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The Creep Kinetics of Sand Cast Zinc-Based Alloys No. 2, ACuzinc5, and ACuzinc10

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Abstract

Compressive creep tests have been carried out on zinc-rich alloys No.2 (Zn-4% Al-2.8% Cu-0.03% Mg), ACuZinc5 (Zn-3% Al-5.2% Cu-0.04% Mg) and ACuZinc10 (Zn-3.5% Al-9.3% Cu-0.03% Mg) in the stress range 20 to 100 MPa and at 70 to 160°C. Along with creep, other properties of ACuZinc alloys are claimed to be better than conventional zinc alloys No.3 and No.5, and ZA alloys. The primary creep contraction was generally found to increase with increasing copper content in a non-linear fashion. The secondary creep rates of No.2 were slightly lower than those of ACuZinc5 and ACuZinc10. Based on the above equation, continuous design stresses were calculated under different testing conditions which showed that both ACuZinc alloys were inferior in creep strength to No.2 due to its lower secondary creep rates. The results and microstructure of alloys also showed that in all three alloys, the creep-controlling mechanism is the dislocation climb over second-phase (ε) particles.

Keywords: Compressive creep; Zinc-rich alloys; Primary creep; Secondary creep rate; Creep controlling mechanism

Introduction

Zinc-based castings are extensively used in automotive industry, machinery, tools, plumbing and heating supplies, office equipment, optical products, sporting goods, toys and many other different applications [1]. These alloys have relatively low melting temperatures, excellent ability in casting, good resistance to corrosion, lower density, lower material cost and long term dimensional stability [2-4]. Due to these properties, they are preferred in comparison with the other non-ferrous alloys.

Creep properties of materials used in commercial applications are very important for designers, particularly at moderately elevated temperatures. In the current study, the compressive creep characteristics of three sand-cast zinc alloys No.2, ACuZinc5 and ACuZinc10 have been analysed. Alloy No.2 is a conventional zinc alloy, whereas ACuZinc5 and ACuZinc10 are two new high copper zinc-based alloys developed by General Motors Research Laboratory [5]. These are high performance ternary zinc-copper-aluminium alloys which are suitable for manufacturing net shape die castings. Both ACuZinc alloys are claimed to be more creep-resistant, harder, and having more wear resistance than some other zinc alloys [5-7]. It was found that the creep data correlated well using a simple empirical relationship between applied stress, test temperature and time to total creep strains of 0.5, 0.7 and 1.0%.

Experimental Work

Chemical composition of the experimental alloys

The chemical composition of the alloys was determined by atomic-absorption spectroscopy.

Compressive creep machine

The tests were carried out on a compressive creep machine, designed particularly for compressive creep testing of zinc-based alloys. Most of the fabrication and machining work of machine was accomplished in the Manufacturing and Production Engineering Laboratory of Aston University. The machine is of the standard lever loading type with a lever arm ratio of 10:1.

Creep test specimens

The specimens used for testing were prepared from sand castings of alloys. These specimens were of cylindrical shape, having the following finished dimensions:

Length=30 mm, diameter=13 mm, bore (plain)=8 mm.

The alloys were prepared in Aston University foundry with guaranteed composition. During the production of these test samples, the machining operation was carefully controlled so as to reduce variations in surface finish to a minimum.

Results of Creep Tests

The results were presented in the form of graphs plotted as creep strain (%) versus time (ks) for all alloys as shown in Figures 1 and 2. In all cases, the curves showed the same general form. i.e. a primary creep stage which exhibited a steadily decreasing strain rate followed by a linear steady-state region (secondary creep stage), whereas tertiary creep was not observed in most of the curves due to short duration of tests. From these curves, the primary creep contraction, the secondary creep rates and times to produce creep strains of 0.5, 0.7 and 1%.

Primary creep contraction

The values of primary creep contraction (%) for all alloys were obtained by extrapolating the linear secondary creep portion of the curves back to zero time. From results, it was observed that the average values of primary creep for all three alloys were generally increased with increasing stress and copper content.

