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Comparative load-relaxation behaviour of high-aluminium zinc-based alloys

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The load relaxation behaviour of sand-cast alloys ZA8, ZA12, ZA27, Cosmal, SuperCosmal and LM25 were measured at test temperatures of 80, 100 and 120°C. ISO-metric 6 × 1 steel screws were set into cut-threaded sand castings with a preload of 6 kN, and the gradual loss of load was monitored for a period of 10,000 minutes (166.7 hours). The rate of load relaxation increased with temperature, and declined with time.The aluminium alloy LM25 had the best resistance to load relaxation amongst the alloys tested, followed in decreasing order by SuperCosmal, Cosmal and the ZA alloys. All the ZA alloys had very similar resistance to load relaxation, but ZA12 was marginally better and ZA8 marginally poorer than ZA27. Among this group of alloys, with different detailed chemistry, aluminium content appeared to be the most important factor in determining resistance to load relaxation. The kinetics of load relaxation could be described by an expression similar to that obeyed by other zinc alloys in pressure-diecast form: $\ln P = \alpha[Q/RT - \ln B - \ln t]$ where P is the load retained after time t at absolute temperature T, α and B are constants, Q is an effective activation energy for relaxation and R the gas constant. A systematic variation of the constants α and Q showed that the correlation was only approximate. © *2001 Kluwer Academic Publishers*

1. Introduction

The commercial alloys No. 3 and No. 5 (BS1004 Alloys A and B) are the most widely used zinc-based alloys, enjoying many advantages over aluminium-based casting alloys, such as lower casting temperatures, lower energy requirement for melting, longer die life, and superior as-cast surface qualities. They also have excellent mechanical and physical properties at ambient temperatures, but problems may be caused by their low creep resistance [1]. A group of higher-aluminium general-purpose zinc alloys, consisting of the alloys ZA8, ZA12 and ZA27, was developed for more demanding applications. These alloys have high strength and hardness, improved creep resistance and lower densities and although developed originally for sand and gravity casting, they are now being used in growing amounts for pressure die-cast components [1].

One property of all zinc alloys which is relatively uncommon is a high intrinsic damping capacity, especially in alloys whose aluminium content is close to the eutectoid value of 22 wt% [2]. High damping is generally associated with comparatively low resistance to creep deformation at even moderately elevated temperatures, but recent work on tensile creep has shown that the ZA alloys are significantly better than alloys 3 and 5, and can be used for service at temperatures up to about 100–120°C [3–7]. The recently introduced Cosmal alloy was also designed to provide a significant damping capacity, and with the high-aluminium version SuperCosmal, also offers light weight and reasonable castability combined with good mechanical properties and excellent creep resistance [8]. The chemical compositions of the ZA and Cosmal alloys are shown in Table I.

Zinc alloy castings are widely used for automotive and other components which experience above-ambient temperatures in service. Often steel fasteners are used to fix such castings together or mount a casting onto another structure, using torque-limiting tools to ensure that the joints are clamped together with a sufficient preload to maintain structural integrity. However creep-related load relaxation is a recently recognized problem in riveted or screwed joints whenever the operating temperature is much above ambient levels. In non-ferrous castings this is caused by creep deformation of the casting body and/or the threads, which allows a gradual axial movement of the steel screw and thus a progressive relaxation of the preload. Effectively, load relaxation is the time- and temperature-dependent conversion of elastic strain into plastic strain. Only very limited theoretical and practical studies of load relaxation in zinc-based alloys are known [9–12], so considering the rising demand for zinc alloy castings, there is a need to investigate their load relaxation behaviour. The well-known

TABLE I Chemical composition of the alloys (wt%)

	Al	Mg	Mn	Si	Cu	Zn
ZA8	8.0–8.8	0.015–0.030	—	—	0.8–1.3	bal
ZA12	10.5–11.5	0.015–0.030	—	—	0.5–1.2	bal
ZA27	25–28	0.010–0.020	—	—	2.0–2.5	bal
Cosmal	40	<0.005	0.3	3	1.03	bal
SuperCosmal	60	<0.005	0.3	6	1.02	bal
LM25	bal	0.20–0.45	0.3	6.4–7.5	0.44	0.1

aluminium alloy LM25 is widely used in automotive applications, and although weaker, devoid of intrinsic damping and more difficult to cast, has a very high creep resistance, and is used here as a comparator for the zinc-based alloys. Its chemical composition is shown in Table I.

