Preload relaxation of steel fasteners in ACuZinc alloy sand-castings

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Abstract

The general preload loss of threaded steel fasteners set into sand-castings of two ACuZinc (Al-Cu-Zn) alloys, i.e. ACuZinc5 and ACuZinc10 at a constant temperature of 80, 100 and 120°C was continuously monitored. The equipment used for these tests consists of a calibrated load cell, an oil-bath, and a data-acquisition system. The load cell is used to monitor the preload loss in ISO M6 × 1 steel screws set into sand-castings made from alloys ACuZinc5 and ACuZinc10, and tightened to produce an initial preload of 6 kN. The oil-bath is used to heat and maintain the required test temperature throughout the experiment. All tests were conducted in duplicate for periods of up to about 160 hours. The data-acquisition system is used to record the load-relaxation data continuously for the whole test period.

The results showed that for both alloys, the initial preload loss was rapid, followed by an approximately logrithmic decay, with no lower limit. ACuZinc10 had better resistance to load loss than ACuZinc5 under all testing conditions. Both ACuZinc alloys were found superior than zinc alloys No.3, No.5 and No.2 for load-relaxation strength, due to the higher copper contents which contribute greatly to their resistance to load loss in the form of second-phase (ε) particles.

Riassunto

Il lavoro descrive il monitoraggio continuo della perdita generale di precarico verificatasi a temperature costanti di 80°, 100° e 120° in viti filettate di acciaio inserite in getti in forma di terra in due leghe ACuZn, e precisamente ACuZn5 e ACuZn10. Le apparecchiature utilizzate per le prove sono un cella di carico tarata, un bagno d'olio ed un sistema per l'acquisizione dei dati. La cella viene adoperata per monitorare la perdita di precarico in viti d'acciaio ISO M6 × 1 introdotte in getti in forma di terra in ACuZn5 e ACuZn10 e poi avvitate in modo tale da produrre un precarico iniziale di 6 kN. Il bagno serve a generare le temperature richieste e mantenerle durante l'esperimento. Ogni prova è stata eseguita in parallelo su due campioni e per periodi fino a 160 ore. Il sistema acquisizione dati viene impiegato per registrare in modo continuo e durante ogni periodo i dati sul rilassamento del precarico.

I risultati hanno indicato che per quanto riguarda tutte le due leghe la perdita è inizialmente rapida, seguita poi da un decadimento pressoché logaritmico senza limite inferiore. La resistenza al rilassamento della lega ACuZn10 si è rivelata la migliore in tutte le condizioni di prova. Inoltre entrambe le leghe si sono dimostrate dotate di resistenze superiori a quelle delle leghe di Zn N 3 e N 2 in virtù del più alto tenore di Cu che nella forma di particelle di seconda fase (ε) molto contribuisce alla resistenza alle perdite di carico.

INTRODUCTION

ACuZinc5 and ACuZinc10 are two new high copper zinc-based alloys developed [1] in the General Motors Research Laboratory. These alloys are considered more creep-resistant, stronger and having more wear resistance than some other zinc alloys [1,2].

Zinc alloy castings are widely used for automotive components. In all these components, fasteners are used to fix them to other structures, or join individual parts together as a subassembly. These fasteners (bolts or screws) with normal or self-tapping thread forms are set in pre-threaded or plain holes [3].

The bolts or screws are tightened to a pre-determined torque so that a tensile preload may be induced in the fastener [4], but due to much less stiffness of fasteners than the flanges or bosses which they clamp together, a small elastic displacement of the clamped components does not increase the preload on the fastener appreciably. Torques may therefore be applied to fastener safely and the initial normal stress is close to the yield stress for the material [5].

The preload-relaxation has been observed in assemblies subjected to high service temperatures and creep effects may become significant. Since the melting temperature of steel is high, the creep process in steel fasteners is considered insignificant at temperatures less than about 350°C, whereas creep may occur at near ambient temperatures for zinc alloys [6]. Thus for steel fasteners used in zinc alloy castings at service temperature more than 0.4 T_m where T_m is melting temperature of zinc alloys, the contribution of fastener creep is negligible, and any preload relaxation can be attributed to plastic deformation in the casting. During this process, creep allows a gradual displacement of the fastener relative to the casting, so that the preload is reduced.

