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Solidification

SESSION CHAIR

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Effects of Cu, Mg, and Sr Additions on the Mechanical Properties and Machinability of Near-Eutectic Al-11%S Casting Alloys

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Abstract

This study was conducted with the intention of investigating a new experimental alloy, namely the 396 alloy which belongs to the Al-Si near-eutectic cast alloy group and contains about 11%Si. In the light of the above, the main purpose of the work is to report on the changes observed in the mechanical and/or machinability criteria resulting from the effects of the presence of two levels of Cu, namely 2.25% and 3.5%; and of the effects of two levels of Mg, namely 0.3 and 0.6%. In addition to the preceding, the effects of Mg-free alloys and Sr-modification on these same alloys were also investigated.

The results demonstrate that the increase in the levels of Cu and/or Mg in the 396-T6 alloy has a detrimental effect on drill life. Such an effect may be attributed to the formation of large amounts of the coarse blocklike Al_2Cu phase, together with the formation of thick plates of the Al-Si-Cu-Mg phase. The Mg-free experimental alloy displays the lowest cutting force and moment in addition to producing the highest number of holes in the alloys studied. A comparison of the non-modified alloy and the Sr-modified alloy (containing the same level of Mg and Cu additions) in terms of the number of holes drilled, reveals that the morphology of Si particles has a noticeable effect in governing the tool life of near-eutectic Al-Si alloys.

Introduction

Cast aluminum-silicon alloys contain mainly Cu and Mg as the major alloying elements. Magnesium is normally used to improve the mechanical properties of the alloy through the precipitation of the Mg_2Si and Al_2CuMg intermetallics.[1] The Cu and Mg content of the alloys determine the precipitation strengthening and the volume fraction of Cu-rich and Mg-rich intermetallics obtained.[2] Regulating the morphology, volume fraction, and distribution of these intermetallics will improve the alloy matrix homogeneity and hence improve its machinability.[3]

Yamada and Tanaka[4] reported that when aluminum casting alloys contain both 1% Cu and 0.5% Mg, the finished surface in the turning process is considerably improved, and there is only a slight effect apparent with regard to tool wear and the cutting force. This improvement in the finished surface may be attributed to a significant increase in the hardness of the matrix. Such an increase in matrix hardness of up to about 80 BHN is effective in improving the finished surface of the alloys studied, since the shear angle increases noticeably with the increase in matrix hardness.

Jorstad[5] found that, in aluminum alloys containing copper and silicon, a small magnesium addition of about 0.3 wt% caused a significant increase in the material work-hardenability and drastically reduced the tendency towards built-up edge formation on the cutting tool; Mg hardens the alloy matrix and by doing so reduces the friction between tool and work piece, resulting in shorter and tighter chips, as well as providing a better surface finish.

Tash *et al.*[3] investigated the effects of metallurgical parameters on the drilling performance of heat-treated Al-alloys containing different proportions of Mg and Cu. They showed that a small amount of Mg added to 319 alloys, about 0.1 wt%, improves alloy machinability and reduces the cutting force and moment, thereby allowing for a high number of holes to be drilled and tapped.

Tests performed at Alcoa Research Laboratories[6] have demonstrated that copper in Al-Si alloys affords a smoother surface finish, smaller and more tightly coiled chips, and a reduced burring tendency, attributable largely to the strengthening aspect provided by this element. Tool-wear is not greatly influenced by copper content in Al-Si alloys, although this parameter can increase by as much as 50% in the presence of substantial quantities of undissolved Al-Cu and/or Al-Cu-Mg phases.

It should be mentioned here that numerous studies have been carried out integrating the formation of the as-cast microstructure as well as the effects of solution heat treatment and aging on the microstructure and mechanical behaviour of Al-Si-Cu-Mg alloys. Only a few studies so far, however, have dealt with the influence of alloying elements and melt treatment on the machining performance of near-eutectic Al-11%Si cast alloys. Consequently, in the view of the above, the main objective of this study was to examine the Al-11%Si cast alloys, as the basis for understanding the role of Cu, Mg, and Sr on the mechanical and machinability properties of these alloys.