2. Experimental work

2.1. Alloys

ZA8, ZA12, ZA27, SuperCosmal and LM25 were provided by Britannia Alloys & Chemicals Ltd., UK in the form of ingots with guaranteed composition. Cosmal was prepared in our own foundry to the specified composition.

2.2. Casting of alloys

Sand casting was used because it was suitable for all the alloys being investigated, with low tooling costs. Each alloy was melted in a gas-fired crucible furnace and cast with a 50°C superheat into a green sand mould to form simple cylindrical castings 18 mm in diameter and 100 mm long. After cooling in situ for about half an hour the casting was broken out of its mould. No fluxes were used in casting, but in the case of LM25 the melt was degassed with hexachlorine just prior to pouring.

2.3. Test specimens and load-relaxation testing equipment

Fully-machined hollow cylindrical test specimens 30 mm long and 18 mm in outer diameter were made from the sand castings with a CLA finish of 1–14 μm. These had a bore machined to the dimension recommended for a 6 mm ISO-metric thread with 75% thread engagement, and were threaded with an M6 × l cutting tap.

The load relaxation testing equipment consisted of a group of up to five load monitoring cells, an oil bath and the data acquisition system. A load monitoring cell (Fig. 1), with a calculated stiffness of 129 kN/mm, was used for the continuous monitoring of load in a commercial fastener screwed into a test casting. It consisted of a short tension rod to which the head of a steel screw was clamped, which transmitted the tensile stress in the screw through a compression load cell to the flat circular steel reaction plate against which the face of the screwed casting was pressed. When the casting was threaded onto the fastener, it simulated the effect of inserting a screw into a hole, and could be rotated to take up clearance, but final tightening to give the required preload was carried out using an hexagonal nut on the threaded upper end of the tension rod. The doughnut-shaped compression load cell had a maximum non-linearity of ±0.5% FS, and its operating temperature range was −54°C to +121°C.

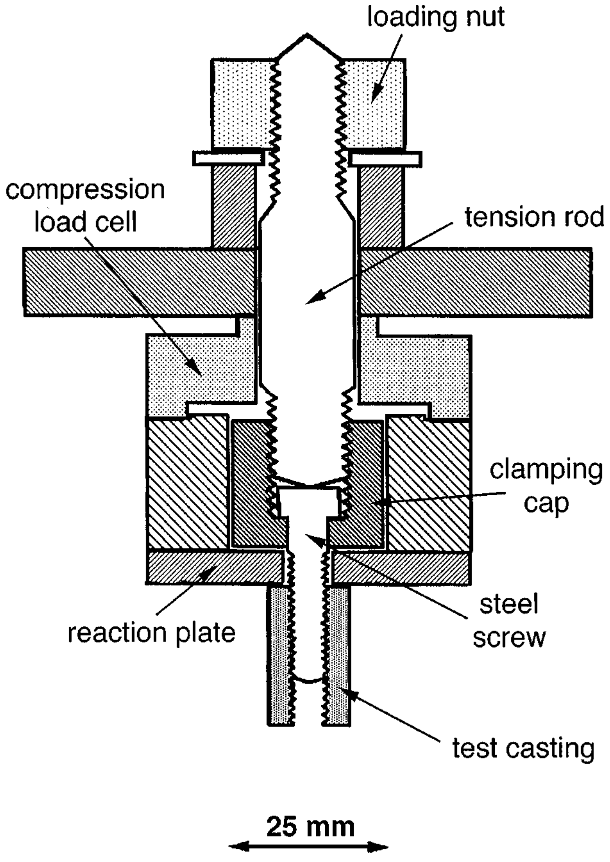

Figure 1 Representation of the arrangement for conducting load-relaxation tests on simple hollow cylindrical specimens.

