Effect of Iron and Combined Iron and Beryllium Additions on the Fracture Toughness and Microstructures of Squeeze-Cast Al-7Si-0.3Mg Alloy

S. Murali, A. Trivedi, K.S. Shamanna, and K.S.S. Murthy

Squeeze casting is a near-net-shape process of casting under pressure that yields a fine-grain structure with higher density and mechanical properties compared to conventional casting processes. Iron is the most commonly present impurity element in Al-7Si-0.3Mg, the alloy investigated. An increase in iron content significantly decreases fracture toughness. However, trace additions of beryllium completely neutralize the detrimental effect of iron. The variables of the squeeze casting process greatly govern the microstructures and macrostructures and thus the defects in the casting. This case study deals with Al-7Si-0.3Mg squeeze-cast cranks with four major defects—blistering, debonding, porosity, and patches of silicon segregation on the casting surface—and the appropriate remedial measures to eliminate these defects.

Keywords
aluminum alloys, beryllium, iron, squeeze casting

1. Introduction

SQUEEZE casting involves pressurizing a predetermined quantity of liquid metal between the two die halves during solidification to generate a near-net-shape casting. The process basically combines features of casting and forging, which in turn yield high structural integrity and configurational complexity. Squeeze casting is also called liquid metal forging, semisolid casting or forging, pressure recrystallization, and extrusion casting (Ref 1).

The process produces highly dense, pore-free castings with isotropic microstructures, eliminates casting appendages (e.g., runners and risers), and results in grain refinement. Adaptability to mass production, lower forging pressures, and the possibility of achieving a higher aspect ratio (50 to 1) make the process economically viable (Ref 2). In general, materials that can be squeeze cast include aluminum alloys, copper alloys, alloy steels, and tool steels. This process even finds application in the manufacture of metal-matrix composites.

The key process variables identified for squeeze casting are (Ref 2-5):

- *Pressure:* The pressure applied during solidification is responsible for improving mechanical properties, refining grain structure, increasing heat-transfer coefficient, controlling volume shrinkage, generating dimensional accuracy, and controlling the interfacial air gap between the die and molten metal. The recommended pressure duration is 30 to 120 s (and should not be less than 5 s), and the pressure applied generally varies between 50 and 140 MPa (Ref 4).
- *Melt and die temperatures:* Optimization of these two variables is essential in order to control premature solidification and soldering (which occurs between the component and die). It has been found that ultimate tensile strength and elongation improve with an increase in pressure from atmospheric pressure to 690 MPa at all die and molten metal temperatures, whereas the increase in yield strength is marginal (Ref 6). The die temperature is generally maintained in the range of 190 to 315 °C, and the pouring temperature will have a superheat of 50 to 60 °C (Ref 4).
- *Time delay:* The delay between the pouring of molten metal into the die and the application of pressure is also very important to achieve a sound casting. Undue delays result in the need for high squeezing pressure, initiation of premature solidification (largely near the die wall), and incomplete die closure. However, the time delay should not be less than 5 s.
- *Liquid metal volume:* Molten metal must be metered (preferably not to exceed 10% of the casting volume) to ensure close dimensional control (Ref 3).
- *Die coating:* The coating controls the heat-transfer coefficient at the metal/die interface. A properly selected die coat should yield the lowest resistance to heat flow at all pressures and should not result in soldering between the die and the casting surface.

These process variables greatly govern microstructures. Consequently, they also improve casting soundness and mechanical properties, as does thorough degassing of the melt in order to remove hydrogen and other gases. Solid inclusions are removed by use of a filter.

This study focuses on Al-7Si-0.3Mg, which has good casting characteristics and is categorized as a high-strength cast aluminum alloy. Consistent production capability and suitability to heat treatment have made this alloy readily acceptable in automobile, defense, and aircraft applications. Proper care must be taken to avoid iron contamination during melting and casting, since iron is the most commonly picked up impurity element. The deleterious effect of iron as an impurity in Al-7Si-0.3Mg alloy has been well established for both sand and chill castings (Ref 7, 8). The effect of trace element additions, especially beryllium, in counteracting the effect of iron has also

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been thoroughly investigated for chill- and sand-cast Al-7Si-0.3Mg (Ref 9, 10). However, very little information is available concerning the deleterious effect of iron on squeeze-cast Al-7Si-0.3Mg alloy and the role of beryllium trace addition as a neutralizer.

This paper presents results of a study on the effects of iron impurities and neutralization of these impurities by beryllium additions, as well as the consequent effect on fracture toughness. The effect of process variables on the quality of squeeze-cast cranks made from Al-7Si-0.3Mg alloy (Fig. 1) is investigated. A microstructural study of the defects of the cranks is discussed, as are remedies to overcome these defects.