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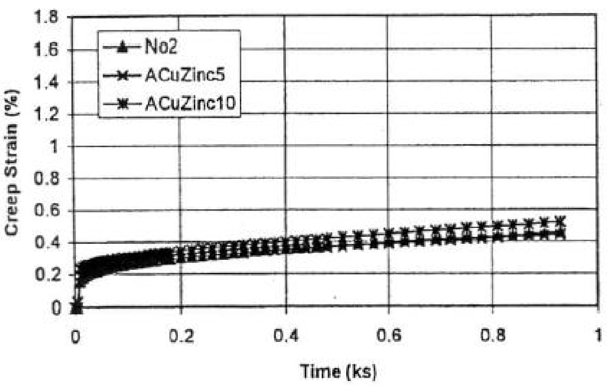

Figure 1: Comparison of creep curves for alloys at 100 MPa and 130°C.

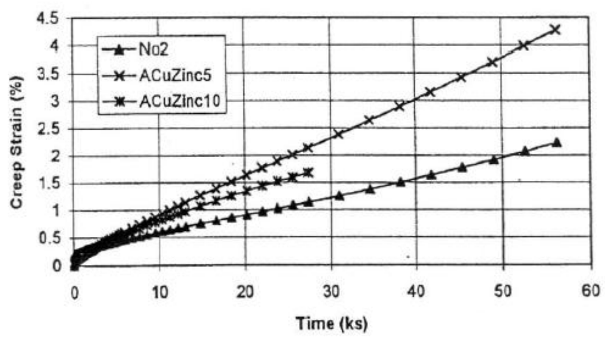

Figure 2: Comparison of creep curves for alloys at 40MPa and 160°C.

Secondary creep rate

The secondary creep rate is the average rate of strain in the linear portion of the creep curve which follows the primary stage. The secondary creep rates of the alloys No.2 were slightly lower than those of ACuZinc5 and ACuZinc10. Also, the secondary creep rates of ACuZinc10 were generally higher than those of ACuZinc5. The values of stress exponents (n) for alloys No.2, ACuZinc5 and ACuZinc10 were found to be 3.8, 3.7 and 4.0, respectively.

Total creep contraction

The times to a total creep contraction of 0.5, 0.7 and 1% were obtained from the creep curves for all alloys. The in times to I% creep strain for alloys were then plotted as a function of the reciprocal of the testing temperature (K) at different stresses. These plots were linear with a constant slope (Q/R) over much of the stress range used. The values of the activation energy for creep (Q) were calculated as 99, 103 and 107 kJ/mole for alloys No.2, ACuZinc5 and ACuZinc10, respectively.

Discussion of Experimental Results

Correlation of compressive creep data

Savaskan and Murphy used the following empirical equation to correlate their creep data of gravity-cast zinc-based alloys:

$$f(\varepsilon) = A\, t\, \sigma^{n} \exp(-Q/RT) \qquad (1)$$

where A is a constant which takes into account the effects of composition and metallurgical structure, t is the creep test time, σ the nominal stress, n the stress exponent, Q an effective activation energy for creep, R the gas constant, T the absolute test temperature, and f(ε) is an undefined function of the creep strain ε [8]. When A, σ, Q, n and T are constant, f(ε) represents the shape of the creep strain versus time curve. Taking logarithms and rearranging at constant strain, Equation (1) becomes:

$$n\, t = C' - n\,(\ln \sigma) + Q/RT \qquad (2)$$

Where C′ is a new constant which incorporates A and ε.

The creep behaviour of these zinc alloys has been shown to be related to the testing conditions by this empirical equation over a wide range of stress and temperature. The In time to a given % strain versus the creep parameter [Q/RT-n (lnσ)] was then plotted, giving linear plots of unit slope and intercept C′ along the In time (s) ordinate. C′ is a characteristic constant (creep constant) for the alloy and the chosen creep strain (%), and the differences in creep behaviour of the alloys are derived solely from differences in the values of the creep constant (C′). Graphs of ln time to creep strains of 0.5 and 1.0% versus the creep parameter were drawn using the original data from individual creep curves for each alloy.

