Causes of the formation of longitudinal surface cracks on the DC-cast 7039 aluminium alloy

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The longitudinal surface cracks occurring on the DC-cast 7039 aluminium alloy were investigated. The cracks were characterized by a grooved appearance on the exterior surface and a branching and porous morphology in the interior area. Microscopic analysis showed that the crack opening was of an abnormal chilled structure, while the interior region was of slowly solidified structures. EPMA and DTA indicated that Mg–Zn intermetallic compounds were formed in the crack interior boundaries. The results suggested that the cracks originated from the uneven chill conditions of the mould. The liquid melt in front of the hot spot was enclosed by the rapidly growing solidified shell and the bridged liquid melt then suffered from a slow cooling rate, forming shrinkage cracks and pores. Formation of Mg–Zn intermetallic compound arising from the slow solidification may enhance the crack occurrence. The cracks were completely eliminated by the improvement in the mould cooling efficiency.

1. Introduction
Aluminium alloys of the Al–Zn–Mg–Cu system are important classes of heat-treatable alloys. The yield and highest strength required are attainable by suitable ageing treatments. Most of the metallurgical factors affecting the product's properties are closely related to the casting process [1–6]. The direct-chill (DC) casting process has been thought to yield many advantages in grain-size improvement, homogeneous solute distribution, and intermetallic constitution. However, because of the wide solidification range of this category of alloys, ingot cracking often plagues the production of these alloys when the DC-casting method is used [6–10].

The major setback in the production of 7039 aluminium alloy is the serious longitudinal surface cracks which appear on the DC-cast ingots. Some studies on the formation of these surface cracks have been reported [7–12]. The bleeding and hot-tear cracking are considered to be caused by the inadequate cooling conditions of the mould and the casting speed [7, 9, 10, 11]. On the other hand, a cold crack caused by too rapid a cooling of the solidified ingot was also reported by some plants [8, 12].

The present work set out to investigate the causes of the formation of the longitudinal surface cracks occurring on the DC-cast 7039 aluminium ingots, by microscopic examination and electron probe microanalysis (EPMA).

2. Experimental details
Samples were cut from the cracked ingot. The cracks showed up as a groove opening on the exterior surface and extended deeply into the interior of the ingot as shown in Fig. 1.

A small piece of the sample was taken from the cracked area for micro-examination. The sample was ground to 800 grit with SiC paper and polished to 0.05 μm with diamond paste lubrication. After polishing, the sample was caustically etched with Keller's reagent to reveal the grain boundaries. The microstructure of the crack and its surroundings were studied in detail by optical microscopy and SEM. The constituents in the cracking area were analysed with EPMA.

The chemical composition of the ingot was checked with the wet chemistry analysis method. The liquidus and solidus temperatures were determined by differential themal analysis (DTA). Samples for chemical composition analysis and DTA were prepared from the normal region of the ingot. The DTA heating and cooling rates were $10^\circ C\ min^{-1}$. The sample was heated from room temperature to 800° C, and held at that temperature for 5 min, then cooled to room temperature again. Argon gas was introduced for atmosphere control and the reference sample was α-Al_2O_3 powder.

3. Results and discussion
The chemical compositions of the sample are listed in Table I. The alloy contained about 4% Zn, 3% Mg and some iron, copper manganese and chromium.

The opening of the crack is of a groove shape. Under lower magnification, the interior of the crack exhibited branching and porous structures as shown in Fig. 2. These morphologies are somewhat different from those of the thermal stress-induced cracking as yet experienced. The opening of a crack occurring in

TABLE I Chemical compositions of 7039 aluminium alloy

Si	Fe	Cu	Mn	Mg	Cr	Zn
0.10	0.12	0.11	0.28	2.75	0.16	4.12

0022–2461/88 $03.00 + .12

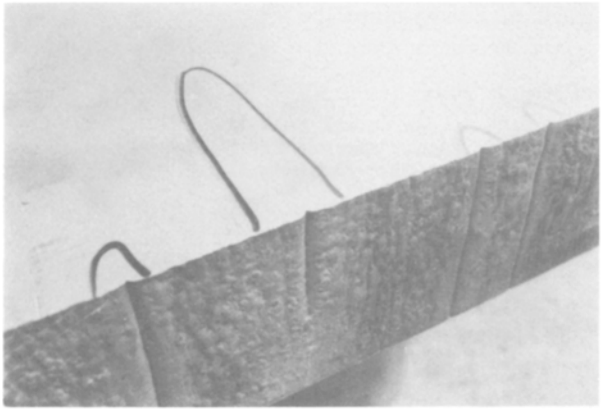

Figure 1 The feature of the longitudinal surface cracks.