Table 1 Chemical composition of the alloys prepared(a)

Composition, wt%				
Si	Mg	Fe	Be	Cu
7.11	0.44	0.10	...	<0.1
7.80	0.45	0.12	...	<0.1
7.53	0.43	0.31	...	<0.1
7.62	0.38	0.40	...	<0.1
7.80	0.43	0.70	...	<0.1
7.74	0.42	0.13	0.11	<0.1
7.50	0.40	0.18	0.11	<0.1
7.50	0.45	0.38	0.12	<0.1
7.59	0.43	0.53	0.18	<0.1
7.45	0.46	0.72	0.26	<0.1

(a) Analyzed in Spectro-Vac (Baird make, USA) model DV-50

2. Iron Impurity

2.1 *Microstructures*

The presence of iron in the alloy (Table 1) leads to the formation of β-$FeSiAl_5$ intermetallic compound; however, it has been observed that the β-compound is finer in squeeze-cast alloys than in conventionally cast alloys (Table 2). In normal Al-

Table 2 Length of β-phase and diagonal length of Be-Fe hexagonal phase observed in variously cast alloys containing iron and beryllium

Type of casting	Length of maximum β-phase, μm	Diagonal length of maximum Be-Fe phase, μm
Sand	270	56
Chill (10 °C/min)	70	28
Squeeze (66 MPa)	95	24