Previously some experimental investigationswere conducted to determine the preload relaxation behaviour of commercial zinc alloy pressure-die castings in the temperature range 22-80°C [3,4], and also zinc alloys (No.3, No.5 and No.2) sand-castings in the temperature range 80-120°C [7]. Zinc alloys ACuZinc5 and ACuZinc10 were however not tested for preload relaxation in the previous studies, and therefore both ACuZinc alloys in sand-cast form were used to investigate their load-relaxation behaviour in the temperature range 80-120°C. The results of load-relaxation for ACuZinc5 and ACuZinc10 from the current study were also compared with those of zinc alloys No.3, No.5 and No.2 obtained from a previous research work [7].

TESTING EQUIPMENT

The equipment used for testing was similar to that used in the previous studies of zinc alloys for preload relaxation [3,7]. The main parts of the equipment are: a load-measuring device, an oil-bath and a data-acquisition system.
The load-measuring device was used for the continuous monitoring of load in the commercial fasteners used. It consisted of a short tension rod to which the head of the fastener was attached, and reacted the tensile stress in the fastener through a load cell. The load cell is shown in Figure 1.
The oil-bath was used to heat the specimen and maintain the same temperature throughout the test. The maximum operating temperature of bath was 150°C, and had a temperature controlling accuracy of ±0.1°C.
The data-acquisition system was used to record the results of tests in the form of retained load (N) versus the test time (Mins.). Variable speed logging was a useful feature provided by the system. This allowed to program the data logging speed to suit the application, i.e. at the initial stage of the tests, more data readings were measured and recorded than the later stages of the test. The time interval between two readings at the start of the tests was 5 and 10 seconds, whereas in the last stage of the tests, this interval was kept as one hour.