Experimental Procedures

Alloys Preparation and Casting Procedures

The as-received 396 ingots were cut into smaller pieces, dried, and melted in charges of 100kg each for the preparation of the various alloy compositions. Melting was carried out in a SiC crucible of 120-kg capacity, using an electrical resistance furnace in which the melting temperature was maintained at 750±5°C (13820±41F).

All the alloys were grain-refined by adding 0.20 wt% Ti as Al-5%Ti-1%B in rod form and modified by adding 200 ppm Sr in the form of an Al-10%Sr master alloy by means of a perforated graphite bell. Taking the grain-refined and modified alloy, coded M1, as a reference, additions of Cu, and Mg were then made to the alloy to study the effects of these elements on the mechanical properties and machinability characteristics of the grain-refined and modified M1 alloy. Measured quantities of pure aluminum, silicon, copper, and magnesium were used to prepare two further experimental alloys, namely the non-modified M0 alloy, and the M9 alloy belonging to the Al-Si-Cu alloy group, in order to study the effects of Sr-modification and that of Mg-free alloys, respectively, on the machinability of Al-10.8%Si near-eutectic alloys. The chemical compositions of the alloys used and their respective codes are listed in Table 1, where each composition is the average obtained from three arc-spark spectrometric tests performed on the corresponding chemical analysis samples.

The melt was poured into a graphite-coated waffle-plate metallic mold which had been preheated to 450°C (842F) to prepare the casting blocks for machinability studies; eighteen machinability test blocks were cast. The heat treatments were selected in such a way as to establish the hardness level as a common factor for all the alloys studied, within the range of 110 ± 10 BHN. Solution heat treatments were carried out at 490°C/8h (914F/8h) for the 396 alloys. The solution heat-treated samples were quenched in warm water at 65°C (149F), followed by artificial aging at 200°C (392F) for 5 hours *i.e.* the samples were T6-tempered. Both solution and aging heat treatments were carried out in a forced-air electric furnace with a programmable temperature controller accurate to within ± 2°C (36F).

Table1. Average chemical composition of the alloys used in this study

Alloy Code	Element % wt)								
	Si	Fe	Cu	Mn	Mg	Ti	Sr	Al	Mn/Fe
M0	10.84	0.57	2.81	0.56	0.30	0.11	0.000	bal.	0.98
M1	11.38	0.46	2.22	0.54	0.33	0.16	0.018	bal.	1.17
M5	11.38	0.502	3.31	0.591	0.347	0.17	0.0250	bal.	1.685
M6	11.52	0.466	3.42	0.582	0.6	0.16	0.0229	bal.	1.631
M9	10.77	0.57	3.67	0.55	0.002	0.11	0.002	bal.	1.67

Mechanical Tests

Hardness measurements were carried out on the heat-treated samples using a Brinell hardness tester, using a steel ball indenter of 10 mm diameter and a load of 500 kg applied for 30s. Four blocks were randomly selected from among the eighteen test blocks prepared for each alloy condition. The average hardness value for the four blocks selected per alloy was then obtained and designated as representing the hardness value for that alloy condition.

Tensile test bars were produced by pouring the degassed molten metal into a permanent steel mold, type ASTM B-108, which had been preheated to 450°C (842F). This mold provides two tensile bars per casting, each with a gauge length of 50mm and a cross-sectional diameter of 12.7mm. Five bars were prepared for each alloy composition. The heat-treated test bars were pulled to fracture at room temperature, at a strain rate of 4×10^{-4}/s, using a servohydraulic mechanical testing machine.

Machining Procedures

Drilling tests were performed using a Makino A88E high-speed horizontal machining center with maximum power of 40 HP (30 kW) and a maximum rotation speed of 18,000 rpm under fixed machining conditions of speed, feed, length of cut, tool type, and coolant as applied to the examination of the alloys under discussion. The experimental set-up consisted of the A88E machine, a dynamometer with four sensors, charge amplifiers, and an A/D converter; this set-up was applied for the online measurement of drilling forces and moments, while a toolmaker's microscope was used for observing the tool-wear characteristics. The drilling tests were carried out at rotational speeds of 11,000 rpm using a feed rate of 1.117m/min with each hole being 28.38mm deep. A synthetic metalworking fluid concentrate composed of 5% cutting fluid + 95% liquid, known as CIMTECH® 310, was pumped at high pressure through the drill to ensure adequate cooling and chip evacuation.