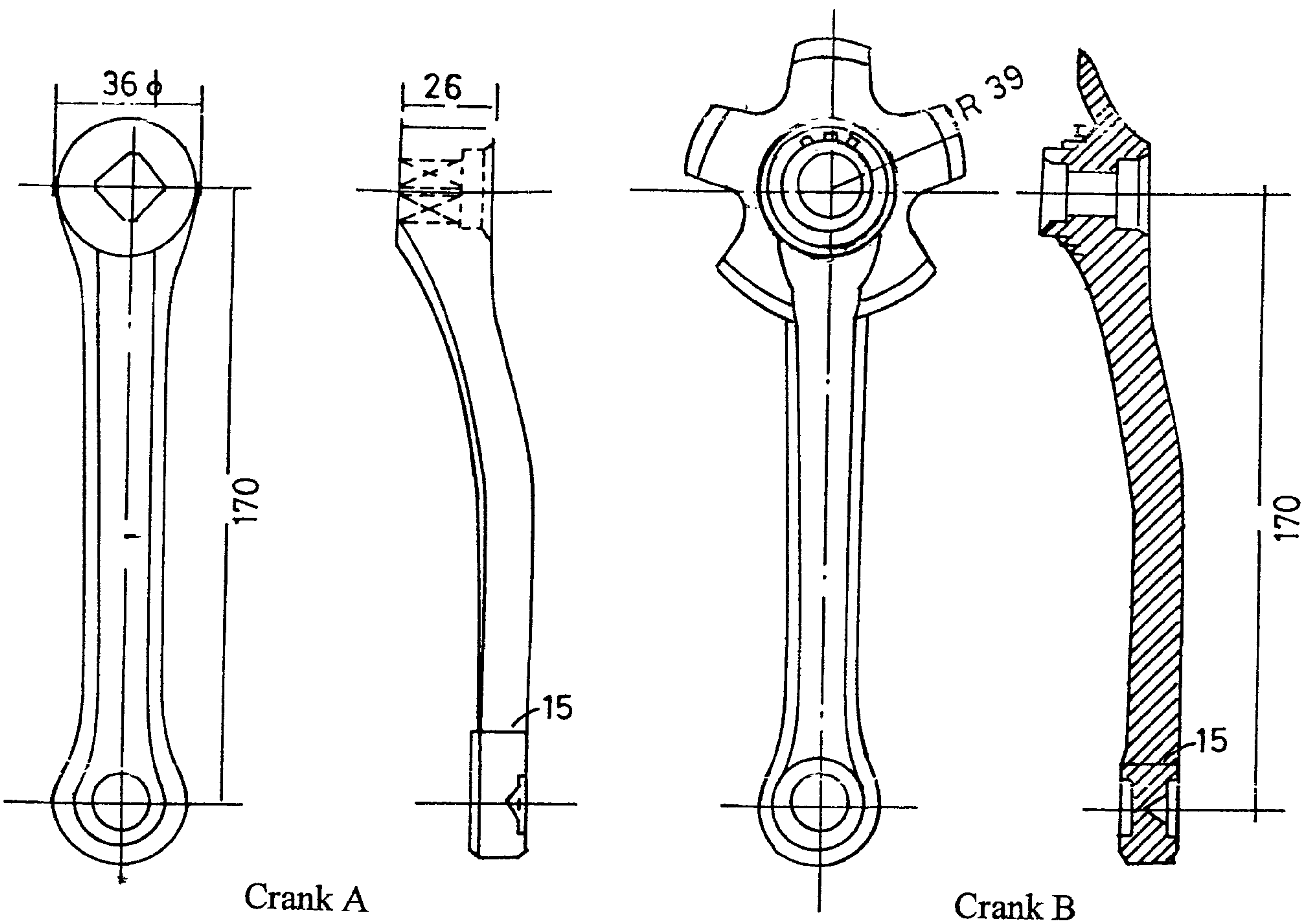


Fig. 1 Dimensions (in millimeters) of two squeeze-cast Al-7Si-0.3Mg cranks

Si-Mg alloy, β-phase is mostly seen in interdendritic regions (Fig. 2a). Addition of a small amount of beryllium to Al-Si-Mg-Fe alloy results in the formation of a new phase—(Be-Fe)-BeSiFe_2Al_8 (Ref 9, 10), which has a morphology of hexagonal shapes or Chinese scripts quite different from that of the β-phase in normal Al-Si-Mg-Fe alloy (where it will have a large needle shape). Furthermore, Be-Fe phases are seen only inside the α-aluminum dendrites (Fig. 2b) (Ref 11). The size of the hexagonal Be-Fe phase is finer in squeeze-cast alloys than in conventional cast alloys (Table 2). A squeeze-cast alloy containing 0.72% Fe and 0.26% Be possesses more hexagonal Be-Fe phase than Chinese script intermetallics compared to sand- or chill-cast alloys (containing similar beryllium and iron levels), where both Chinese script and hexagonal morphologies are equally present (Ref 9, 10). The alloys have been squeeze cast at 66 MPa pressure with a time delay of 25 s and a die temperature of 175 to 200 °C.

2.2 *Fracture Toughness*

Dynamic fracture toughness (K_d) measurements obtained for squeeze-cast Al-7Si-0.3Mg alloy from impact tests using standard Charpy V-notch (CVN) specimens revealed significant decreases in K_d values for increasing iron levels up to 0.7% (Fig. 3). However, adding trace amounts of beryllium completely nullified the detrimental effect of iron impurities (Fig. 3). In addition, slightly higher K_d values were observed at all iron levels, which is attributable to grain refinement by the beryllium additions (Table 3). To support these results, fracture toughness tests using short-rod chevron-notch (SRCN) specimens (Fig. 4) were also conducted. Values for K_{SRCN} fracture toughness are obtained using:

Table 3 Grain size of squeeze-cast Al-7Si-0.3Mg

Fe and Be content, %	Grain size, μm
0.7 Fe	760
0.72 Fe, 0.26 Be	640

$$K_{SRCN} = P_{max} \frac{F_m}{B(W)^{1/2}}$$

where

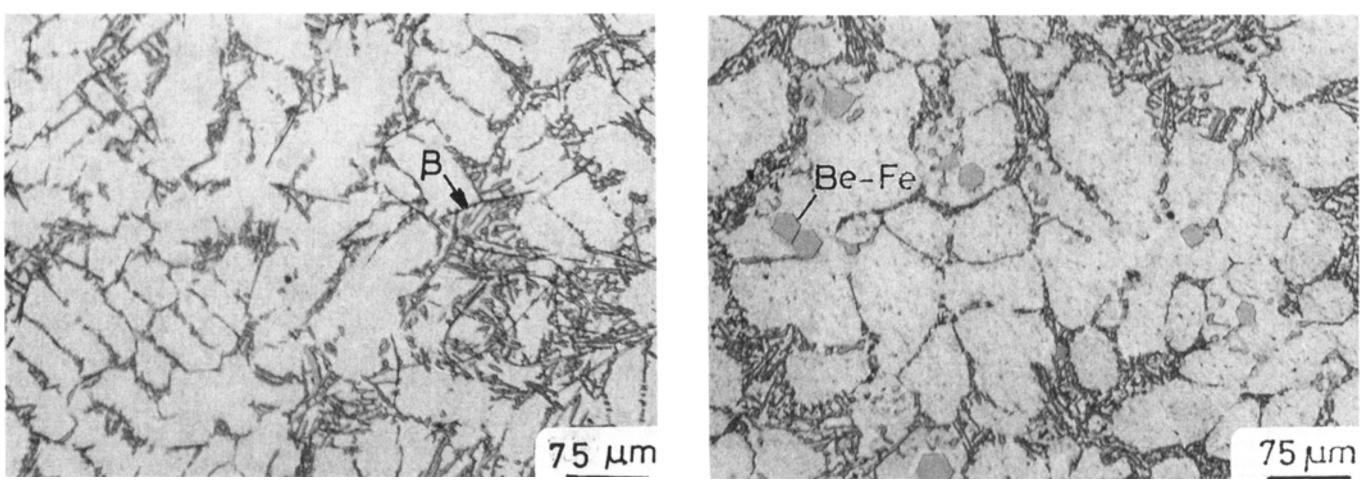
$$F_m = \frac{AW}{B(1 - \nu^2)}$$

and P_{max} is maximum (peak) load (KN) obtained from the load crack-opening displacement curve, A is Barker's normalized factor (equal to 20.8 at $\nu = 0.3$), B is specimen diameter (m), W is specimen length (m), and ν is Poisson's ratio.

Similar to K_d, K_{SRCN} decreased significantly with increasing iron content up to 0.7%. With the addition of beryllium, however, K_{SRCN} remained nearly constant at all iron levels, once again confirming that the harmful effect of iron is neutralized by beryllium addition (Fig. 3).