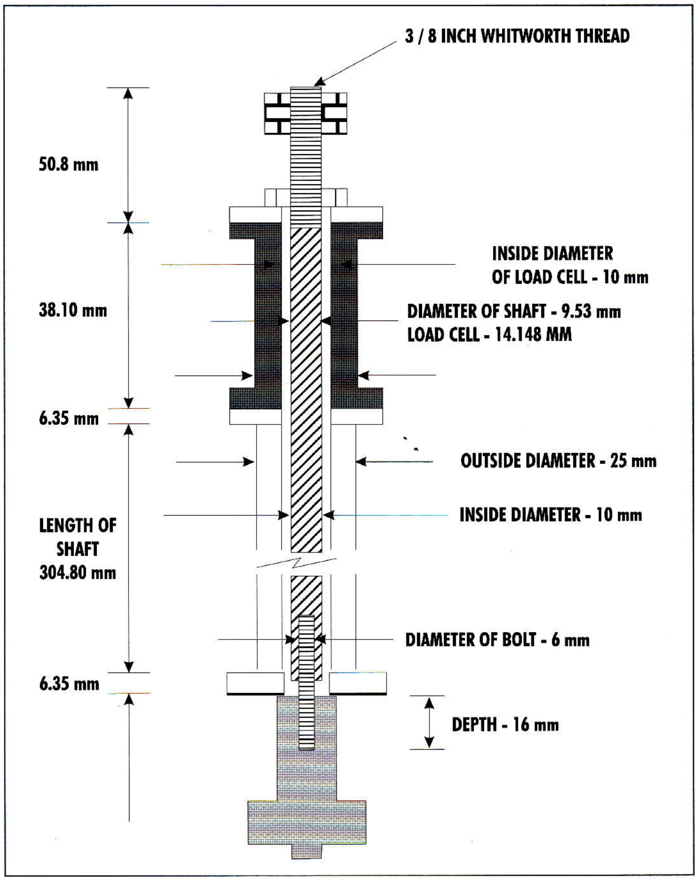

Fig. 1: Load Cell

PREPARATION OF ALLOYS

The chemical composition of the alloys was determined by atomic-absorption spectroscopy and the results are given in Table 1.
Both ACuZinc alloys were prepared at the foundry of Aston University. To prepare ACuZinc5 and ACuZinc10, high purity (99.99%) zinc and aluminium (99.985%) were used. The calculated amount of zinc and aluminium was melted in a standard box-type gas-air furnace at about 600°C. Since both ACuZinc alloys contain copper contents, a calculated weight of hardener (50% Cu and 50% Al) was therefore added to the melt, and then vigorously stirred. ACuZinc5 and ACuZinc10 have a very small amount of magnesium (0.03 ~ 0.04%), and to avoid the losses of magnesium, it was added to the melt at as low a temperature as possible. The mixture was again vigorously stirred. The resultant alloys ACuZinc5 and ACuZinc10, were then poured into a sand mould to prepare the required castings.

TABLE 1 - Chemical composition of the experimental alloys (wt. %)

Alloy	Al	Cu	Mg	Zn
ACuZinc5	3.07	5.20	0.04	Balance
ACuZinc10	3.51	9.33	0.03	Balance

THE TEST SPECIMEN

The test specimens used for the tests were prepared from the sand castings of ACuZinc5 and ACuZinc10. The specimens were of cylindrical shape, having the following dimensions: length = 30 mm, diameter = 13 mm, and bore (threaded) = 6 mm.

These specimens were produced on a lathe in the Manufacturing and Production Engineering Laboratory of Aston University. During the production of the test samples, the machining operation was carefully controlled so as to reduce the surface finish variations to a minimum.

TESTING PROCEDURE

A M6 x 1 (ISO standard) threaded screw was locked into the tension rod, and the load monitor assembled. The test piece was then threaded onto the screw up to 16mm depth, which was the desired engagement of screw. The entire monitoring assembly was dipped into the hot oil at constant required test temperature, and left for about 2 or 3 hours to equilibrate.

To start the experiment, the tension rod and screw were loaded by turning the fine-pitch nut at the top of the rod. This process was continued until the initial load of approximately 6000N which was recorded by the load cell , could be achieved. This whole process completed in a very short time.

The data-acquisition (logging) system was started as tightening commenced. The preload loss was then continuously monitored by the load cell for a period of up to about 155 hours, after which the test was terminated. Up to four tests were carried out simultaneously, and the test temperature was kept constant with a variation of 0.5°C.

The results of experiments were recorded by data-acquisition system, and displayed on a computer in the form of time (s) versus load (N) relaxed.

All load relaxation tests were carried out in duplicate, and if results were not satisfactory, i.e. appreciable scatter was found in the results, some additional tests were also performed at those particular test conditions. The average values of the results were calculated and the mean values taken to represent the load relaxation behaviour of these zinc-based alloys.

RESULTS & DISCUSSION

The results were plotted in the form of load (N) relaxed versus the test time (Mins.) for both alloys, and are shown in Figures 2, 3 and 4. These figures represent the load-relaxation data of the alloys obtained for duplicate tests made at 80, 100 and 120°C, respectively. In all cases, the initial load loss was high, diminishing gradually with time, but not ceasing. Although some variation in the initial part of the curves was observed, almost all of the curves approximated to a logarithmic decay of load with time. The relaxation data also revealed that the amount of load loss increased rapidly with test temperature.

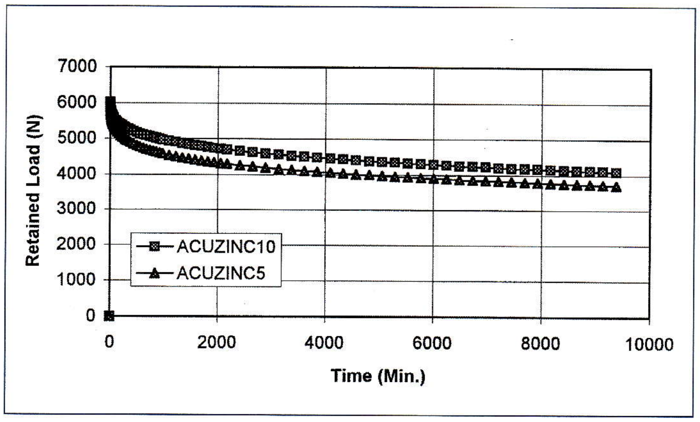

Fig. 2: Load-Relaxation of ACuZinc10 and ACuZinc5 at 80oC.