A commercial data acquisition system was used to record the results of load relaxation tests. It had a data logging programme which was used with an IBM-compatible computer, and the data was transferred on disc to another computer running a Lotus 123 spread sheet.

Five test specimens could be tested simultaneously by immersion in an electrically-heated oil bath fitted with a stirrer which circulated the oil to maintain a selected uniform temperature throughout the bath. The oil bath had a capacity of 30 litres and the maximum working temperature was 150°C. The temperature controller attached to the oil bath showed the oil temperature in digital form and controlled the test temperature with an accuracy of ±0.5°C.

2.4. Load relaxation testing procedudre

A nominally 6 mm diameter and 1 mm pitch (M6 × l) ISO-metric steel screw was locked to the tension rod of the load monitor by a clamping cap, and fitted into the load monitoring assembly with the end of the screw protruding through the reaction plate. The test piece was screwed over it to a thread engagement depth of 16 mm while taking up the clearance. The test-piece/

load-monitor assembly was then immersed in the oil bath set to the required test temperature for two hours before the test commenced, so that the whole assembly acquired the same temperature.

At the start of a test, a load was applied to the test casting by tightening the loading nut on the top of the rod until the computer display showed 6 kN. Then the data acquisition system was started and the residual load continuously monitored for a period of up to 10,000 minutes (166.7 hours) at each temperature. The recorded data was in the form of time (minutes) versus retained load (N), and the time interval was 0.5 minute initially but was progressively increased to a maximum of 4 hours.

All tests were carried out in duplicate and if appreciable scatter was found in the results, some additional tests were also performed at those particular temperatures. The average values of the results were used to represent the load relaxation behaviour of the alloys tested.

3. Results and discussion

The average retained load versus time data were used to plot the relaxation curves of Figs 2–4. These showed the relaxation behaviour of all the alloys at temperatures of 80, 100 and 120°C respectively. In all cases a steep initial decline in retained load was followed by a more gradual decline, but the overall rates varied considerably with temperature and alloy composition, as discussed below.

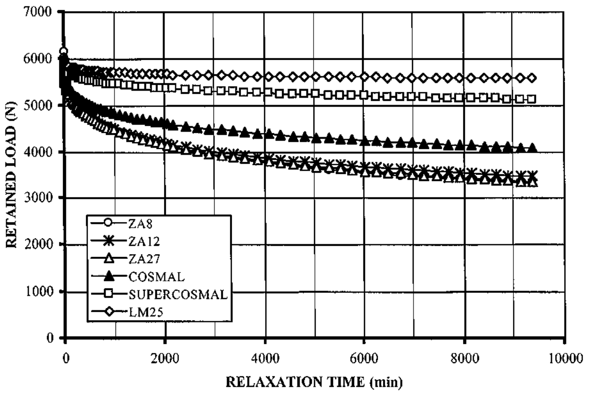

Figure 2 Average load relaxation curves for alloys ZA8, ZA12, ZA27, Cosmal, SuperCosmal and LM25, tested at 80°C.

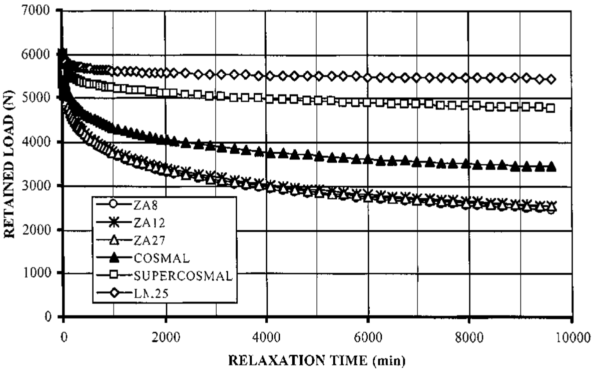

Figure 3 Average load relaxation curves for alloys ZA8, ZA12, ZA27, Cosmal, SuperCosmal and LM25, tested at 100°C.