2.3 *Fractographs*

Scanning electron microscope (SEM) observation of a fractured surface of a squeeze-cast alloy at low iron level (0.1%) (Fig. 5a) revealed cellular fracture similar to that in sand- or chill-cast alloys; however, the cells observed in the squeeze-cast alloy were finer. A cellular mode of fracture was also apparent at low iron level (0.13%) with a beryllium addition of 0.11%. At higher iron levels in squeeze-cast alloys, brittle cleavage and intergranular fracture were observed (Fig. 5b), similar to conventionally cast alloys (Ref 10). In an alloy containing both iron and beryllium (0.72% Fe, 0.26% Be), the cellular fracture was similar to that in a low-iron (0.13% Fe, with and without 0.11% Be addition) squeeze-cast alloy (Fig. 5c). Thus, addition of beryllium completely counters the harmful effect of iron and also yields a fracture mode similar to that of low-iron alloy. Earlier investigations (Ref 9, 10) have revealed pyramids surrounded with cells in high-iron beryllium-added sand- and chill-cast alloys. This type of structure is rarely seen in high-iron beryllium-added squeeze-cast alloys.



(a) (b)

Fig. 2 Microstructures of Al-7Si-0.3Mg-0.7Fe alloy squeeze cast at 66 MPa pressure. (a) Without beryllium. (b) With 0.26% Be

3. Defects Observed in Squeeze-Cast Cranks of Al-7Si-0.3Mg Alloy

3.1 *Silicon Segregation*

Irregular black patches were observed on the polished surface of the casting. Such patches are caused by silicon segregation and are more often observed on the surface of the casting (Fig. 6a) than in its interior (Fig. 6b). Silicon segregation is generally referred to as "extrusion segregation" (Ref 12) of secondary phases in a squeeze-cast alloy. This effect is attributable to faster cooling rate due to low die temperature and high pouring temperature,

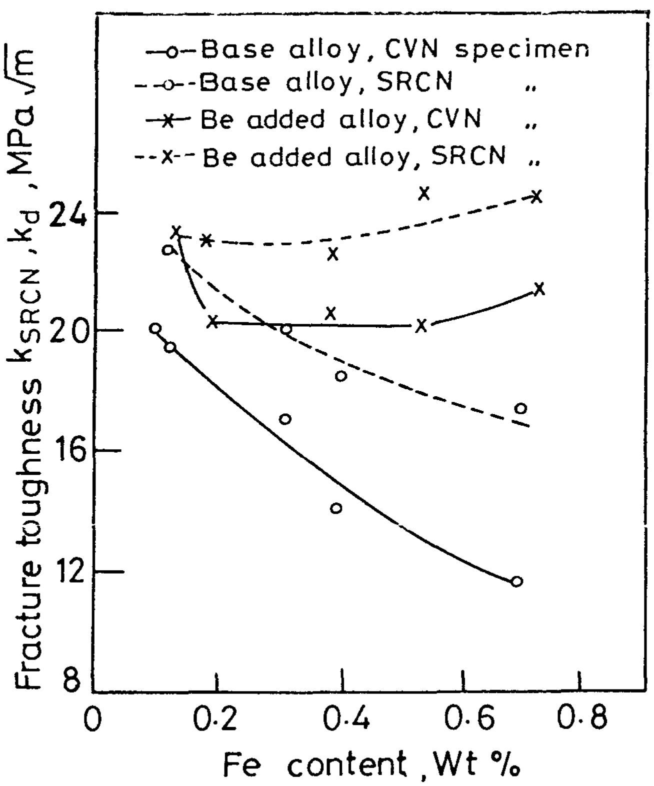


Fig. 3 Effect of beryllium addition on fracture toughness for Al-7Si-0.3Mg alloy with varying iron contents squeeze cast at 66 MPa pressure