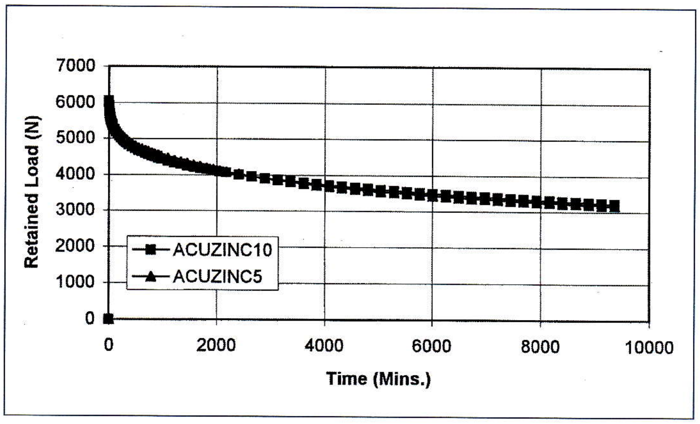

Fig. 3: Load-Relaxation of ACuZinc10 and ACuZinc5 at 100oC.

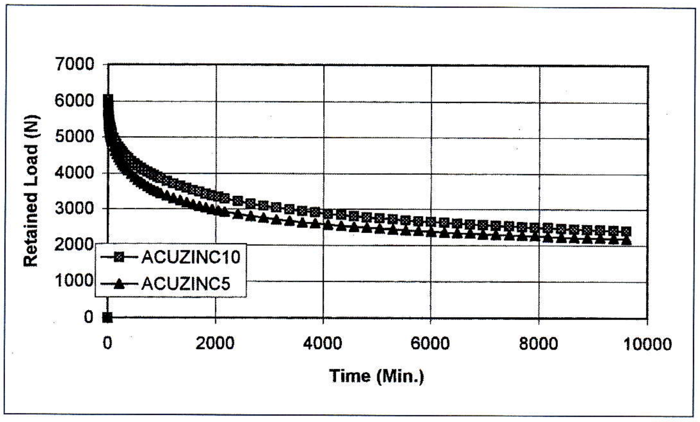

Fig. 4: Load-Relaxation of ACuZinc10 and ACuZinc5 at 120oC.

The curves showed clear differences in the comparative resistance to load loss of both alloys. ACuZinc10 had better resistance to load loss than ACuZinc5 under all testing conditions, as shown in Figures 2 to 4. The variation of retained load (N) with reciprocal temperature at 50, 100 and 150 hours time for both ACuZinc alloys can be seen in Figures 5 to 7. These graphs show the effect of short and long-term load-relaxation tests. The short-term effects of load- relaxation can be observed in 50 h time graphs, while 150 h time graphs demonstrate the long-term effect. These plots showed that ACuZinc10 had higher resistance to load-relaxation than ACuZinc5 at both short and long time periods (Figs. 5-7). The variation of the retained load (N) against the copper content (%) at 80, 100 and 120°C was plotted at 50, 100 and 150 hours, and are shown in Figures 8, 9 and 10, respectively. These graphs show the effect of copper content on load relaxation behaviour of both alloys. It was clear from these plots that ACuZinc5 was inferior in load-relaxation strength than ACuZinc10 at all temperatures, and the difference was greater at 80°C as compared to other test temperatures (Figures 8-10). This indicated that for ACuZinc alloys, the resistance to load loss increased with increasing copper content.