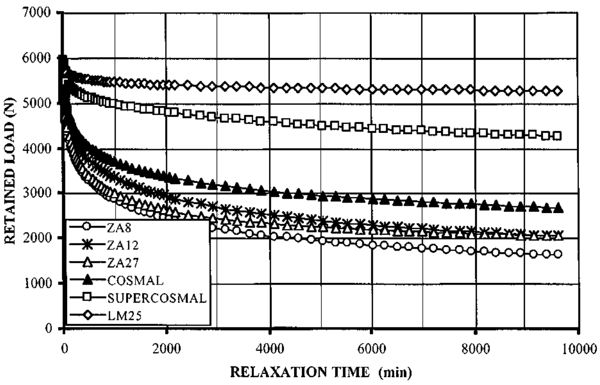

Figure 4 Average load relaxation curves for alloys ZA8, ZA12, ZA27, Cosmal, SuperCosmal and LM25, tested at 120°C.

3.1. ZA alloys

When tested at 80°C, the ZA alloys had almost the same rate of load loss, with ZA12 marginally better than ZA8 and ZA27, (Fig. 2). The retained load after 150 hours at 80°C was 3340 N for ZA8, 3495 N for ZA12 and 3379 N for ZA27, or 55.7%, 58.3% and 56.3% respectively. At 100°C the rate of load relaxation was greatly increased (Fig. 3), but the alloys had the same relative resistance as at 80°C. The retained loads after 150 hours at this temperature were 2505 N, 2589 N and 2569 N or 41.8, 43.2 and 42.8% for ZA8, ZA12 and ZA27 respectively. At 120°C ZA12 had a better resistance to load loss than ZA27 at first, but with the passage of time ZA27 improved its relative performance (Fig. 4), and after 150 hours had almost the same retained load as ZA12, ie 2086 N for ZA27 and 2092 N for ZA12, representing retentions of 34.8 and 34.9% respectively. ZA8 retained only 1670 N or 27.8%. The load retention data for these alloys are listed in Table II.

Temperature clearly had a strong effect in all three alloys in increasing the degree of load relaxation. Taking the averages for the three alloys, increasing the test temperature from 80°C to 100°C reduced the 150 hour retained load by 14%, and a further increase to 120°C reduced it by another 10%.

From these data, it was clear that there were no remarkable differences between the three ZA alloys, but ZA8 was slightly less resistant to load relaxation than the others, especially at the highest test temperature, and ZA12 marginally the best. When creep-tested in compression, ZA8 was the most creep resistant of the three alloys, and ZA27 the least [13], and these alloys lie in the same order when creep tested in tension in

TABLE II Load retention after 150 hours at different temperatures

	Temperature					
	80°C		100°C		120°C	
Alloy	(N)	(%)	(N)	(%)	(N)	(%)
ZA8	3340	55.7	2505	41.8	1670	27.8
ZA12	3495	58.3	2589	43.2	2092	34.9
ZA27	3379	56.3	2569	42.8	2086	34.8
Cosmal	4097	68.3	3476	57.9	2721	45.4
SuperCosmal	5127	85.5	4808	80.1	4302	71.7
LM25	5581	93.0	5470	91.2	5290	88.2