The values of the constant C′ were obtained from the creep data for the alloys and % contractions. At different temperatures, the design stresses required to produce 0.2%, 0.5%, 0.7% or 1.0% creep strain in 100,000 h were calculated using Eq. (2), and are given in Table 1. On the basis of these design stresses (σ), it may be concluded that both ACuZinc alloys were inferior in creep strength to alloy No.2, whereas ACuZinc5 had a slightly better creep resistance than ACuZinc10 under all conditions.

Microstructure of the Alloys

The structure of the alloy No.2 after creep testing at l00 MPa and l60°C in the form of SEM and optical micrographs, are shown in Figures 3 and 4, respectively. The structure consisted of many large and a few small primary dendrites surrounded by a relatively small volume of lamellar eutectic. Many small and dark particles of the Al-rich former β phase were associated with primary η particles Figure 3. It is clear from optical micrograph that the eutectic areas also contained some massive ε-phase particles due to slow cooling during sand casting process. These ε-phase particles were not detected in the SEM micrographs.

Figure 5 shows the optical micrograph of ACuZinc5 after testing at 100 MPa and 160°C. In contrast to alloy No.2, the structure of

Temperature(°C)		**70**	**100**	**130**	**160**
No.2	0.2	8.71	4.33	2.39	1.43
	0.5	19.94	9.93	5.47	3.28
	0.7	24.94	12.42	6.85	4.10
	1.0	28.78	14.32	7.90	4.73
ACuZinc5	0.2	6.75	3.36	1.85	1.11
	0.5	19.80	9.86	5.43	3.26
	0.7	23.73	11.81	6.51	3.90
	1.0	27.70	13.79	7.60	4.56
ACuZinc10	0.2	5.59	2.78	1.54	0.92
	0.5	18.92	9.42	5.19	3.11
	0.7	21.27	10.59	5.84	3.50
	1.0	22.79	11.34	6.25	3.75

Table 1: Maximum continuous design stresses (MPa) to produce % strain in 100,000 hours.

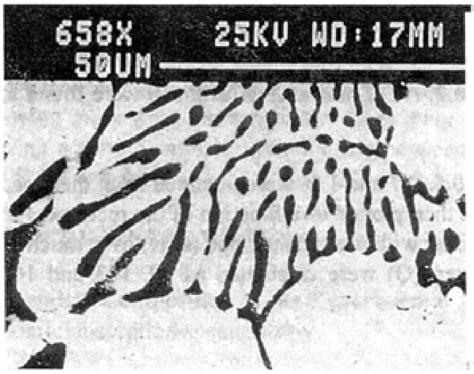

Figure 3: High magnification. SEM micrograph of alloy No.2 tested at 100 MPa and 160°C.

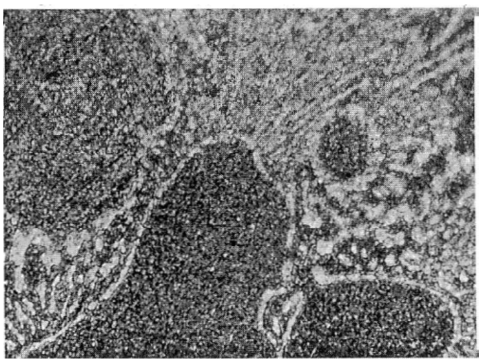

Figure 4: High magnification optical micrograph. AlloyNo.2 tested at 100 MPa and 160°C.

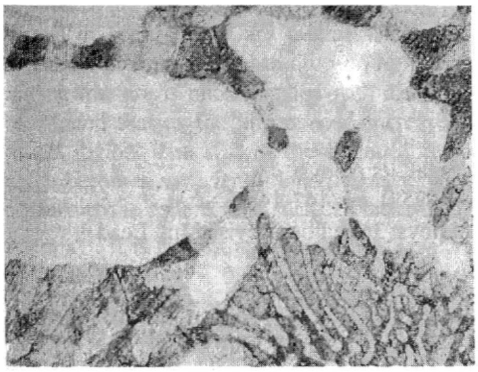

Figure 5: Optical micrograph of ACuZinc5 tested at 100 MPa and 160°C, at high magnification, showing primary ε dendrites and massive η particles with eutectic.