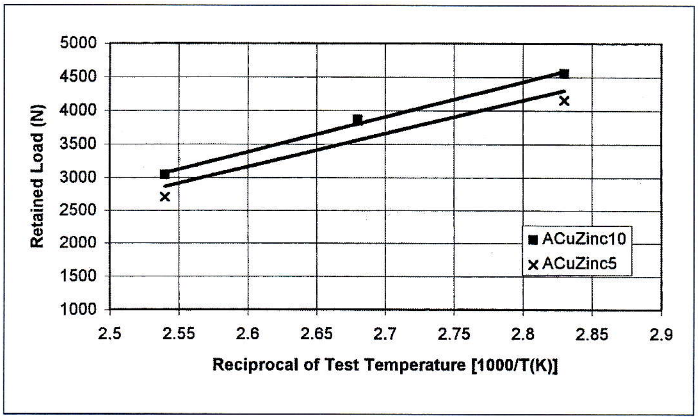

Fig. 5: Variation of 50 hour load with reciprocal temperature for alloys ACuZinc10 and ACuZinc5.

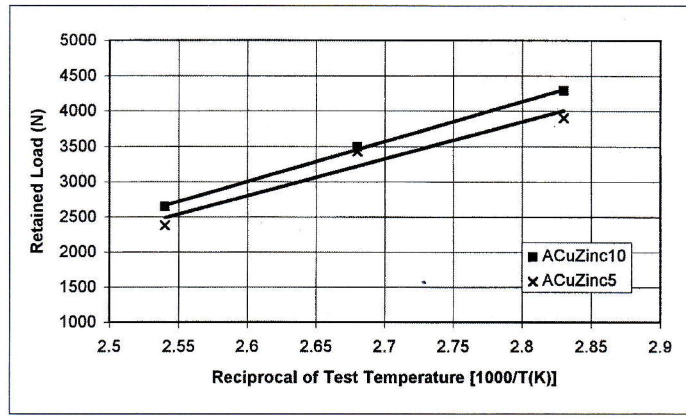

Fig. 6: Variation of 100 hour load with reciprocal temperature for alloys ACuZinc10 and ACuZinc5.

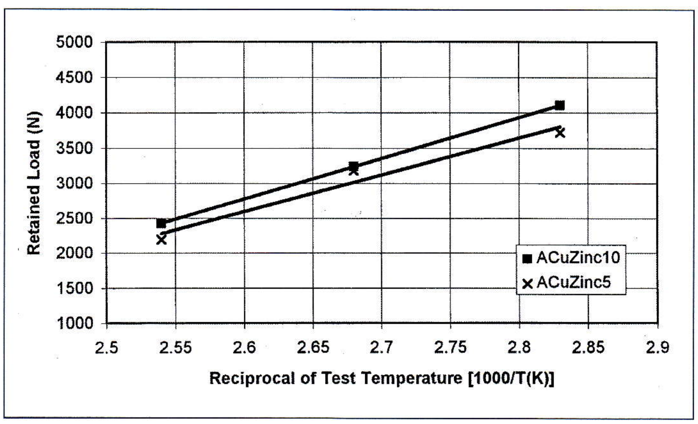

Fig. 7: Variation of 150 hour load with reciprocal temperature for alloys ACuZinc10 and ACuZinc5.

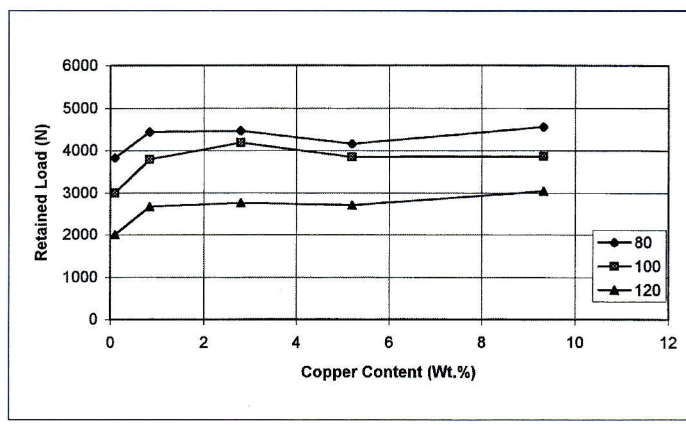

Fig. 8: Variation of 50 hour load with copper content for alloys No3, No5, No2, ACuZinc5 and ACuZinc10 at 80, 100 and 120oC.

