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THERMODYNAMIC MODELLING ON THE MUTUAL EFFECT OF COPPER, MANGANESE AND IRON ADDITION IN AL-SI-CU FOR SEMISOLID PROCESSING

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ABSTRACT

Semisolid metal (SSM) processing or Thixoforming is a new method for forming alloys in the semisolid state to near net shaped products. All the alloys which have been used to date for thixoforming were developed originally for either casting or forging operations. Thus, there is a lack of specific alloys for semi solid processing that present good fluidity, low viscosity and small grain size. Thermodynamic calculation software, such as Java-based Material Properties (JMatPro), provides a tool for predicting thixoformability of aluminium alloys. Here, the effects of compositional variations, in particular the effect of copper, manganese and iron additions on the thixoformability of alloy A319 have been investigated. This software was used to determine the processing temperature at 0.4 fraction liquid, working window temperature, fraction liquid sensitivity, solidification range and phase diagram during semisolid processing. The alloys modelled were divided into two groups according to their copper, manganese and iron contents. The working window temperatures ($\Delta T^{0.3/0.5}$) for alloys in all two groups were enlarged at the range of 8°C to 14°C while the slope of the fraction liquid versus temperature curves at 0.4 fraction liquid become less steep from 0.014°C^{-1} to 0.010 C^{-1}. The processing temperatures of modified alloys at 0.4 fraction liquid have decreased from around 558°C to 550°C and this would benefit the thixoformability of the selected material. Phase diagram was used to show the location of the intermetallic phases (i.e. $Al_5Cu_2MG_8Si_6$, α-Al(Fe,Mn)Si and Al_2Cu) that dissolve in the

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semisolid zone. The results indicate the suitability of these modified alloys as a potential material for semisolid processing.

Key Words: Thixoforming, JMatPro, Thixoformability, Alloy design, Phase diagram.

INTRODUCTION

Semi Solid Metal Processing (SSM) or Thixoforming has become one of the important technological developments as hybrid near net shape forming method that combines the casting as well as forging. This technology promises major advantages such as prolonged die life due to less thermal shock, less air entrapment, weight savings in components with less porosity than conventional die casting and also improved usage of feedstock materials (Omar et al. 2005). Furthermore, thixoformed parts are reported to be subsequently higher in quality than die castings but lower in cost than forgings (Birol 2008). This recently developed technology was derived from basic studies initiated by Flemings and his co-workers in the 1970s (Flemings et al. 1976). They found the microstructure of continuously stirred materials was spheroidal whereas the material which was cooled into the semisolid state without stirring was dendritic. The material with the spheroidal microstructure in the semisolid state was thixotopic, which means when it is sheared it thins and flows and when it is allowed to stand, it thickens again (Atkinson 2010, Alfan et al. 2010, Omar et al. 2011). All the alloys which have been used to date for thixoforming were developed originally for either casting or forging operations. Therefore, there is a clear need to develop a range of alloys specially tailored for the needs of semisolid processing (Paes et al. 2005).

The focus of this paper is to discuss the use of JMatPro software in order to investigate quantitatively the effect of alloying elements particularly the effect of copper, manganese and iron additions in A319 aluminium alloy. Thermodynamic calculations have been carried out to design alloys based on the Al-Si-Cu system for semisolid processing. A selected alloy composition has been assessed upon its suitability for thixoforming. This thixoformability prediction can later be validated through experimental measurement in order to observe the microstructural evolution as well as mechanical properties of the new alloys.

JMATPRO SIMULATION

In this work, JMatPro or Java-based Material Properties software is used to analyze the effects of alloy compositions in A319 (shown in table 1) aluminium alloy. Solidification occurs under non-equilibrium conditions which can be modelled using the so-called Scheil approach. Fraction liquid sensitivity and temperature range for solidification are the critical parameters for fundamental work of new alloys development. The compositions of modified A319 (two different groups) alloys are given in Table 2 with variations in Copper (Cu), Manganese (Mn) and iron (Fe) elements.