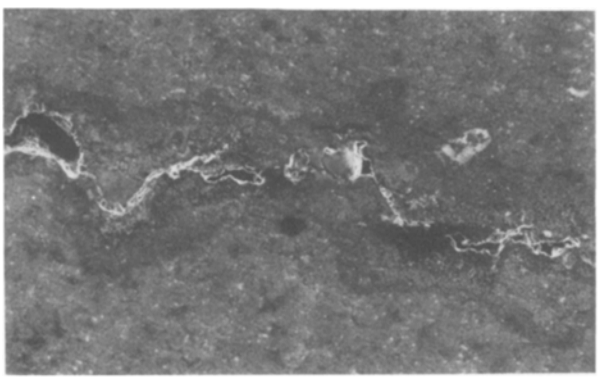

Figure 2 The interior of a crack exhibiting branching and porous structure. ×32.

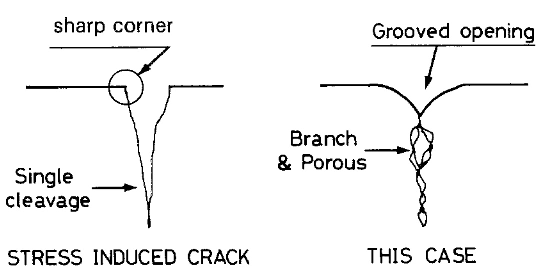

Figure 3 The appearance of the crack is different from a stress-induced crack.

the solidified shell is characterized by a sharp corner shape, and the crack is of a split cleavage inward as schematically shown in Fig. 3 for comparison. The crack characterized by the branching and porous morphology is somewhat similar to the centre-line crack or shrinkage pipe as seen in continuously cast slabs.

More peculiar is the grooved opening. It resembles the transverse oscillation marks arising from alternately opposing and reinforcing the tendency for the shell to be pulled inwards bodily as a result of contraction in solidifying the meniscus edge. However, it is unlikely that longitudinal cracking will occur. Nevertheless, the grooved opening implies that this area could involve the contraction of the solidifying surface.

Fig. 4 shows that there was a chilled zone in the outermost area along the casting surface. The chilled layer became progressively thinner as the grooving proceeded and finally disappeared prior to the crack tip. This evidence clearly indicates that the crack opening was initially an inadequately chilled hot spot. The length of the inadequately chilled surface was estimated to be 1 to 2 mm.

Searching along the crack "river", it was found that the "banks" were full of "foot-prints", "islands", "daisies", and "gulfs", as shown in Fig. 5. These are the solidification structures arising from the slow cooling of the constitutional melt [13]. The foot-prints and islands are the cellular structure and the daisies are the coarse dendrites in the cast structure, while the gulfs could be the shrinkage pores.

X-ray mapping of elemental distribution by EPMA indicated that intermetallic compounds were formed in these areas. The intermetallic compound in the dendrite spaces contained silicon. Another intermetallic compound containing magnesium, zinc and copper was located in the grain boundary. A small amount of aluminium was identified in these regions, as can be seen from Fig. 6.

All the evidence suggested that firstly, the liquid originally located in the crack region suffered from a slower cooling rate and delayed solidification; secondly, the crack is a shrinkage crack rather than a solid shell