pressure diecast form [14]. In all three alloys, the as-cast structure consists of primary dendrites in an eutectic matrix. ZA8 and ZA12 differ only in the relatively smaller amount of eutectic in the higher aluminium alloy; but ZA27 has a different primary phase (α') with a higher aluminium content than the primary β of ZA8 and ZA12, and the eutectic is reduced to small interdendritic pools of copper-saturated zinc which contain discrete particles (1–2 μm) of the metastable copper-rich epsilon phase ($CuZn_4$). Electron metallographic studies have shown that in as-cast zinc alloys with only 1% Cu, copper is preferentially segregated into the zinc matrix of the eutectic and decomposed β phase where it forms a dense precipitation of tiny ($\sim$100 nm) plates of epsilon phase on cooling [15]. Although the epsilon phase is thermodynamically unstable below 280°C, and must eventually be replaced by the equilibrium T$'$ phase, it persists in zinc castings for many years at ambient temperatures. This precipitate is considered to be responsible for the superior creep properties of, for example, Alloy 5 compared with Alloy 3, and contributes to the excellent creep resistance of ZA8 [15]. In ZA27 the zinc phase also contains fine precipitates of epsilon phase [16] but the amount is small, and the good creep resistance is attributed to the intrinsic creep resistance of the copper-hardened fcc aluminium matrix of the primary phase.

Changes take place to the structures of all three alloys on aging or creep testing, but the effects are slight below about 150°C. Nevertheless it is probable that the basically different structure of ZA27 compared with ZA8 and ZA12, as well as its response to aging, are responsible for the different relative load relaxation resistances under different test conditions which were found in this study.

3.2. High damping capacity Cosmal alloys and LM25

Comparing the two Cosmal alloys, SuperCosmal was much better in resistance to load relaxation than Cosmal under all test conditions, as seen from the comparison graphs of Figs 2–4. The retained loads after 150 hours at 80°C were 4097 N and 5127 N for Cosmal and SuperCosmal respectively, equivalent to 68.3 and 85.5%. In both alloys the loss in load increased with increase in temperature, i.e. for Cosmal and SuperCosmal at 100°C the load retained after 150 hours was 57.9 and 80.1% respectively, while at 120°C it was 45.4 and 71.7% respectively (Table II). LM25 was greatly superior in resistance to load relaxation to all of the zinc-based alloys with load retentions (after the same durations) of 5581 N, 5470 N and 5290 N, corresponding to 93.0, 9l.2 and 88.2% at 80, 100 and 120°C respectively. These data are shown in Table II.

3.3. Comparison of ZA alloys, high damping capacity alloys and LM25

When the 150 hour load retention results of the ZA alloys were compared with those of the Cosmal group and LM25, it was evident that the high-damping alloys were more resistant to load loss than ZA alloys at all test temperatures, and less sensitive to temperature, (Fig. 5). The load retained by Cosmal at 80°C was nearly 12% higher than the average for the ZA alloys at that temperature, and this increased to over 15% at 100°C and fell back to 13% at 120°C. SuperCosmal was even more resistant to load relaxation, with a retained load 29% above the average for the ZA alloys at 80°C, 38% at 100°C, and 39% at 120°C. However, even this excellent performance was eclipsed by that of the aluminium alloy LM25 which had a load retention some 36% above that of the ZA alloys at 80°C, 49% at 100°C and 56% at 120°C, the improvement showing a much reduced sensitivity to increased temperature compared with the high-zinc alloys. Therefore, on the basis of the results of these load relaxation tests, it can be concluded that the high damping capacity Cosmal-group alloys and LM25 are more suitable for higher temperature applications where load relaxation is a determining factor.

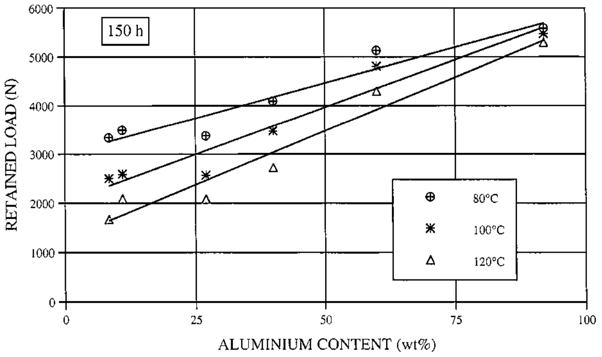

Figure 5 Variation of 150 hour retained load with aluminium content for all the alloys tested, showing near linear variation.