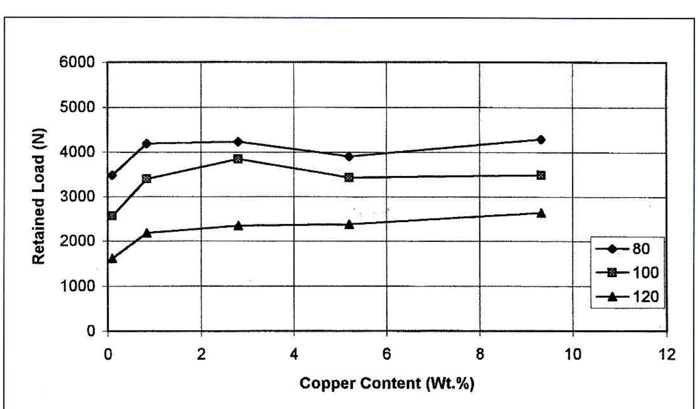

Fig. 9: Variation of 100 hour load with copper content for alloys No3, No5, No2, ACuZinc5 and ACuZinc10 at 80, 100 and 120oC.

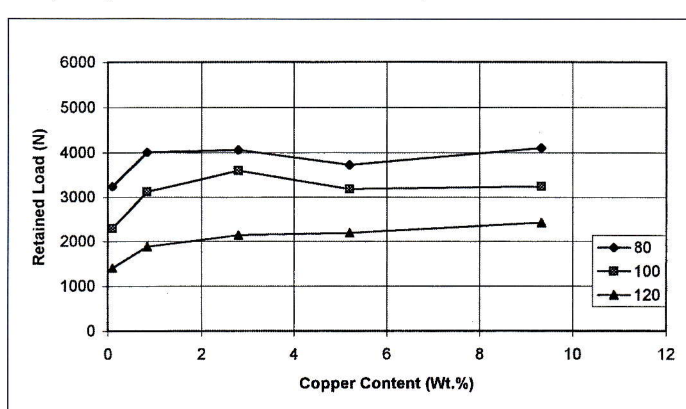

Fig. 10: Variation of 150 hour load with copper content for alloys No3, No5, No2, ACuZinc5 and ACuZinc10 at 80, 100 and 120oC.

METALLOGRAPHY OF THE EXPERIMENTAL ALLOYS

The Scanning Electron Microscopy (SEM) in back-scattered electron imaging mode and optical microscopy was used to study the microstructure of both ACuZinc alloys. The structure of ACuZinc5 in the as-cast condition is shown in Fig. 11. The structure consisted of primary Cu-rich ε dendrites (small and large) with massive h particles, surrounded by a ternary (α + ε + η) eutectic. It was also observed that eutectic volume was much less than the primary e dendrites. The primary Cu-rich e-phase in ACuZinc5 is harder and stronger than the other phases (α and η) and acts as a reinforcement in the matrix. Since tensile strength of alloys is governed by the type of primary phase, the strength and creep properties of ACuZinc5 are enhanced due to the presence of Cu-rich ε-phase which constitutes about 30% of the microstructure of ACuZinc5.

The structure (SEM) of ACuZinc5 after being tested for load-relaxation at 120°C, is shown in Fig. 12. The structure contained large and small primary Cu-rich ε dendrites surrounded by a ternary (α + ε + η) eutectic. The volume of eutectic was much less as compared to primary ε dendrites, which was also observed in the structures of as-cast and creep-tested samples. The eutectic was coarsened and consisted of thin lamellae and particulates.

Fig. 13 shows the SEM micrograph of ACuZinc5 after testing at 120°C at high magnification. The ternary eutectic was heterogeneous and can be seen dictinctly from η and ε-phase particles. Small e-particles were also visible in interdendritic areas. This micrograph also showed that the ternary eutectic had much less volume than the primary ε-dendrites and h particles. The η particles were due to high zinc contents.