Results and Discussion

Microstructures

Silicon Particle Characteristics. The morphology of eutectic Si plays a vital role in determining the machinability characteristics of cast Al-Si near-eutectic alloys. Table 2 summarizes the silicon particle characteristics obtained from quantified measurements of the alloys investigated. As can be seen from this table and from Figure 1(a), the Si particles are present in the form of coarse acicular plates with an aspect ratio of 3.51 in the T6 heat-treated condition for the non-modified experimental M0 alloy. The addition of 200 ppm of Sr transforms the morphology of Si particles from an acicular form to a fibrous one, as may be observed in the M1 alloy which has an aspect ratio of 1.77; this addition also increases the roundness ratio from 32.8% to 70%, as shown in Figure 1(b). The average Si particle length decreases from 20.80 μm in the M0 alloy to 2.96 μm in the M1 alloy, while the average area decreases from 65.70 μm^2 to 4.30 μm^2, i.e. by about 86% and 93%, respectively. As a result of the decrease in the size of the particles, the density of the Si particle increases from 2604 to 28,000 particles/mm^2, implying that the eutectic Si particles have become fibrous and finely divided in the presence of Sr, as indicated in the micrograph shown in Figure 1(b).

It is also found that increasing the level of Cu and Mg leads to an increase in the average length and area of the Si particles, as shown in Table 2. The Si-particle length increases from 2.96 μm in the M1 alloy to 4.80 μm in the M5 alloy which contains 3.31% Cu and 0.35% Mg, and to 4.60 μm in the M6 alloy containing 3.42% Cu and 0.58% Mg, while the average particle area increases from 4.30 μm^2 to 10.00 μm^2 and 7.89 μm^2, respectively. Moreover, the aspect ratio of the Si particle increases from 1.77 in the M1 alloy to 1.95 in the M6 alloy, *i.e.* it increases by about 10%. The presence of Mg and Cu also affects the roundness ratio of the eutectic Si particles; increased Mg content results in a clear reduction in the roundness ratio which is most pronounced at a higher Cu content, as in the M6 alloy, while the roundness ratio decreases from 70% in the M1 alloy to 55.6% in the M6 alloy. Thus, from the point of view of these observations, the addition of Mg and Cu may be deemed to diminish the effects of Sr as a Si-particle modifier, and to decrease the particle density as a result.

Table 2. Summary of the eutectic Si-particle measurements for the alloys studied

Alloy Code	Particle Area (μm^2)		Particle Length (μm)		Roundness Ratio (%)		Aspect Ratio		Density (particles/ mm^2)
	Av	SD	Av	SD	Av	SD	Av	SD	
M0	65.70	84.10	20.80	17.10	32.80	18.20	3.51	2.32	2604
M1	4.30	6.51	2.96	2.49	70.00	17.30	1.77	0.784	28000
M5	10.00	7.60	4.80	2.49	60.00	16.50	1.71	0.61	12542
M6	7.89	8.18	4.60	3.40	55.60	18.50	1.95	0.92	19252
M9	61.30	86.10	18.10	17.80	35.80	23.60	3.56	2.43	3064