There are significant differences in the detailed chemistry of the three groups of alloys, but it is clear that aluminium content *per se* had a strong effect on load retention. The 150 hour load retention for each alloy at each test temperature is plotted against aluminium content in Fig. 5. This shows a roughly linear dependence of retained load on aluminium content; emphasising that whatever the possibly disparate effects of minor alloying elements and structure, the prime factor in this group is the aluminium content.

3.4. Kinetics of load relaxation

In the load relaxation tests in this study, plastic creep deformation allows the fastener to be gradually drawn out of the casting and the boss surface compressed, and these combined creep deformations cause the load in the tension rod to diminish with time. The measured load in the fastener (P) is proportionately related to the creep deformation of the casting through the stiffness (k) of the load-cell/fastener/casting structure. For any elastically loaded body,

$$P = k\delta$$

where δ is the elastic deflection caused by introducing the load P. In the load relaxation tests reported here, the load is gradually reduced as δ is reduced by the combined plastic creep strains in the thread and boss of the casting. Thus if δ_0 is the initial deflection, then after a period of time:

$$P = k(\delta_0 - l\varepsilon)$$

where l is an effective length of the parts of the casting subjected to creep and ε is the sum of the various creep strains. Since the load is related to elastic deflection through the stiffness, then the retained load after a certain amount of creep will depend on the stiffness of the assembly: a low-stiffness assembly will have a large initial value of δ_0 for a given load P, and will suffer a proportionately smaller reduction in load for a given creep strain. However stress also has a powerful effect on creep rate, so a higher retained load gives rise to more creep deformation. Because of these opposing effects, load relaxation in a real application is difficult to predict from laboratory studies. Furthermore, the contribution of the casting to the overall stiffness is significant and varies with temperature, and also the effective length of the assembly changes as load is progressively redistributed along the engaged threads of the casting, which further complicates any theoretical model for load relaxation. However for a given geometry, the measured kinetics of load relaxation allow retained loads after a chosen period of time to be estimated, and may give a guide as to the behaviour which might be expected under an extended range of operating temperatures.

Previous work on pressure-diecast versions of the zinc-based alloys 3, 5 and ZA8 [12] has shown that for times in excess of 1000 minutes, load relaxation could be correlated using an expression of the form:

$$\ln P = \alpha[Q/RT - \ln B - \ln t]$$

where P is the load retained after time t at absolute temperature T, α and B are constants, Q is an effective activation energy for relaxation and R the gas constant. A systematic variation of α with temperature and Q with time was reported [12], showing that the correlation was only approximate.

According to the above equation, plotting ln P versus ln t at a fixed temperature should yield a straight line of slope $-\alpha$ and intercept $\alpha[Q/RT - \ln B]$. Using the experimental data for times in excess of 1000 minutes, graphs of ln P versus ln t were drawn at the three test temperatures of 80, 100 and 120°C and are shown in Figs 6, 7 and 8 respectively. These plots all yielded straight lines, showing good agreement with the above equation for all alloys at all temperatures, but a systematic increase of α with temperature was observed for each alloy except ZA27, in which α attained a maximum value at the intermediate temperature. The calculated values of α and the mean value of α for each alloy are listed in Table III, the mean values showing a strong decrease in α with increased aluminium content.

TABLE III Calculated values of the power-law constant α for temperatures of 80, 100 and 120°C

	Constant α			
Alloy	80°C	100°C	120°C	Mean
ZA8	0.137	0.183	0.250	0.190
ZA12	0.115	0.178	0.222	0.172
ZA27	0.130	0.180	0.160	0.157
Cosmal	0.077	0.103	0.122	0.101
SuperCosmal	0.029	0.040	0.071	0.047
LM25	0.010	0.014	0.015	0.013

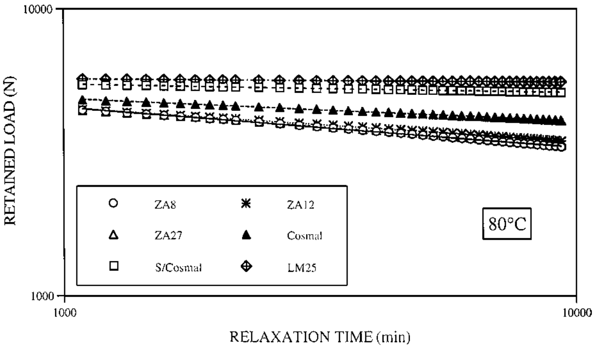

Figure 6 Average load relaxation data for all alloys for durations in excess of 1000 minutes at 80°C, plotted on logarithmic axes, showing power-law fit.

