys exhibiting the highest strength level, but in the same time high level of susceptibility to fracture and stress corrosion.

Mechanical properties of AlZnMgCu alloys are depended on chemical composition, primarily on total Zn+Mg content and Zn/Mg ratio, on the presence of Mn, Cr, Zr metals and impurities Fe and Si, on the microstructure as a result of fabrication thermomechanical and heat treatment conditions, e.g. on morphology, distribution and volume portion of intermetallic (IM) phases and texture.

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In the microstructure of AlZnMgCu alloy, the presence of three types of particles could be expected (1, 2, 3):

- large inclusions, 0.1 to 10 μm in diameter, produced during crystalization (solidification), mainly unsoluble IM phases rich in Fe and Si; these phases are weak points regarding the fracture resistance properties;
- intermediate particles, rich in Cr, Mn, or Zr, 0.05 to 0.5 μm in size;
- small precipitates, with dimensions 0.01 to 0.5 μm, as a result of solid solution decomposition - thermal precipitation (ageing).

Based on requirement to develop Al alloy with ultimate tensile strength above 650 MPa (R_m>650 MPa) and satisfactory level of ductility and fracture toughness, several alloys had been designed with Zn content between 6 and 8.8% and Mg content of 2.15 to 3.5 %, saving the same amount of other alloying elements (Cu, Mn, Cr, Zr). In order to get a closer insight in metallurgical effects of hot and cold work, thermomechanical and heat treatments on microstructural variations and mechanical properties, appropriate tests had been performed with designed alloys. The morphology and distribution of unsoluble phases sized above 0.6 μm had been investigated by quantitative metallographic analysis and their influence on fracture resistance evaluated.

The paper presents the results of comparative fracture mechanics tests of AlZnMgCu alloys of different chemical composition and heat treatments.

EXPERIMENTAL DATA

Material. Chemical compositions of some experimental alloys are presented in Table 1. Experimental heats had been produced by regular procedure: casting, homogenization and extrusion into bars with cross-section 20x50mm. Heat treatment consisted of solution heat treatment 460°C/2h, quenching in water and precipitation (ageing) according to different regimes:

a. one step ageing on temperatures 80-140°C during 1 to 24 hours;
b. two steps ageing: I step 80-100-120°C during 1 to 16 hours;
II step 120-200°C during 24 to 6 hours.

Test results. Tensile properties, ultimate tensile strength R_m and yield strength $R_{p0,2}$ are tested on small size proportional specimens, 8mm in diameter. Graphic presentation in Figure 1 is a result of tested 200 heats of AlZnMgCu alloys, heat treated at 460 C for 2 hours, water quenched and artificially aged in one step (120°C/24h). From statistics evaluation following relations could be derived for Zn and Mg in wt%:

TABLE 1 - Chemical composition of experimental alloys

Alloy Designation	Chemical composition wt (%) Zn	Mg	Cu	Mn	Cr	Zr	Impurities Fe	Si
A02	6.00	2.20	2.58	0.28	0.25	0.15	0.28	0.11
B01	7.15	3.15	1.53	0.23	0.22	0.15	0.28	0.11
C02	7.38	2.21	1.44	0.29	0.24	0.15	0.28	0.11
C03	7.20	2.21	1.44	0.29	0.24	0.15	0.21	0.06
C04	7.20	2.15	1.46	0.28	0.16	0.12	0.12	0.05
D02	8.30	3.30	1.63	0.24	0.23	0.15	0.28	0.15
D03	8.20	2.35	1.45	0.29	0.19	0.15	0.15	0.07
D04	8.80	3.50	1.45	0.27	0.21	0.15	0.14	0.07

$$R_m = 461.74 + 20.16\,Zn + 33.82\,Mg$$
$$R_{p0.2} = 350.81 + 28.40\,Zn + 35.10\,Mg$$

Plain strain fracture toughness, K_{Ic}, had been tested according to ASTM E 399 on SE(B) spesimens of 20x40mm cross-section. Fatique pre-crack was produced on high-frequency pulsating machine. Figure 2 presents the results obtained for several alloys of different Zn and Mg contents, produced according above given regime. Fracture toughness, as depended on Zn and Mg wt %, can be defined in following form:

$$K_{Ic} = 66.78 - 2.6\,Zn - 7.22\,Mg$$

Typical results for tensile properties and fracture toughness, obtained for different alloys and various heat treatment regimes are listed in Table 2.

In order to get a closer insight in mechanical properties, in Figure 3 K_{Ic} is presented versus yield strength for tested alloys given in Table 2. It is clear from Figure 3 that CO alloy series could be accepted for in detail analysis as most promising regarding strength and fracture resistance, offering K_{Ic} ranged between 28.9 and 41.4 $MPa\cdot\sqrt{m}$ for yield strength between 630 and 665 MPa, well higher values compared to specified ones.