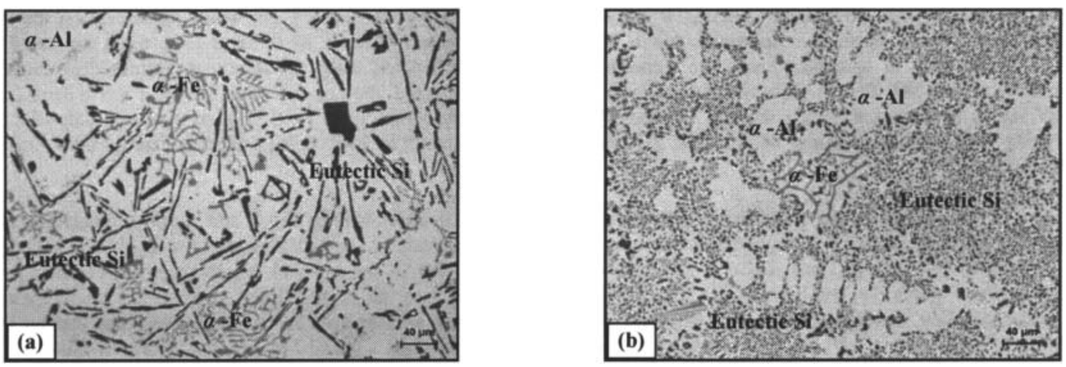


Figure 1 Optical micrographs showing the effects of Sr-addition on Si morphology in grain-refined and heat-treated Al-10.8% Si alloy: (a) 0 Sr-M0 alloy; (b) 200 ppm Sr-M1 alloy.

Mechanical Properties

Hardness measurements were carried out on the heat-treated machinability test blocks to ensure that they possessed the required hardness levels. The average hardness value and standard deviations for each alloy composition studied are provided in Table 3. The corresponding hardness data indicate that the decrease in the hardness value of the Sr-modified M1 alloy compared to the non-modified M0 alloy is mainly the result of changes in the morphology of the eutectic Si particles, from brittle coarse acicular plates in the M0 alloy to a rounded fibrous form, as shown in Figures 1(a) and (b).

There is a distinct possibility that the hardness increment in M5 and M6 alloys may be attributed to the formation of hard and brittle intermetallic phases of Al_2Cu and Al_2CuMg, as well as to an increased bonding of the silicon particles with the matrix, in which the thermal energy is sufficient to precipitate such intermetallics phases as are coherent with the matrix.[7] It should be mentioned that the hardness values of the machinability test blocks, however, still fall within the required range.

Tensile testing was also carried out to assess the changes occurring in the aluminum matrix and eutectic silicon as a result of the addition of Sr and other alloying elements. Table 3 provides the tensile properties including the YS at a 0.2% offset strain, the UTS, and the %El for the alloys investigated. The modified M1 alloy displays somewhat higher YS, UTS, and %El values than the unmodified M0 alloy, because of the improved eutectic silicon phase morphology caused by Sr modification.

With regard to the addition of Cu and Mg to the M1 alloy, it may be observed that at high Mg levels of ~0.6, the ductility is considerably lower, as observed in the case of the M6 alloy. Such a result may be attributed to the influence of both Sr and Mg on the severity displayed by the Al_2Cu phase segregation, resulting in the formation of large amounts of the coarse blocklike form of the phase. It was also found that the Mg-free M9 alloy displays a significant reduction in the YS and UTS values compared to the M1 reference-alloy. This observation is in satisfactory agreement with results obtained from previous work[8] which reported that the addition of Mg proves to be an excellent way of achieving a high level of tensile strength, however at the expense of ductility.

Table 3. Summary of mechanical properties for the 396 alloys studied

Alloy Code	BHN (MPa)	YS (MPa)	UTS (MPa)	El (%)
M0	119 ± 3.45	346.11 ± 5.92	382.78 ± 2.36	0.92 ± 0.09
M1	108 ± 3.56	358.10 ± 1.55	394.04 ± 6.27	0.98 ± 0.12
M5	117 ± 3.19	358.94 ± 7.45	369.99 ± 8.54	0.76 ± 0.14
M6	120 ± 4.45	392.7 ± 6.8	396.14 ± 6.8	0.66 ± 0.02
M9	104 ± 4.55	200.65 ± 4.70	300.82 ± 19.16	1.70 ± 0.47