ACuZinc5 consisted of primary Cu-rich ε dendrites with large and small size zinc-rich η particles, surrounded by the ternary (α+ε+η) eutectic. The η particles were due to high zinc contents in the composition. The micrograph also showed that the ternary eutectic had much less volume than the primary ε dendrites and massive η particles. The structure of ACuZinc10 tested at 100 MPa and I60°C is shown in Figure 6. In general, the structure was similar to that of ACuZinc5 except the volume fraction of the primary phase was far greater than that of ACuZinc5. This higher volume of primary ε-phase was due

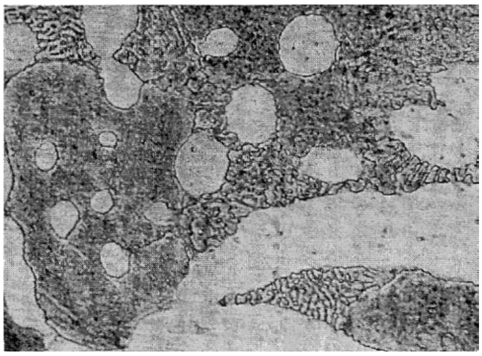

Figure 6: Optical micrograph of ACuZinc10 tested at 100 MPa and 160°C, at high magnification, showing primary ε dendrites and ternary eutectic.

to the higher percentage of copper in ACuZinc10. The structure had small size η phase particles only in the ternary eutectic, contrary to the structure of ACuZinc5 which had massive particles of η phase. The microstructure had also greater volume of primary ε-phase dendrites than ACuZinc5, i.e. about 50% of the whole structure. The micrograph also revealed that the volume fraction and size of the ε dendrites increased with increasing copper.

Creep mechanism

A satisfactory procedure of identifying the rate-controlling or dominant creep mechanism may be offered by comparing the calculated values of the stress exponent (n) and the activation energy (Q) with the values of these parameters predicted theoretically for different creep processes. Another important consideration for a dominant creep mechanism is the analysis of microstructure of the alloys. Based on the climb of dislocations over second-phase particles, Ansell and Weertman proposed a model, predicting a stress exponent of 4 [9]. This value is in close agreement with the stress exponent values obtained for the alloys No.2, ACuZinc5 and ACuZinc10. Since these alloys have copper content of 2.5 - l0%, copper-rich ε-phase therefore acts as a second phase and its precipitates block the movement of dislocations. Therefore, on the basis of the tests results and microstructure of the alloys, it is reasonable to conclude that in alloys No.2, ACuZinc5 and ACuZinc10, the creep controlling mechanism is climb of dislocations over second-phase (ε) particles.

Conclusions

The creep equation: $f(\varepsilon)=A\,t\,\sigma^n \exp(-Q/RT)$ may be used to correlate the experimental data of the zinc-based alloys No.2, ACuZinc5 and ACuZinc10.

The values of the stress exponents (n) were found to be 3.8, 3.7 and 4.0 for alloys No.2, ACuZinc5 and ACuZinc10, respectively, while the corresponding values of the activation energy for creep (Q) were 99, 103 and 107 kJ/mole.

The secondary creep rates and the design stresses determined from the experimental data showed that alloy No.2 had a substantially higher creep resistance than ACuZinc5 and ACuZinc10 under all testing conditions, whereas ACuZinc5 had a slightly better creep resistance than ACuZinc10 over all strains.

The creep controlling mechanism is the climb of dislocations over second-phase particles in all three alloys. The results also showed that copper content of more than about 3% in these zinc-rich alloys did not improve the creep resistance in compression as was expected because alloy No2 had the best creep strength among all the alloys tested. Although both ACuZinc5 and ACuZinc10 have regular eutectic morphology, the massive primary dendrites of ε if less creep-resistant in compression, may not assist in increasing the creep strength of both ACuZinc alloys, and may well reduce it.

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