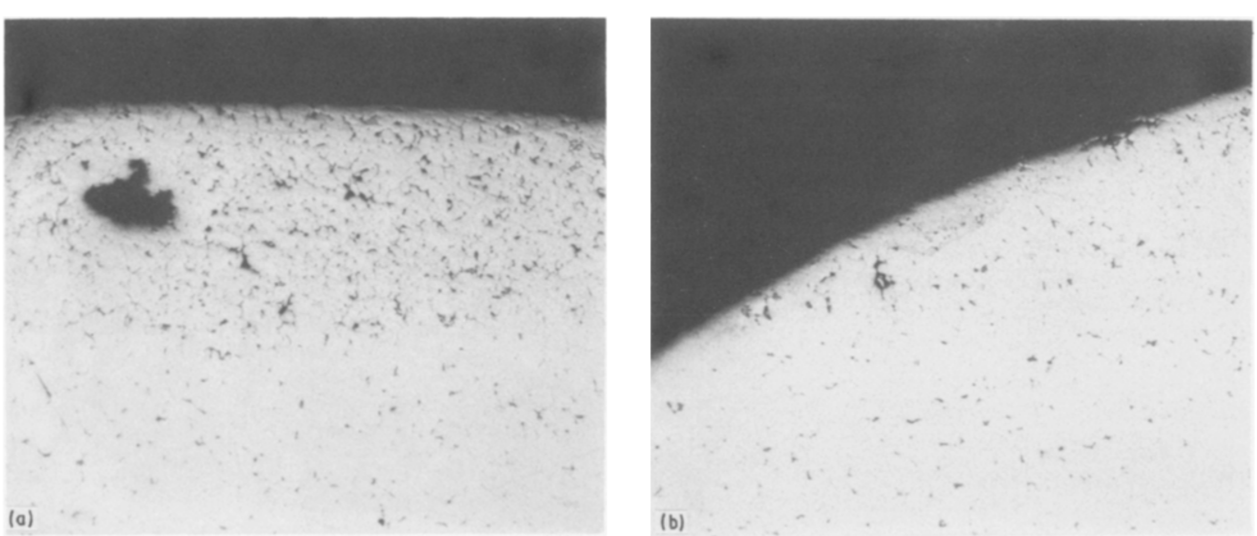

Figure 4 (a) The normal surface of the ingot with a chilled layer. (b) The abnormal area around the crack opening. ×40.

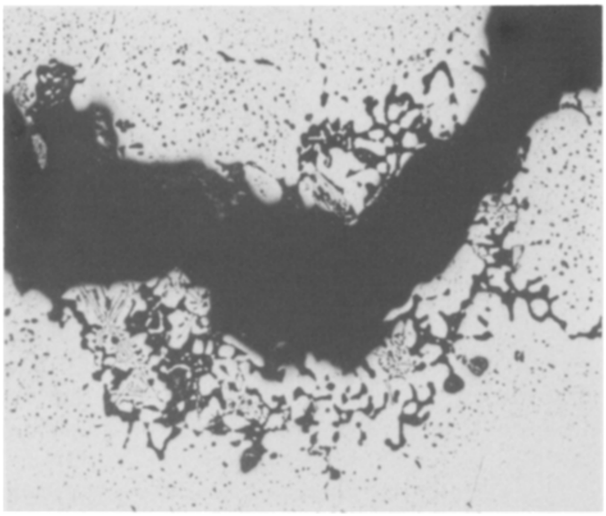

Figure 5 Microstructure of the crack interior. $\times 160$.

cracking. Furthermore, the original melt in the cracked region was a mother melt, instead of a segregated melt.

Various types of surface cracks formed during the DC-casting process have been studied and reported by many pioneers [7–12]. Most of the surface cracking is concerned with the cooling conditions of the mould. The formation of an air gap is one of the most important factors affecting the occurrence of longitudinal surface cracks. The air gap arises from the tendency of the solidified shell to be pulled inward as a result of the contraction in the solidified ingot. The contraction stress and the metallostatic pressure may cause solidified shell cracking. With alloys of wide solidification range, the temperature of the shell may exceed the solidus temperature of the low melting point intermetallic compound. The low melting point interdendritic substance may introduce hot tearing or exude to