Table-1. Chemical Composition of A319 (all in wt.%)

Chemical Composition	Si	Cu	Mg	Mn	Fe	Zn	Al
A319	5.5-6.5	3.0-4.0	0.10	0.50	0.8	1.0	Bal
A319 (JMatPro)	6.1	3.01	0.10	0.50	0.8	1.0	Bal

Table-2. Chemical Composition of modified A319. (all in wt.%)

Chemical Composition	Si	Cu	Mg	Mn	Fe	Zn	Al
Group 1	6.0	4.0-6.0	0.10	0.5	1.0	1.0	Bal
Group 2	6.0	4.0-6.0	0.10	1.0	1.5	1.0	Bal

RESULT AND DISCUSSION

Fraction Liquid Sensitivity, Processing Temperature and Solidification Range

Temperature sensitivity of fraction liquid (f_L) at SSM processing temperature is a very important parameter in order to ensure a wide and stable processing window during SSM processing. Fraction liquid sensitivity can be defined from the slope (shown in Figure 1) of the fraction liquid versus temperature curve as $(df_L/dT)f_L$. It is necessary that the fraction liquid does not change too rapidly with temperature in the working window and 0.3-0.5 volume fraction liquid is thought to be desirable for thixoformability (Liu et al. 2005). In this study, 0.4 fraction liquid (f_L) is chosen as a measuring point because of this is mid-way through the working range of 30-50% liquid (Camacho et al. 2003, Liu et al., 2005). When the temperature sensitivity is large, a slight variation in temperature induces a large change in the fraction liquid. Hence, small changes in temperature can lead to increase in fraction liquid and therefore non-favorable microstructure for SSM processing due to inhomogeneous deformation and liquid segregation during mould filling (Patel 2005). Therefore, a smaller fraction liquid sensitivity at semisolid processing temperature indicates better SSM processability. Tables 3 and 4 show SSM parameters for A319 and modified A319 aluminium alloys given by JMatPro software. It can be seen clearly from these tables that the value of $(df_L/dT)f_{L=0.4}$ decreased with the range of 0.015 °C^{-1} to 0.010 °C^{-1}. It also believed, for good processability, $(df_L/dT)f_{L=0.4}$ should less than 0.020 at the SSM processing temperature ($T_{0.4\,fL}$). This means 2% change in fraction liquid of the slurry is permitted for every 1°C change in $T_{0.4\,fL}$. The processing temperatures for alloys in all two groups at $T_{0.4\,fL}$ are significantly decreased within the range of 558°C to 550°C and this is good for thixoforming process. Temperature control $T_{\pm 3°C}$ during SSM processing is suitable and achievable under this processing condition.

Solidification usually defined as the temperature range between liquidus and solidus of a given alloy (Liu et al. 2005, Patel 2005). The temperature interval between the liquidus and solidus should not be too wide because it may lead to poor resistance to hot tearing. This means the processing temperature $T_{0.4\,fL}$ and solidus temperature play an important role in SSM processing. It is proposed in this work, in order to get a good processability and high resistance to hot tearing, the solidification temperature range should be around 40-48°C. There were also significant changes in the curves in modified alloys above 0.4 fraction liquid. It can be seen clearly in Figure 1, when the copper is increased, it will leads to shorter solidification times and as a consequence their respective 'highest knees' were also shifted to higher fraction liquid. In this region, the binary eutectic temperature at which α-solid solutions starts melting and the amount of liquid at the 'highest knee' represent the amount of eutectic in the structure.

Figure-1. Calculated fraction liquid vs. temperature given by JMatPro for group 1 alloys.

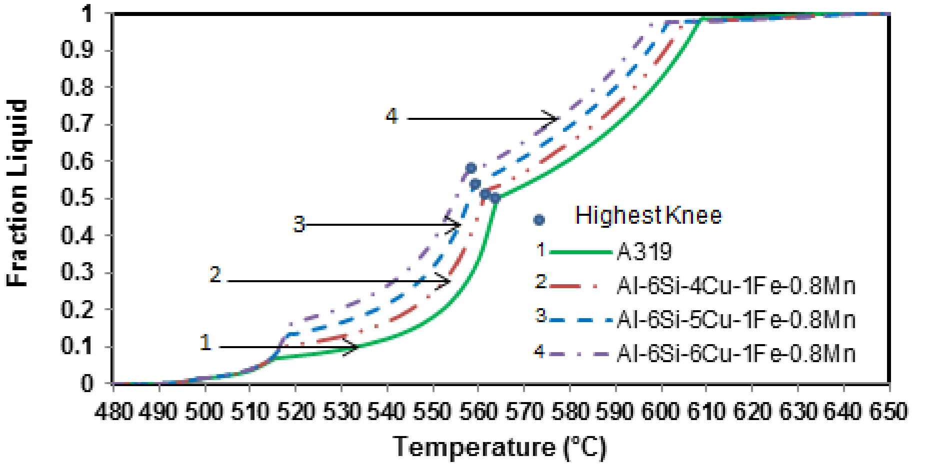


Table-3. SSM parameters given by JMatPro software for A319.