Figure 14 shows the as-cast structure (SEM) of ACuZinc10. The structure contained the primary Cu-rich (e) dendrites which are surrounded by the ternary (α + ε + η) eutectic as observed in the structure of ACuZinc5. 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 e-phase was due to the higher percentage (~10%) of copper in ACuZinc10. It was also observed that the primary e dendrites had a much larger volume than the eutectic matrix.

The structure (SEM) of ACuZinc10 after being tested for load-relaxation at 120°C, is shown in Figure 15. The structure contains long branch-like Cu-rich (ε) dendrites surrounded by the lamellar ternary (a + e + h) eutectic. The volume fraction of the primary particles is greater than that of the eutectic and ACuZinc5. In general, the sructure was similar to that of the creep-tested sample. In both structures, the edges of primary dendrites are surrounded by aluminium-rich particles.

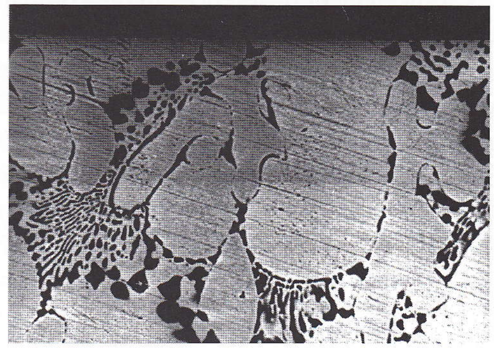

Fig. 11: As-Cast structure (SEM) of ACuZinc5, showing primary e dendrites and ternary eutectic.

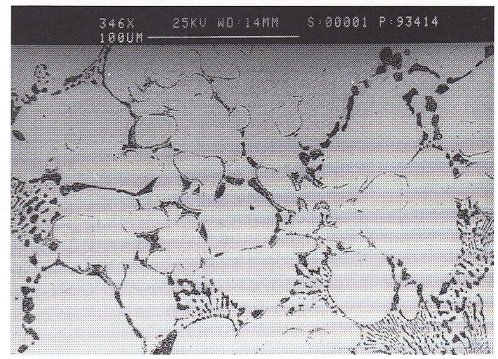

Fig. 12: SEM micrograph of ACuZinc5 tested for load-relaxation at 120°C.

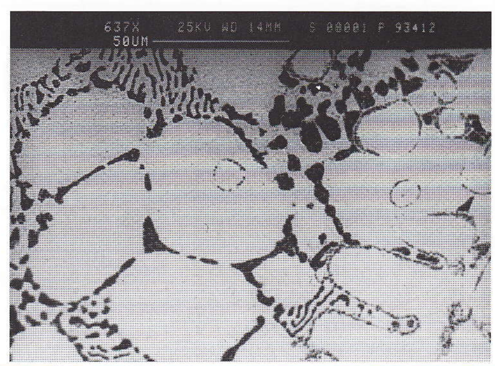

Fig. 13: SEM micrograph of ACuZinc5 tested for load-relaxation at 120°C (high magnification), showing primary ε dendrites and η particles with ternary eutectic.

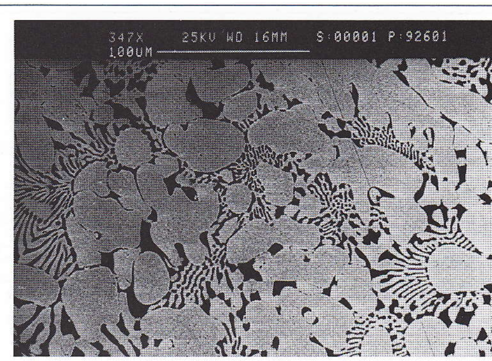

Fig. 14: SEM. As-Cast structure of ACuZinc10 showing primary ε dendrites and ternary eutectic.

RELAXATION RATE-CONTROLLING MECHANISMS

Both ACuZinc alloys are considered as high-copper zinc-based alloys. From optical micrograph of ACuZinc5, it was observed that this alloy contains a considerable amount of large η phase masses in addition to the primary e-phase dendrites. It is therefore located in the transient zone between the η phase and the ε-phase groups of alloys. ACuZinc10 contains more ε-phase dendrites, but η- phase only in the ternary eutectic. However, the volume fraction of ε in ACuZinc10 is far greater than the volume fraction in ACuZinc5 due to the higher copper content. The e-phase is harder and stronger than the other phases and it is supposed that this phase is also creep-resistant. ε acts as a reinforcement in the matrix, and hence their superior properties. The ternary eutectic is heterogeneous, and distinct from primary ε and η dendrites.