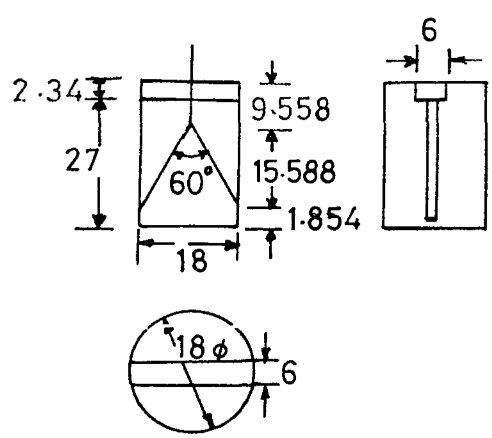


Fig. 4 Dimensions (in millimeters) of SRCN specimen

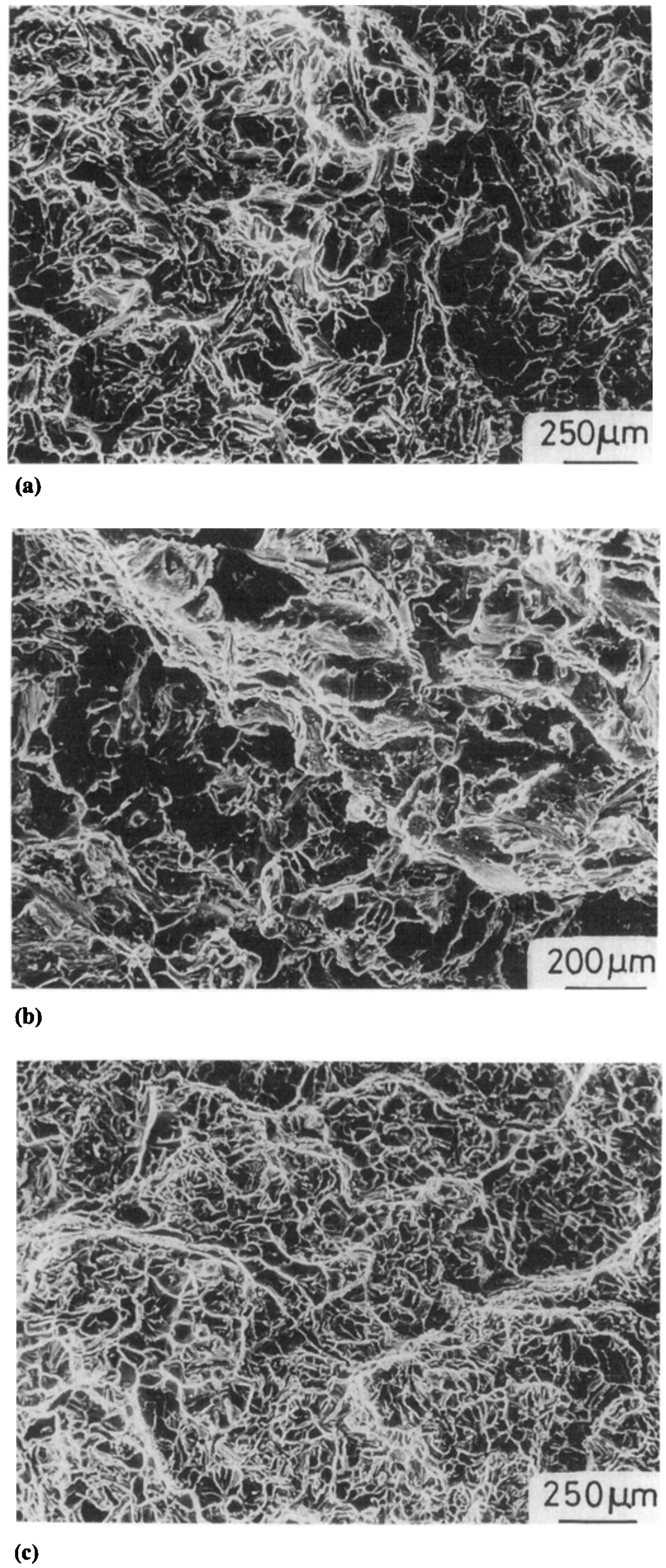
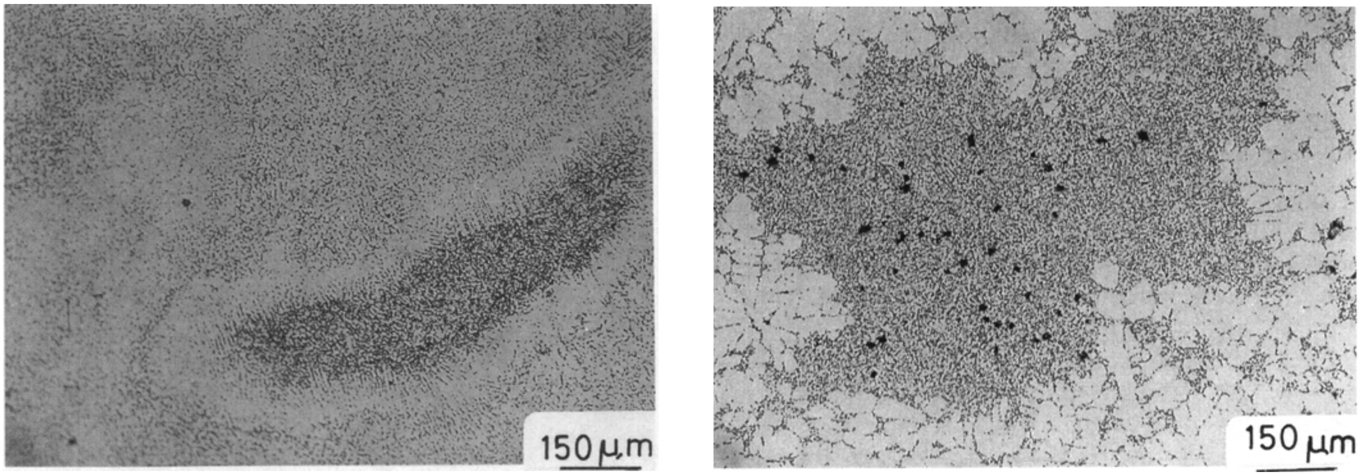
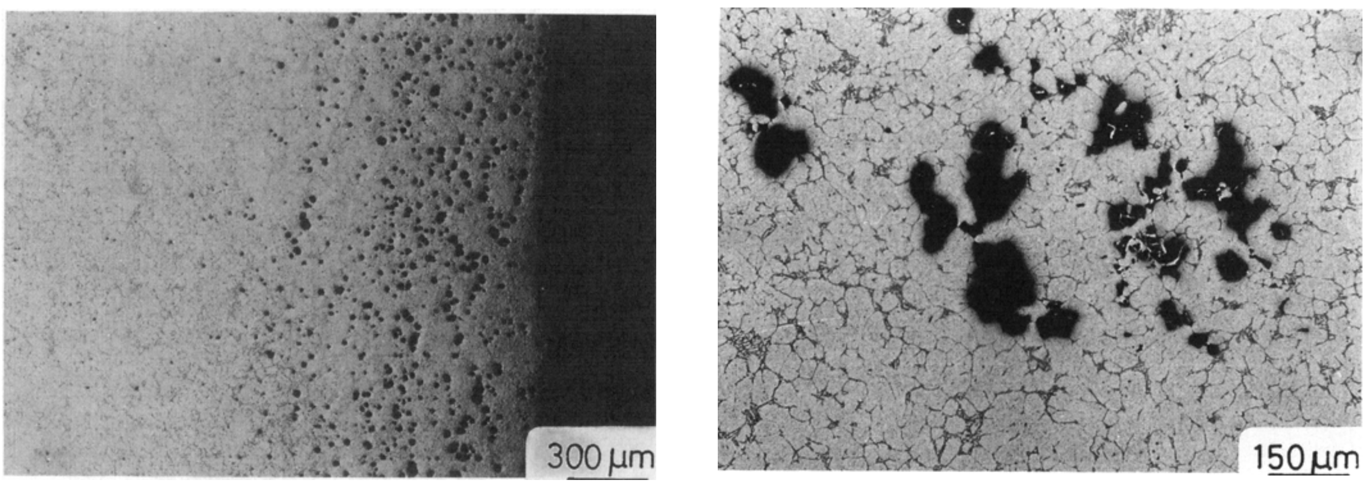