Alloy	$T_{0.4fL}$ (°C)	$T_{\pm 3°C}$ (°C)	$(df_L/dT)f_{L=0.4}$ (°C^{-1})	$T_{0.3/0.5\ fL}$ (°C)	$\Delta T^{0.3/0.5}$ (°C)
A319	562	559-555	0.021	558-568	10

Table-4. SSM parameters given by JMatPro software for modified A319.

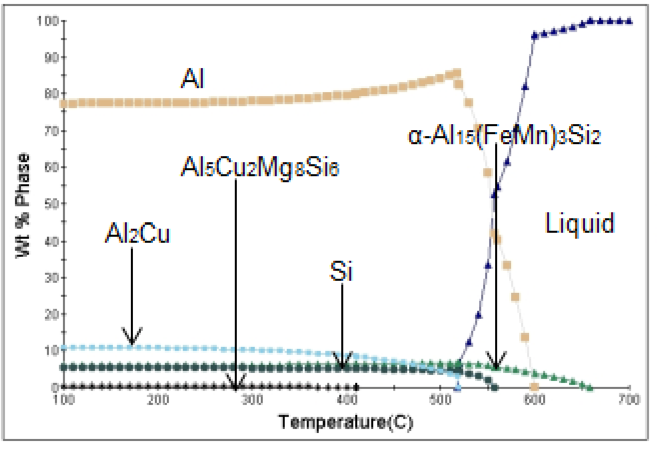
Alloy groups	Modified A319	$T_{0.4fL}$ (°C)	$T_{\pm 3°C}$ (°C)	$df_L/dT)_{fL=0.4}$ (°C^{-1})	$\Delta T^{0.3/0.5}$ (°C)
	Al-6Si-4Cu-1Fe-0.8Mn	558	555-561	0.014	8
1	Al-6Si-5Cu-1Fe-0.8Mn	554	551-557	0.012	10
	Al-6Si-6Cu-1Fe-0.8Mn	550	547-553	0.010	12
	Al-6Si-4Cu-1.5Fe-1.2Mn	558	555-561	0.015	10
2	Al-6Si-5Cu-1.5Fe-1.2Mn	554	551-557	0.013	12
	Al-6Si-6Cu-1.5Fe-1.2Mn	550	547-553	0.010	14

Phase Diagram of Modified A319

An intermetallic compound in cast aluminium alloys plays an important role in influencing their mechanical properties. These compounds are formed by entering transition elements especially iron, manganese, copper and nickel into cast Al-Si-Cu alloys in order to increase the hardness and improve wear resistance (Shabestari et al. 2010). Phase diagram of modified alloys (shown in Figure 2), shows the presence of intermetallic phases Al_2Cu, quaternary ($Al_5Cu_2MG_8Si_6$) Q phase and α-Al(FeMn)Si. Each of these phase represent different characteristics for the aluminium alloys. For instance, copper plays an important role in giving the strengthening effect by precipitation of

Al_2Cu in Al-Fe-Si-Cu system. The proper amount of manganese promotes the formation of α-phase instead of β-phase which can increase the tensile strength of the modified alloys.

Figure-2. Phase diagram of Al-6Si-6Cu-1Fe-0.8Mn given by JMatPro software.



CONCLUSION

JMatPro software has been used to investigate the effects of compositional variations particularly the effects of copper, manganese and iron addition on the thixoformability of alloy A319. This software was used to determine the working window temperature, fraction liquid sensitivity, processing temperature, solidification range as well as the ‘highest knee’ between 0.3 and 0.5 fraction liquid on the fraction liquid versus temperature curves. These criteria were used to develop new aluminium alloys based on Al-Si-Cu alloys. The working window temperatures ($\Delta T^{0.3/0.5}$) for alloys in all two groups were enlarged at the range of 8°C to 14°C and the slope of the fraction liquid versus temperature curves at 0.4 fraction liquid has become less steep from 0.014°C^{-1} to 0.010°C^{-1}. The processing temperatures of modified alloys at 0.4 fraction liquid has decreased from 558°C to 550°C and this should benefit the thixoformability of these new alloys. The solidification range between processing temperature and solidus temperature is decreased and this is due to the effect of copper addition to the starting A319 aluminium alloy. The ‘highest knee’ on the fraction liquid versus temperature curve plays an important role in order to control the liquid formation during thixoforming process. The alloys in group 1 and 2 have fulfill the alloy design criteria and maybe suitable for thixoforming process.

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