Machining Behavior

The results from drilling tests reveal that the mean total drilling force and moment increase as the number of holes drilled increases, as shown in Figures 2(a) and (b). From this figure, it will be observed that the drilling force and moment display a virtually linear trend during the drilling of the Mg-free M9 alloy, while in comparison the M1 base alloy shows a rapid increase in the cutting force. More specifically, the mean total drilling force of the M1 alloy increases by 103% over the evaluation period of 2160 holes. In contrast, the mean total drilling force of the Mg-free M9 alloy increases from 204N after drilling 90 holes to 316.8N after drilling 3240 holes, *i.e.* approximately a 55% increase. This analysis is in agreement with the mean total drilling moment of the M1 alloy which was found to have increased by 105%, as shown in Figure 4.12(b). On the other hand, the mean total drilling moment of Mg-free M9 alloy increased by 53%.

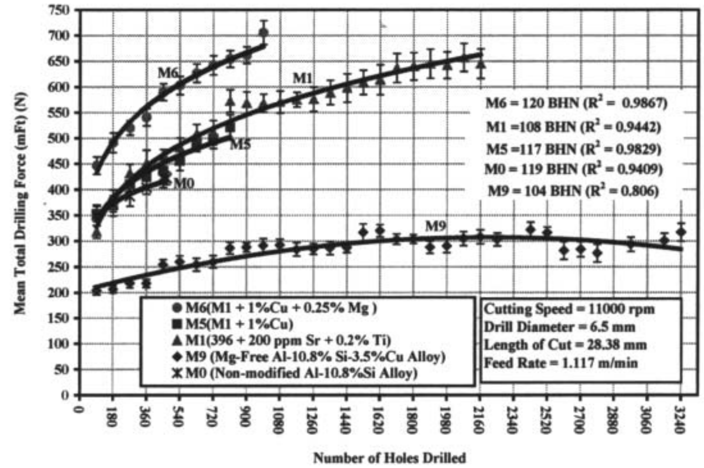
The machining characteristics of the Al-10.8%Si near eutectic alloy depend mainly on the shape, size, and distribution of α-Al dendrites, eutectic Si morphology, and Al_2Cu particles in the interdendritic region. Figures 2(a) and (b) show that the addition of 1% Cu to the M1 alloy, thereby producing the M5 alloy, has only a slightly diminishing effect on the drilling force and moment, compared to the case of the M1 alloy. On the other hand, the increase in the level of Cu and Mg from 2.2% and 0.3% in the M1 alloy to 3.4% and 0.6%, creating the M6 alloy, has a noticeable effect in increasing the mean total drilling force and the mean total drilling moment, by 25% and 20%, compared to the M1 alloy. It will also be clearly observed that the Mg-free M9 alloy displays a significant decrease in the total drilling force and in the total drilling moment compared to the M1 reference alloy; specifically the M9 alloy required an average of 50% lower mean total drilling force (ranging from 35% to 65%), and exhibited an average of 52% lower total drilling moment (ranging from 35% to 69%), as shown in Figure 2.

Tool life is measured in terms of the number of holes drilled under constant machining conditions in M0, M1, M5, M6, and M9 alloys, as shown in Figure 3. In this figure, it will be observed that the M5 alloy containing high levels of Cu or the M6 alloy containing high levels of Cu and Mg, in the form of additions, all have a detrimental effect on drill life, where the drill life of the M1 alloy decreases from 2160 holes/drill to 810 holes/drill and 990 holes/drill in the M5 and M6 alloys, thus corresponding to a reduction in drill life by 63% and 58%, respectively. It is interesting to observe that the Mg-free M9 alloy produces the highest number of holes with 3240 holes/drill; this is followed by the M1 alloy containing 0.3% Mg having 2160 holes/drill, and lastly by the high Mg-content M6 alloy containing 0.6% Mg with 990 holes/drill, as shown in Figure 3. It is thus clear that a high Mg-content of about 0.6% will cause a certain amount of deterioration in tool life, producing higher cutting force and moment, and lowering the number of holes drilled.