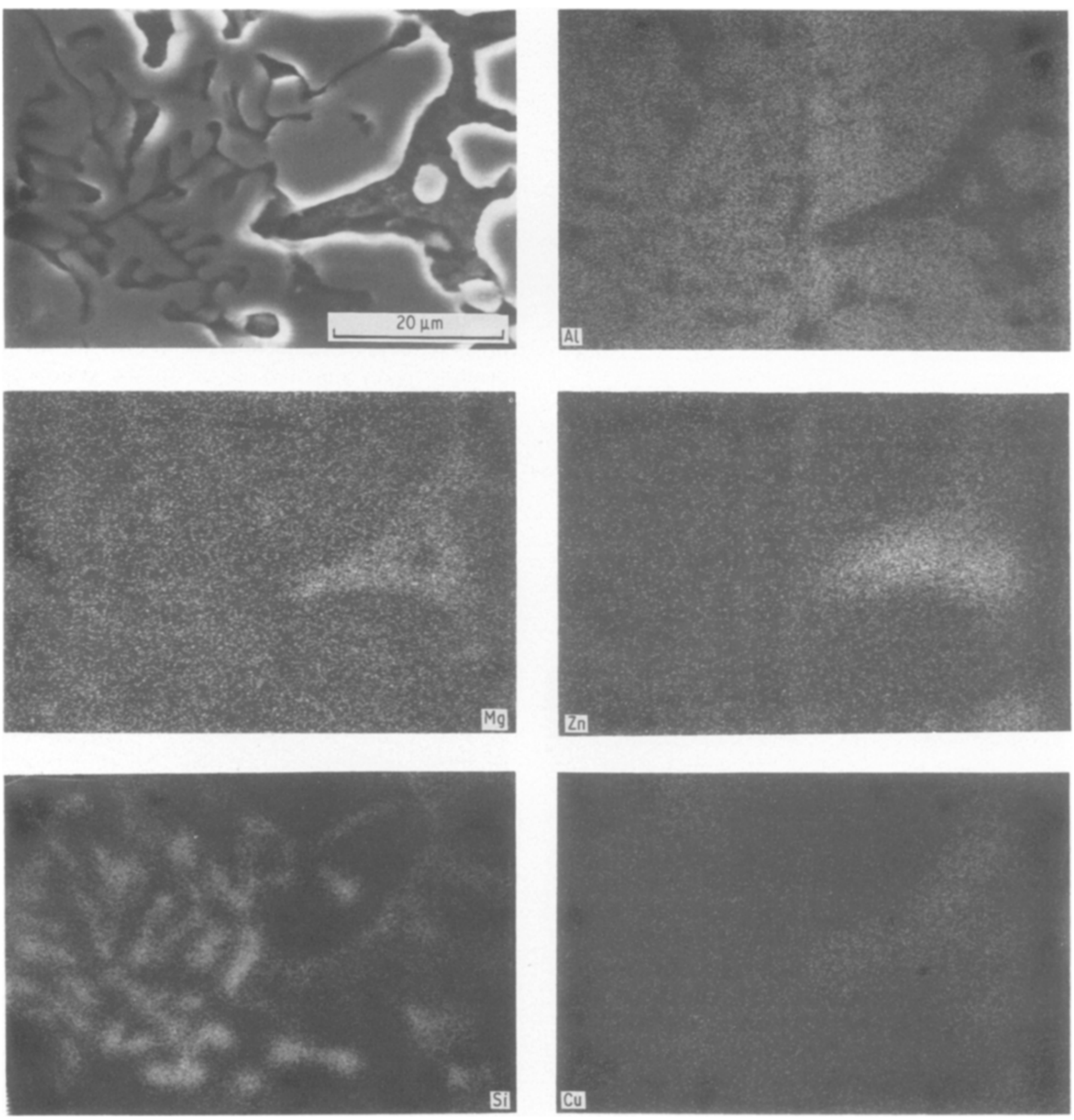

Figure 6 X-ray mapping on the crack boundary.

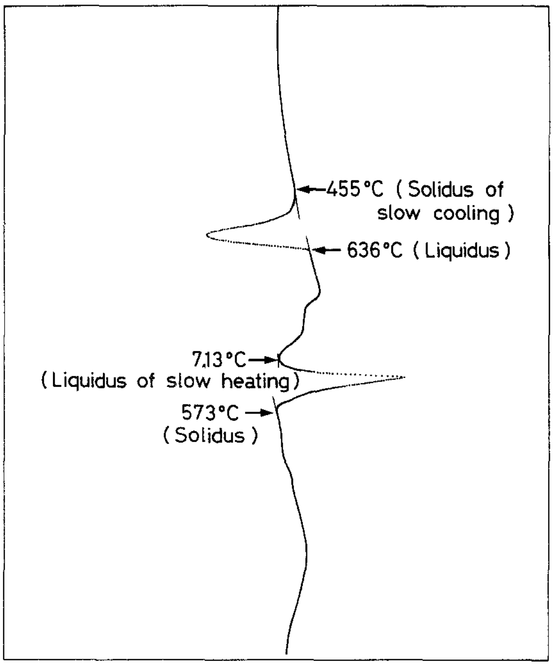

Figure 7 Differential thermal analysis of 7039 alloy.

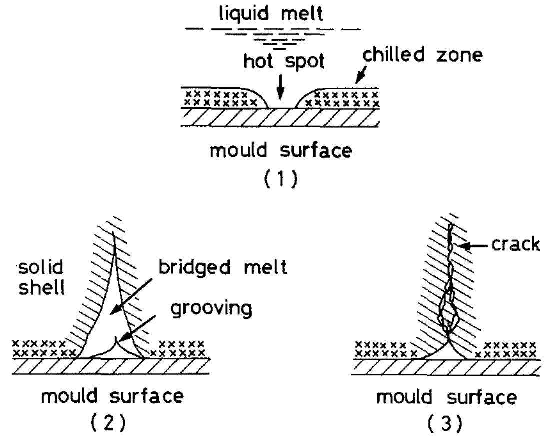

Figure 8 The suggested mechanisms of crack formation.

the surface under the influence of the metallostatic head [6, 7, 9–11].