Fig. 5 SEM fractographs of Al-7Si-0.3Mg alloy squeeze cast at 66 MPa pressure. (a) 0.1% Fe. (b) 0.7% Fe. (c) 0.72% Fe and 0.26% Be



(a) (b)

Fig. 6 Microstructures showing silicon segregation as irregular patches in a defective Al-7Si-0.3Mg squeeze-cast crank. (a) On casting surface. (b) Inside the casting



(a) (b)

Fig. 7 Microstructures of a defective Al-7Si-0.3Mg squeeze-cast crank. (a) Severe gas pores near the casting surface. (b) Shrinkage porosity in the center of the casting

Table 4 Ultimate tensile strength (UTS) and ductility values for squeeze-cast Al-7Si-0.3Mg cranks

Casting	UTS, MPa	Elongation, %
1	295	4
2	144	4
3	95	2.5

Note: The minimum UTS and ductility for Al-7Si-0.3Mg alloy properly squeeze cast at 66 MPa applied pressure should be around 330 MPa and 8%, respectively.

and thus will be quite significant in a thin section like the crank casting. Suggested remedies for such defects are:

- Increase the die temperature and maintain at approximately 200 °C to prevent premature solidification.
- Maintain a moderate melt superheat of 40 to 50 °C to ensure lower pouring temperature.
- Minimize delay time (but no less than 5 s).
- Alternately, if possible, squeeze cast the product upside down so that mere pressure is applied during solidification; this may prevent melt extrusion in the casting.

3.2 *Porosity*

Gas and/or shrinkage porosity is generally minimal in squeeze castings. Hence, components that are properly squeeze cast are commonly called "zero pore" castings.

Even though porosity is not seen on the surface of a good casting, severe gas pores of spheroidal shape along with pinholes were visible throughout the section of the defective casting in Fig. 7(a). The porosity was more extensive toward the surface of the casting than at the center, and was attributed to the presence of a water-base lubricant that may not have vaporized before injection of molten metal into the die. Other reasons for the porosity could be inadequate pressure and/or improper

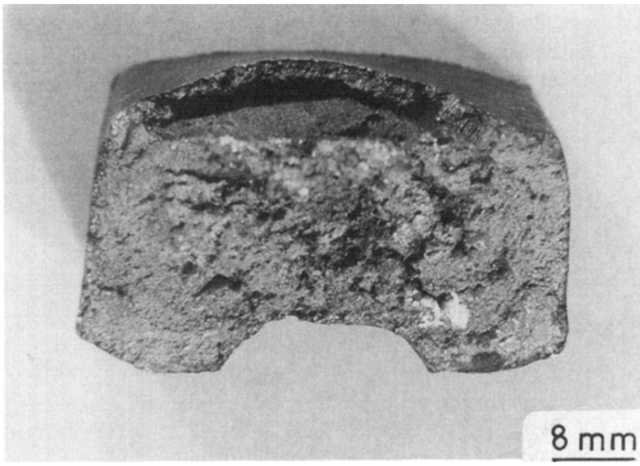


Fig. 8 Macroview of blistering in a defective Al-7Si-0.3Mg squeeze-cast crank

degassing of the melt (which could lead to pinhole porosity). In two of the cranks, severe shrinkage porosity at the center of the casting was also seen (Fig. 7b). This was due to inadequate feeding of the molten liquid. Preventive measures to overcome these defects include:

- Maintain die temperature on the slightly high side (about 200 °C).
- Set the pouring temperature to a slightly higher value (e.g., ~680 °C).
- Increase the existing pressure level to force the feeding.
- Thoroughly degas the melt.
- Ensure proper drying of the die coat.