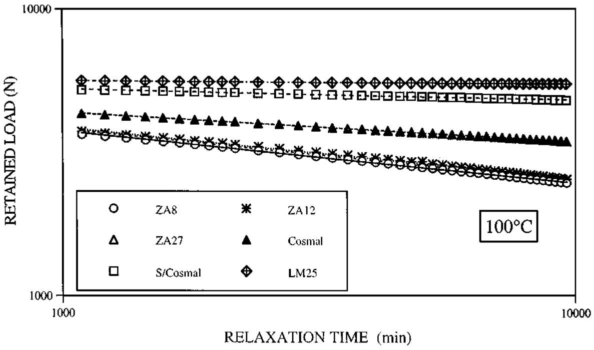

Figure 7 Average load relaxation data for all alloys for durations in excess of 1000 minutes at 100°C, plotted on logarithmic axes, showing power-law fit.

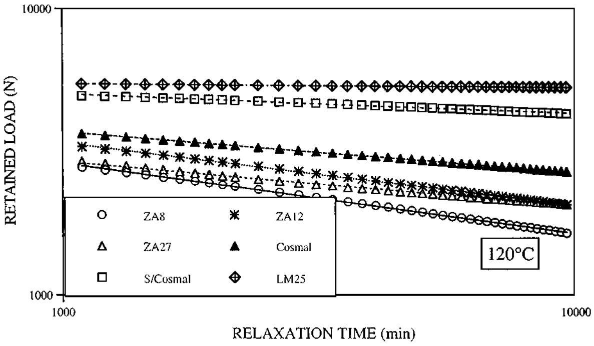

Figure 8 Average load relaxation data for all alloys for times in excess of 1000 minutes at 120°C, plotted on logarithmic axes, showing power-law fit.

Plotting ln P after a selected relaxation time t versus reciprocal temperature should give a straight line with slope $\alpha Q/R$ and intercept $-\alpha(\ln B + \ln t)$. Figs 9, 10 and 11 show the variation of ln P with l/T for all six alloys after 50, 100 and 150 hours respectively. These plots all yielded straight lines with constant slope, and although the number of test temperatures was too small to confirm the expected relationship, the results suggested that the test alloys behaved in a similar manner to the other zinc alloys. Using the mean values of α for

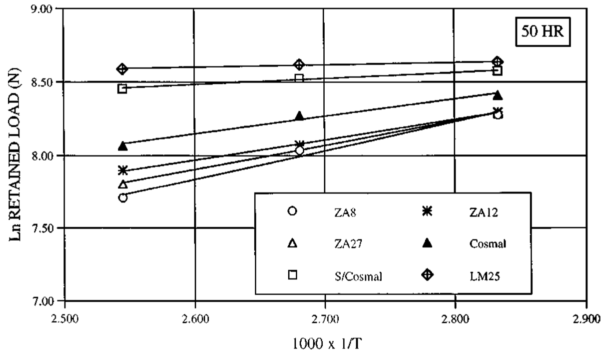

Figure 9 Variation of ln retained load after 50 hours at different temperatures with reciprocal absolute temperature for all alloys.