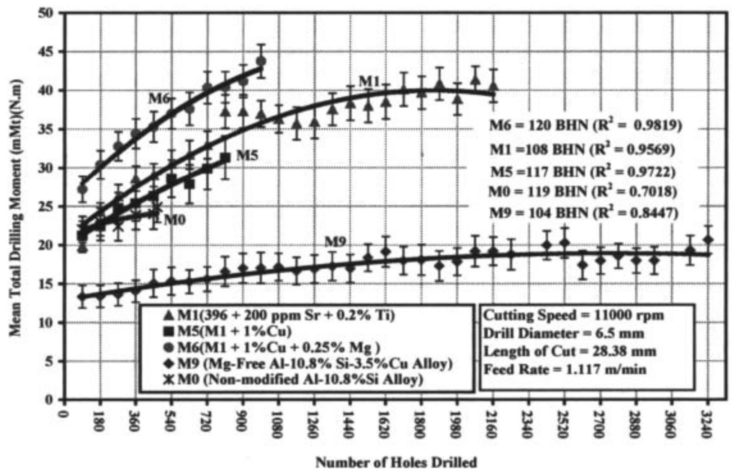
For the purposes of comparison, the non-modified Al-11% Si experimental alloy, coded M0, was used in this study to compare the machining behavior of the non-modified alloy with that of the modified M1 alloy. It will be observed that the non-modified M0 alloy has some slight effect in decreasing the mean total force and moment, by 9% and 13%, when compared to the Sr-modified M1 alloy, as shown in Figures 2(a) and(b). On the other hand, the non-modified M0 alloy has a detrimental effect on drill life, since the M0 alloy produces only 468 holes/drill compared to 2160 holes drilled in case of the Sr-modified M1 alloy.

The higher drilling force and moment generated during the machining of the M6 alloy and the significant reduction in the drill life of the M5 and M6 alloys when compared to the M1 alloy may all be explained in terms of the following effects. Firstly, silicon particle measurements show that an increase in the level of Cu and Mg supplied to the Sr-modified M1 alloy results in an increase in Si-particle size, area, length, and aspect ratio; it also reduces the roundness ratio and particle density. These additions result in altering the microstructure of the M5 and M6 alloys from well-modified to partially-modified, as was confirmed earlier from Table 1. The fracturing of hard coarse silicon particles thus has a major effect on drill breakage.

Secondly, the volume fraction of the undissolved blocklike Al_2Cu phase increases with an increase in Cu-content. In addition, the influence of both Sr and Mg on the segregation of the Al_2Cu phase is expected to increase the severity of the segregation, resulting in the formation of large amounts of the coarse blocklike form of the phase. The increase in the level of Mg-content to ~0.6wt%, creating the M6 alloy, also results in the formation of thick plates of the $Al_5Si_6Cu_2Mg_8$ phase which is, in itself, an insoluble, brittle hard intermetallic phase. Evidence for the severity of copper segregation, together with the formation of thick plates of the Al-Si-Cu-Mg phase as well as of acicular silicon particles was shown clearly in the microstructure of the M6 alloy, Figure 4. From the machinability point of view, such undissolved phase particles represent the abrasive area of the matrix with the potential for causing drill breakage. It has been reported that tool wear can be increased by as much as 50% through the presence of substantial quantities of undissolved Al-Cu and Al-Cu-Mg-Si phases.[6]



(a)



(b)

Figure 2 Effects of Cu, Mg, and Sr additions on the machinability of M1, M5, M6, M0, and M9 alloys in terms of (a) mean total drilling force; and (b) mean total drilling moment required for drilling 90 holes.