Tensile properties obtained for three squeeze-cast cranks are given in Table 4. Reduction in tensile strength is attributed to the silicon segregation and severe shrinkage porosity.

3.3 *Blistering*

Air entrapment generally occurs during turbulence and is commonly created by rapid punch movement and high squeezing pressures. Abrupt changes in cross section and improper venting may further aggravate the turbulence of the liquid metal. This air entrapment located at subsurface depth may blister out once the squeezing pressure is released, whereas entrapment that is deep seated finds its way out during solutionizing (heat treatment) (Ref 12). Large amounts of hydrogen absorption during melting will also cause blistering (Ref 12).

Blistering is more common for geometrical shapes with large surface areas and thin cross sections, such as a crank (Fig. 8). Possible remedies for this defect are:

- Provide proper die venting to avoid air entrapment.
- Reduce the pouring temperature, preferably to approximately 650 °C.
- Decrease the traverse speed of the punch.
- Maintain the die temperature at approximately 200 °C.
- Redesign the die for nonturbulent flow conditions.
- Ensure thorough degassing of the molten metal.

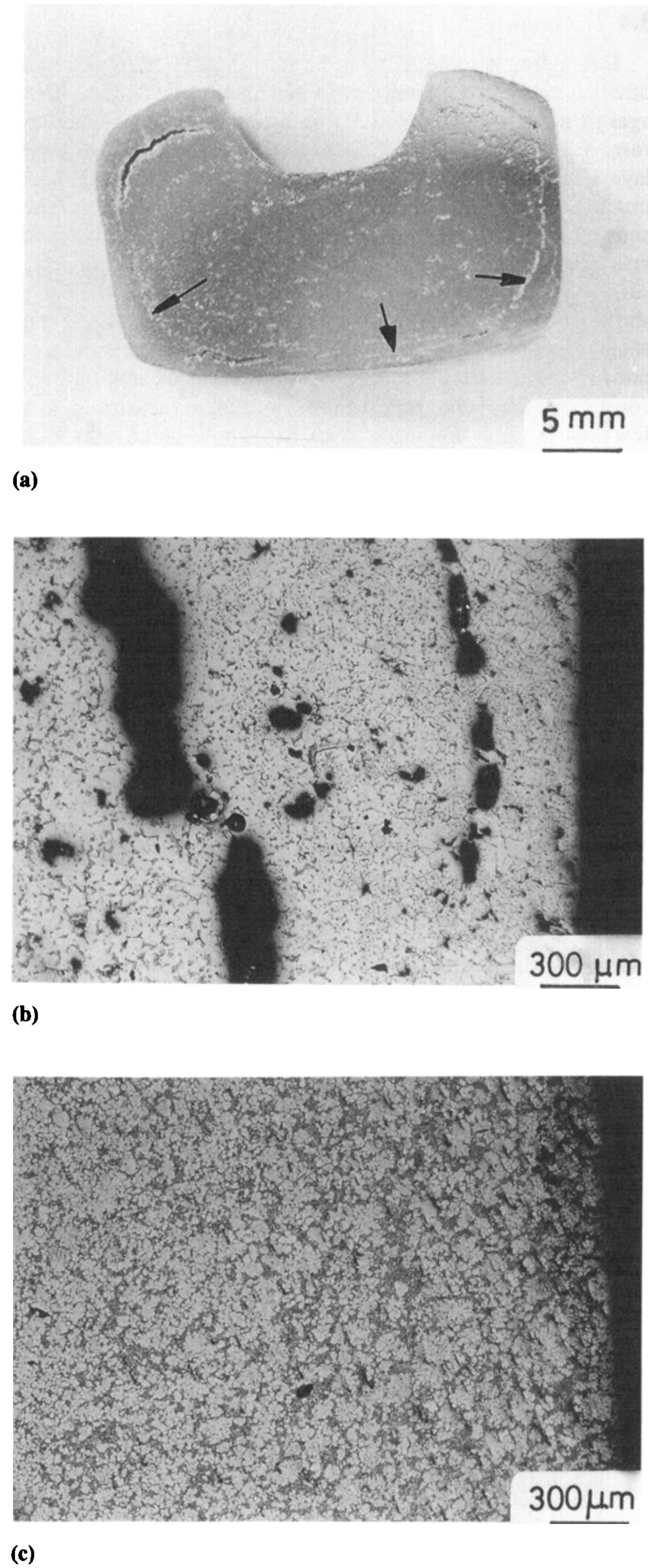


Fig. 9 Microstructures of a defective Al-7Si-0.3Mg squeeze-cast crank. (a) Macroview of debonding. (b) Finer silicon particles near the casting surface and coarser particles away from the crack. (c) Silicon segregation near the casting surface