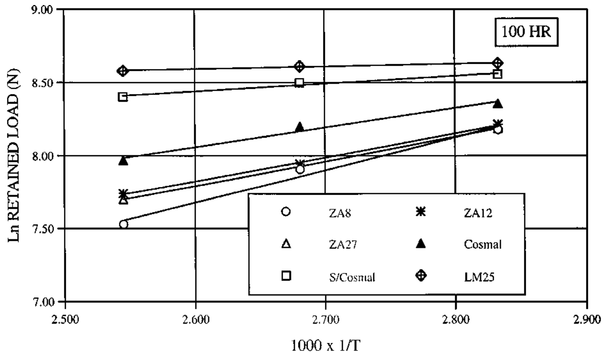

Figure 10 Variation of ln retained load after 100 hours at different temperatures with reciprocal absolute temperature for all alloys.

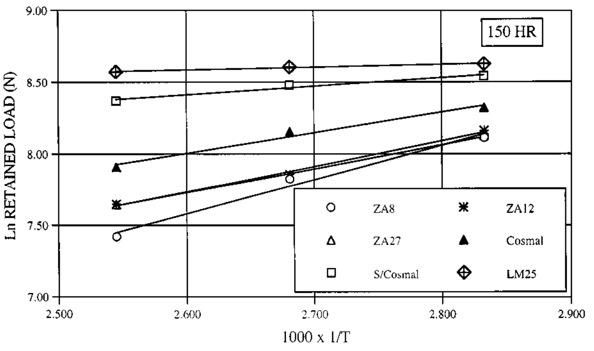

Figure 11 Variation of ln retained load after 150 hours at different temperatures with reciprocal absolute temperature for all alloys.

each alloy from Table III, the values of Q were calculated from the slopes of the graphs in Figs 9–11 for three relaxation times, and are shown, together with the mean Q values for each alloy, in Table IV. This table shows that there was a systematic variation in values of Q: the apparent activation energy increasing strongly with increased time for all the alloys tested except ZA27, which attained a maximum value at the intermediate time. The mean Q values in Table IV are close to those for self diffusion in zinc, and similar to those obtained in other zinc-based alloys [12], but there was a clear increase with aluminium content.

These results indicate that, as with the pressure diecast alloys, the assumed kinetic equation is not strictly adhered to by the alloys investigated here, but provides a reasonable correlation of the data within the range of variables used, and will allow a modest degree of extrapolation. In view of the very slow rates of change at times in excess of 150 hours, extrapolation to longer times is likely to be more accurate than higher or lower temperatures. However load relaxation rate depends not only on the casting alloy and initial load, but on the screw diameter and engagement length, thread pitch and method of forming the thread in the casting, so comparisons with other alloys are only valid if the geometrical factors are the same [10].

TABLE IV Calculated values of the apparent activation energy for relaxation (Q), for relaxation times of 50, 100 and 150 hours, using mean values of power-law constant constant α

		Q (kJ/mol)			
Alloy	α	50 h	100 h	150 h	Mean Q
ZA8	0.190	86.16	98.15	104.89	96.4
ZA12	0.172	66.27	79.23	86.33	77.28
ZA27	0.157	87.59	89.76	88.81	88.72
Cosmal	0.101	96.97	109.57	116.40	107.65
SuperCosmal	0.047	75.71	95.35	107.20	92.75
SuperCosmal	0.013	105.52	114.48	118.32	112.77

4. Conclusions

1) All experimental alloys suffered a rapid initial loss in load which diminished gradually with time. The load retained after a given time diminished with increased test temperature.

2) LM25 was found to have the best resistance to load loss among the alloys tested, followed in decreasing order by SuperCosmal, Cosmal and the ZA alloys.

3) The rates of load loss in ZA alloys were very similar, but ZA12 was marginally more resistant than ZA27 and ZA8 slightly less.

4) The time and temperature dependence of retained load could be described approximately by a relationship of the form:

$$\ln P = \alpha[Q/RT - \ln B - \ln t]$$

where P is the load retained after time t at absolute temperature T, α and B are constants, Q is an apparent activation energy for relaxation, and R is the gas constant.

5) The mean values of the constant α decreased and the mean values of the apparent activation energy Q increased with aluminium content of the alloy.

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