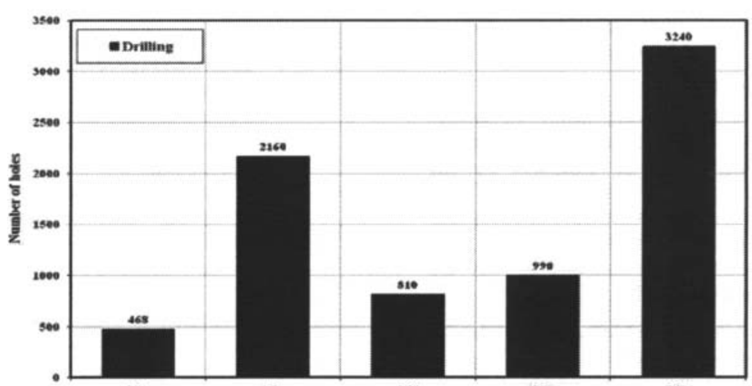
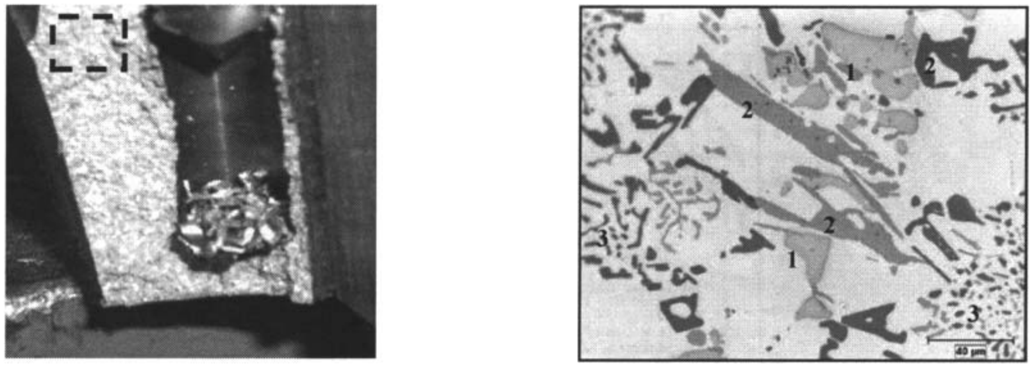


Figure 3 Comparison of tool life of M0, M1, M5, M6, and M9 alloys containing additions of different alloying elements in terms of the number of holes drilled and tapped.



(a) (b)

Figure 4(a) Cross-section of drilled hole in M6 alloy sample, illustrating area investigated; (b) Microstructure of the marked area in (a) showing the influence of both Sr and Mg: (1) segregation of the Al_2Cu phase; (2) formation of thick plates of $Al_5Si_6Cu_2Mg_8$ phase; and (3) acicular silicon particles.

The noticeable difference to be observed in the drilling force, moment, and tool life between the Mg-free M9 alloy and the M1 alloy containing 0.3%Mg may be attributed to the presence of Mg which has proved to be an excellent way of achieving a high level of tensile strength and hardness, however, at the expense of elongation. When approximately 0.3%Mg is added to the M1 alloy, a more marked response to artificial aging is evidenced in the yield strength and ultimate tensile strength values obtained for the T6 treatment compared to the M9 alloy which is a Mg-free alloy; the M1 alloy, however, shows higher values for YS and UTS, by 44% and 24%, respectively, than the M9 alloy, as listed previously in Table 3.

Conclusions

1. The Mg-free M9 alloy displays only a slight increase in the drilling force and moment with the progress of the drilling process, while in comparison, the Mg-containing M1 base alloy shows a rapid increase.
2. The M6 alloy containing high levels of Cu and Mg have a detrimental effect on drill life and cutting forces. The higher drilling force and the reduction in drill life may be attributed to the formation of large amounts of the coarse blocklike Al_2Cu phase, together with the formation of thick plates of the Al-Si-Cu-Mg phase in the alloy.
3. The Mg-free M9 alloy displays the lowest cutting force and moment in addition to producing the highest number of holes drilled/tapped compared to the Mg-containing alloys. This observation may be explained by the cooperative precipitation of the Al_2Cu, Mg_2Si, Al_2CuMg, and $Al_5Si_6Cu_2Mg_8$ hardening phases in Mg-containing alloys which confer greater strength on the alloy than would be the case with the precipitation of only the Al_2Cu phase in the Mg-free M9 alloy.
4. A comparison of the non-modified M0 alloy and the Sr-modified M1 alloy (containing the same level of Mg and Cu additions) in terms of the number of holes drilled, reveals that the morphology of Si particles has a noticeable effect in governing the tool life of near-eutectic Al-Si alloys.

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