3.4 *Debonding*

Debonding is more likely to be seen in Al-Si alloys than in other aluminum alloys and occurs due to excessive fast cooling against a cold punch or die. Ultrafine grains are expected to form to a depth of 1.27 to 2.54 mm (Ref 12). These fine-grain layers will flake off during later operations (shot peening, heat treatment, etc.). The macrostructure observed for the crank showed a crack running along the circumference. This crack was located at a depth of 1.0 to 2.5 mm from the casting outer surface (Fig. 9a). Microstructure at the same location clearly showed finer particles of silicon to the left of the crack and coarser particles of silicon to the right (Fig. 9b). These observations suggest that the surface of the crank casting rapidly cooled and debonded from the inner portion of the casting. In a few areas, silicon segregation was also seen near the surface of the casting (Fig. 9c). The following precautions are suggested to prevent debonding:

- Increase die and punch temperature to approximately 200 °C.
- Minimize delay time (but no less than 5 s).

3.5 *Summary*

Microstructural observations have shown that defects such as silicon segregation, debonding, blistering, and porosity occurred due to improper control of process parameters, leading to poor tensile properties and rejection of the crank castings. The defects identified in the present study confirm earlier observations (Ref 12) on defects in squeeze-cast aluminum alloys.

4. Conclusions

- The presence of iron impurities leads to the formation of β-$FeSiAl_5$ phase in interdendritic regions, resulting in poor fracture toughness (K_d, K_{SRCN}).
- Trace additions of beryllium alter the morphology of β-phase into hexagonal and Chinese script intermetallic phases and form as a new phase—(Be-Fe)-$BeSiFe_2Al_8$. All the Be-Fe phases occur inside the α-aluminum dendrites. The size of the hexagonal Be-Fe phase is finer in squeeze-cast alloys than in sand- or chill-cast alloys. The detrimental effect of iron on fracture toughness (K_d and K_{SRCN}) in squeeze-cast alloys is completely nullified by the addition of beryllium.
- Analysis of Al-7Si-0.3Mg squeeze-cast cranks revealed four major defects: silicon segregation, porosity (gas/shrinkage), blistering, and debonding. Remedial measures for these defects have been suggested.

References

1. G.A. Chadwick and T.M. Yue, Principles and Applications of Squeeze Casting, *Cast. Technol.*, Jan 1989, p 6-12
2. R.F. Lynch, R.P. Olley, and P.C.J. Gallagher, Squeeze Casting of Aluminium, *AFS Trans.*, Vol 83, 1975, p 569-576
3. A.A. Das and S. Chatterjee, Squeeze Casting of an Aluminium Alloy Containing Small Amount of Silicon Carbide Whisker, *Metall. Mater. Technol.*, March 1981, p 137-142
4. J.L. Dorcic and S.K. Verma, Squeeze Casting, *Metals Handbook*, Vol 15, 9th ed., 1988, p 323-327
5. W.F. Shaw and T. Watmough, Squeeze Casting: A Potential Foundry Process, *Foundry*, Vol 97, 1969, p 166-173
6. J.L. Reiss and E.C. Kron, Ultra High Pressure Casting, *Mod. Cast.*, March 1960, p 89-96
7. S. Murali, K.S. Raman, and K.S.S. Murthy, Effect of Magnesium, Iron (Impurity) and Solidification Rates on Fracture Toughness of Al-7Si-0.3Mg Casting Alloy, *Mater. Sci. Eng.*, Vol A151, 1992, p 1-10
8. K.T. Kashyap, S. Murali, K.S. Raman, and K.S.S. Murthy, Overview: Casting and Heat Treatment Variables of Al-7Si-0.3Mg Alloy, *Mater. Sci. Technol.*, Vol 9, March 1993, p 189-203
9. S. Murali, K.S. Raman, and K.S.S. Murthy, Effect of Trace Additions (Be, Cr, Mn and Co) on the Mechanical Properties and Fracture Toughness of Fe-containing Al-7Si-0.3Mg Alloy, *Cast Met.*, Vol 6 (No. 4), 1994, p 189-197
10. S. Murali, K.S. Raman, and K.S.S. Murthy, Morphological Studies on β-$FeSiAl_5$ Phase in Al-7Si-0.3Mg Alloy with Trace Additions of Be, Mn, Cr and Co, *Mater. Charact.*, Vol 33, 1994, p 99-112
11. S. Murali, K.S. Raman, and K.S.S. Murthy, The Formation of β-$FeSiAl_5$ and Be-Fe Phases in Al-7Si-0.3Mg Alloy Containing Be, *Mater. Sci. Eng.*, Vol A190, 1995, p 165-172
12. S. Rajagopal and W.H. Altergott, Quality Control in Squeeze Casting of Aluminium, *AFS Trans.*, Vol 93, 1985, p 145-154