The solidus and liquidus temperatures of 7039 alloy were measured using DTA to be 573 and 636° C, respectively, as shown in Fig. 7. The solidification range is 63° C. If the cracks arose from the formation of an air gap, the outermost opening of the crack should be of a sharp corner shape as demonstrated by the solidified shell, and even a burst feature would appear under the metallostatic pressure. If bleeding or exuding of the interdendritic substance had occurred, a secondary chilled layer would have been identified in the crack opening and the boundaries of the crack interior would have been a layer of homogeneous constitution of the compound, instead of the aluminium matrix accompanying secondary phases. None of these were found in the present work. Although some intermetallic strings were found in the crack boundaries, the matrix was of aluminium constitution. Neither inverse segregation, nor surface segregation, were found in the ingot [10].

The fact that there was no chilled layer in the crack opening region suggests that the ingot surface suffered uneven chilling conditions. Examination of the other ingots cast with the same mould revealed that some coarse grains were found in the surface layer. This finding strongly supports the reasoning that the mould was subjected to uneven chilling conditions during the casting. Under the situation of uneven chilling, the liquid melt in front of the hot spot would be enclosed by the rapidly growing shell to form a canyon. The outer surface of the pool would then solidify and shrink to form a groove. The initial crack might occur on the tip of the groove. As the grooving surface pulled away from contact with the mould surface, the melt bridged in the canyon region would solidify at a slow cooling rate. This resulted in the cellular and dendritic structures accompanying intermetallic strings and shrinkage pores. The suggested mechanisms are schematically shown in Fig. 8.

Quantitative EPMA on the Mg–Zn compound area indicated that the atomic concentrations of magnesium and zinc were 27 to 32% and 20 to 26%, respectively. The concentration of copper was only 1%. Although the X-ray mapping (Fig. 6) showed that little aluminium was distributed in this region, the atomic concentration of aluminium in this region was analysed to be 40 to 50%. The atomic ratio of Mg : Zn is 1.0 to 1.5. these results suggested that the compound is predominantly in $Mg_3Zn_3Al_2$ [14]. Possible reactions involving the formation of $Mg_3Zn_3Al_2$ [14] are

$$\text{Liq.} \rightarrow \text{Al} + Mg_5Al_8 + Mg_3Zn_3Al_2 \quad (1)$$

reaction temperature 720 K

$$\text{Liq.} \rightarrow \text{Al} + Mg_3Zn_3Al_2 \quad (2)$$

reaction temperature 762 K

$$\text{Liq.} \rightarrow \text{Al} + MgZn_2 + Mg_3Zn_3Al_2 \quad (3)$$

reaction temperature 748 K

From DTA (Fig. 7), at the extremely slow cooling rate of $10°\,C\,min^{-1}$, the finishing temperature of solidification was 455° C (728 K). Therefore, Reactions 2 and 3 are more likely to occur during the solidification of the bridged liquid melt. If the cooling rate was slow enough to initiate Reaction 3, $MgZn_2$ might form coexistently with $Mg_3Zn_3Al_2$. The formation of $MgZn_2$ will enhance the formation of shrinkage cracks and pores, because its shrinkage in solidification is as high as 24% [14]. Although the existence of $MgZn_2$ could not be confirmed, formation of the Mg–Zn intermetallic compound does indicate that the solidification temperature of the bridged liquid melt was possibly extended down to the low eutectic point and may have some effect on the crack formation.

Based on the above investigation, action was taken to improve the cooling efficiency of the mould. After that, the longitudinal surface crack was completely eliminated and perfect ingots were obtained.

4. Conclusions

The formation of longitudinal surface cracks in DC-cast 7039 aluminium alloy was investigated by microscopic examination, EPMA and DTA. The results indicated that the cracks originated from the uneven chilling of the mould. The aluminium melt behind the hot spot was enclosed by the rapidly growing solid neighbours which were subjected to normal chill conditions. The exterior surface of the enveloped melt solidified to form a grooved appearance and pulled away from contact with the mould. The interior region of the bridged melt then solidified to form shrinkage pores and cracks under a very slow cooling rate. Mg–Zn intermetallic compounds were formed at the end of solidification and may enhance crack occurrence. The cracks were completely eliminated by improving the cooling efficiency of the mould.

Acknowledgements

The author thanks Mr J. Y. Huang, Manager of Research and Development, and Dr I. L. Cheng, President of Technology, at China Steel Corp., for their support.

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Received 8 April
and accepted 29 June 1987