Since load-relaxation is a deformation process which is closely related to creep and follows the same mechanisms as creep, the results of load-relaxation may therefore be analysed using the general creep theories and mechanisms

From the results of load-relaxation tests on ACuZinc5 and ACuZinc10, it was observed that the higher copper content in both alloys contribute greatly to their relaxation strength under all conditions in the form of ε-phase (second-phase) precipitates. These ε-phase particles play an important role in preventing the dislocation movement and reducing the load-relaxation rate of ACuZinc alloys. Considering the load-relaxation data and the structural details of both alloys, it may be concluded that the rate-controlling mechanism is the climb of dislocations over second-phase (ε) particles for both ACuZinc alloys.

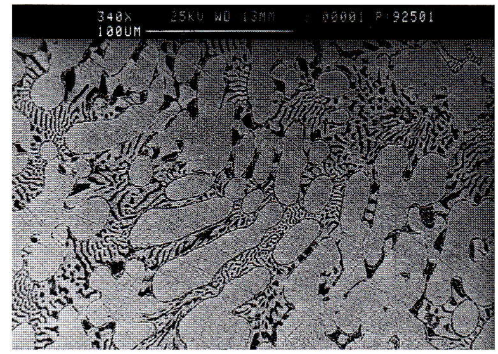

Fig. 15: SEM micrograph of ACuZinc10 tested for load-relaxation at 120°C, shown at medium magnification.

COMPARISON OF RESULTS WITH COMMERCIAL ZINC ALLOYS

When the results of load-relaxation tests for ACuZinc alloys were compared with those of commercial alloys, it was observed that ACuZinc10 was more resistant than alloys No3, No5 and No2 at 80°C. Although ACuZinc5 had better resistance than No3, but alloys No2 and No5 were stronger than ACuZinc5. ACuZinc10 was slightly better than No2 and No5, but both ACuZinc5 and ACuZinc10 showed much higher resistance than No3. At 80°C, ACuZinc5 and ACuZinc10 were 13 % and 21 % stronger than No3, respectively.

At 100°C, alloy No2 was more resistant than ACuZinc5 and ACuZinc10, but both ACuZinc alloys were more resistant than No5 and No3. ACuZinc10 and ACuZinc5 were slightly better than No5, whereas alloy No3 had much lower resistance than ACuZinc alloys. At 100°C, ACuZinc10 had 29 % higher resistance than No3, while ACuZinc5 was 28 % stronger than No3. At comparatively higher test temperature of 120°C, both ACuZinc alloys became more resistant than alloys No3, No5 and No2. The comparative graphs clearly showed that ACuZinc10 was much better than commercial zinc-based alloys. ACuZinc5 was slightly better than No2 and No5, but markedly superior to No3.

The results of load-relaxation tests at 120°C revealed that at higher temperatures, the resistance to load loss increased in alloys having higher copper content, i.e. ACuZinc alloys. Therefore, on the basis of the results of these tests, an important conclusion can be drawn that ACuZinc alloys are suitable for those higher temperature applications where load-relaxation is an important design parameter.

CONCLUSIONS

1. Both ACuZinc alloys showed a rapid load loss initially, followed by an approximately logarithmic decay under all testing conditions.
2. ACuZinc10 had better resistance to load-relaxation than ACuZinc5 at all test temperatures, and for both short and long-term test periods.
3. Higher copper contents enhanced the resistance to load loss under all testing conditions.
4. In general, both ACuZinc alloys had the higher relaxation strength than other zinc alloys No3, No5 and No2, mainly due to higher copper contents which contribute greatly to their relaxation strength in the form of second-phase (e) particles.
5. The climb of dislocations over second phase particles was considered as the rate-controlling mechanism for load-relaxation in both ACuZinc alloys.

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