However, the selection of best relation in strength and fracture toughness of AlZnMgCu alloy is also influenced by Fe content. The effect of Fe content on fracture toughness for selected AlZnMgCu alloys for same Zn and Mg contents is presented in Figure 4.

TABLE 2 - Tensile properties and fracture toughness for different AlZnMgCu alloys and various heat treatment regimes

Alloy designation	Heat tretment ageing (°C/h)	TENSILE PROPERTIES Y.S. $R_{0,2}$ (MPa)	U.T.S. R_m (MPa)	El. A_5 (%)	Fracture toughness K_{Ic} (MPa√m)
A02	120/24	570	640	15.1	35.6
	100/5+160/5	560	630	15.1	37.2
B01	120/24	645	705	15.1	22.5
	100/5+160/5	620	660	13.2	28.5
C02	120/24	660	705	7.5	28.9
	100/5+130/10	645	695	10.8	34.2
	100/5+160/5	635	655	8.7	32.5
C03	120/24	660	700	7.0	32
	100/5+130/10	645	690	9.5	33.1
	100/5+160/5	630	655	9.0	35.1
C04	120/24	650	695	7.8	37.2
	100/5+130/10	645	695	10.1	38.5
	100/5+130/5	645	670	13.1	41.4
D02	120/24	705	735	. 7.1	18.7
	100/5+160/5	625	680	8.8	26.4
D03	120/24	670	710	9.6	27.1
D04	120/24	690	730	8.6	24.5
D05	120/24	705	745	7.0	19.3

Quantitative metallographic analysis. The presence of secondary - intermetallic phases in number, size, volume portion (especially coarse particles, rich in Fe and Si) has been analysed on structural analyzer TAS Plus. The results of this analysis for three types of C0 alloyes are listed in Table 3.

TABLE 3 - Intermetallic phases in selected AlZnMgCu alloys

Alloy Designatio	Number of particles per mm^2	Particle size D Dave	Dave	Volume Fraction Fv,(%)
C02	7347	0.6 4.96-9.18	2.07	1.86
C03	9640	0.6 3.63-7.58	1.68	1.79
C04	17200	0.6 2.12-2.94	1.15	2.14

Fractography. The analysis of fractured surface after fracture mechanics test had been performed on a scaning electron microscope SEM 511 with EDAX 9900 (Philips). Typical results are presented in Figure 5-7.

RESULT ANALYSIS AND DISCUSSION

Performed investigation revealed that generally, for increasing content of Zn and Mg, individual and total, strength properties will increase and fracture toughness properties will decrease. Although required strength (over 650 MPa in ultimate tensile strength) had been achieved by all alloys from Table 1 (except A02 type), only C0 type alloys (~7.3 % Zn, ~2.2 % Mg) had offered a satisfactory fracture toughness. It has also been demonstrated that decreasing Fe content in alloys (C02 → C04), and corresponding decrease in coarse intermetallic particles of second phase content result in increasing fracture resistance (Figure 4). Coarse particles, rich in Fe and Si, are deformed and fractured during tests (Figure 6, C02 alloy), where as fine regularly distributed intermetalic phases contribute to ductile behaviour (Figure 7, C04 alloy). In the last case, the particles are fractured only seldom.

Comparing the results, presented in Table 2 and in Figures 1-4 with the results from Table 3, one can conclude that best combination of strength and fracture toughness properties has been achived by C04 alloy composition, with low Fe content and corresponding regular distribution of fine second phase particles. Two steps precipation ageing regime (100^{o}C/5h + 160^{o}C/5h) for C04 alloy can be recommended when highest fracture toughness is required, resulted in slightly reduced strength parameters compared to one step (120^{o}C/24h) or alternative investigated two steps (100^{o}C/5h + 130^{o}C/10h) precipitation ageing.

REFERENCES

(1) Hahn.G.T. and Rosenfield,A.R., Metallurgical Transactions A, Volume 6A, April, 1975, pp. 653-668.

(2) Garrett G.G and Knott J.F., Metallurgical Transactions A, Volume 9A, September, 1978, pp. 1187-1201.

(3) Develay,R., Revue de L'Aluminium, Novembre, 1976, pp. 521-544.

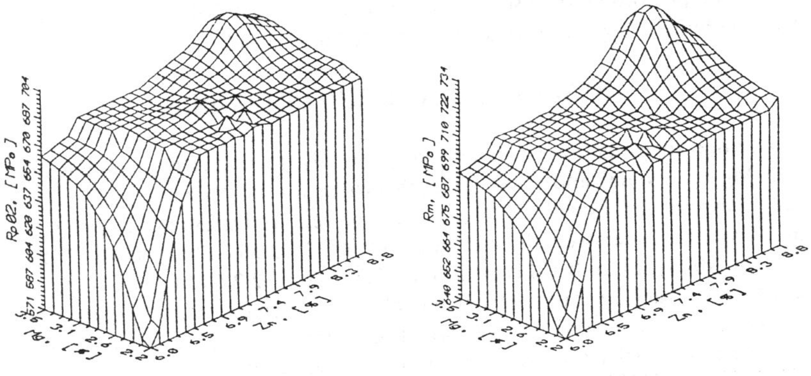

Figure 1 The effect of Mg and Zn content on yield strength $R_{p0.2}$ (a) and ultimate tensile strength R_m (b) of AlZnMgCu alloys

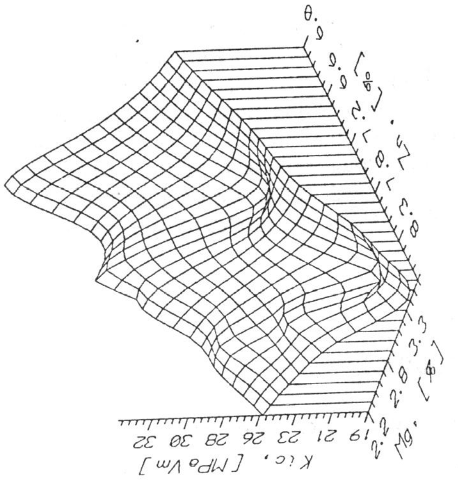

Figure 2 The effect of Mg and Zn content on fracture toughness K_{IC} of AlZnMgCu alloys

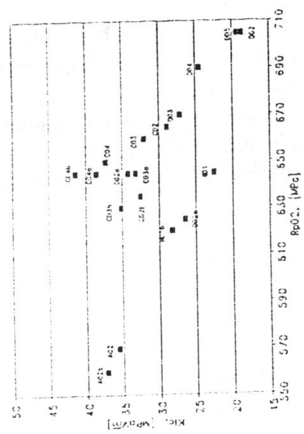

Figure 3 Fracture toughness K_{IC} related to yield strength $R_{p0,2}$ for set of alloys from Table 1 and 2

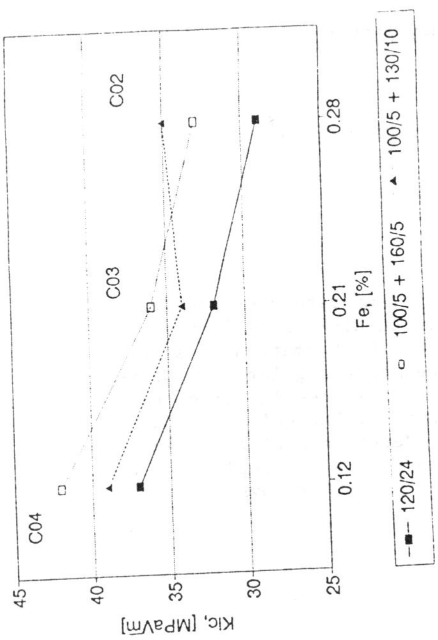

Figure 4 The effect of Fe content on KIC of AlZnMgCu alloys with same Zn and Mg contants for ageing regimes

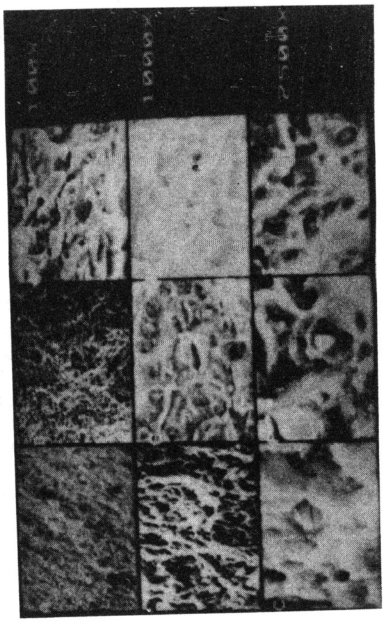

Figure 5 Fractured area of C02, C03 and C04 alloys at different magnifications

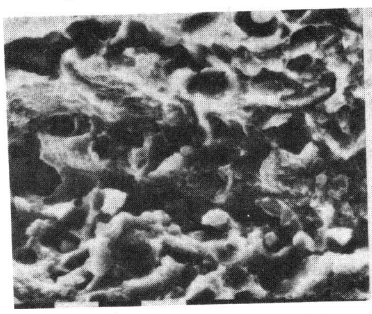

Figure 6 Fractured intermetalics C02 alloy

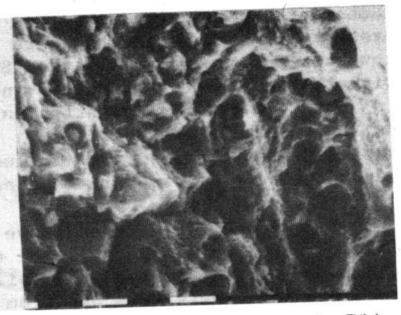

Figure 7 Fractured surface in C04 alloy