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EFFECTS OF MAIN ALLOYING ELEMENTS ON INTERFACE REACTION BETWEEN TOOL STEEL AND MOLTEN ALUMINUM

Effects of Si and Mg as main elements on interface reaction between tool steel and molten Al alloy at 700°C were investigated. Pure aluminum and Al-10mass%Mg alloy showed relatively simple interfacial layers, whereas thicker, multi-layered reaction bonds were found in the diffusion couple of A380 alloy. The diffusion of a large amount of Fe into Al matrix throughout the interfacial layer led to the formation of Al-Fe based intermetallic particles in the Al base metals. The diffusion couple of Al-10mass%Mg alloy showed a similar intermetallic layer as that of pure Al, indicating that 10mass%Mg in the Al melt rarely affected the formation of Al-Fe intermetallic layers. However, A380 alloy showed much expanded soldering area and increased thickness of intermetallic layers. Based on the phase diagram calculated, the solubility of Fe in liquid Al increased significantly with increasing Si content up to apploximately 5mass%, while, in the case of 10mass%Mg addition, the Fe solubility gradually decreased with increasing Mg content. Al-10mass%Mg alloy also showed the same tendency as that of pure Al in the formation and distribution of intermetallic compounds. However, in the Al-12mass%Si alloy, two types of Al-Fe-Si ternary compounds are present on the Al-rich side.

Keywords: Diffusion; Tool steel; Al alloy; Intermetallic compound; Phase diagram

1. Introduction

The interaction of tool steels and Al alloy melts is of great importance to engineering applications, such as die-casting. In the service conditions of pressure die casting, molten Al alloys fill the die cavity at a high velocity and welds to die walls, leading to erosion of die materials. When the Al melt contacts with the die surface, Fe in the die melts into the molten Al, while Al and other elements in the melt permeate into the die. As a result, the interfacial reaction between tool steel and liquid Al causes formation of intermetallic compounds between Fe and Al. Various bonding technologies of Al alloy/steel bimetals using strong diffusion between Al and Fe have been studied [1,2]. The interaction of tool steel with liquid Al has been mainly studied on typical Al-Si based casting alloys such as A380, which contain approximately 12mass% [3-5]. Al-Mg based alloys, which are classified into 5xx series [3], are also one of the most used aluminum castings after Al-Si based alloys. Our study has been mainly focused on development of new Al casting alloys with high Mg contents up to 10mass%. Increase of Mg amount in Al alloy provides improvement of strength and corrosion resistance as well as weight reduction. The aim of this study is to investigate effects of Si and Mg as main elements on interface reaction between tool steel and molten Al alloy.

2. Experimental

Three Al samples were examined in this study; pure Al, A380 (a commercial Al-Si-based cast alloy) and Al-10mass%Mg alloys. It is difficult to hold Al alloy melts containing high Mg contents over 5mass% without explosive oxide growth on the melt surfaces due to the high affinity between oxygen and Mg. Recently, it was reported that adding Mg+Al_2Ca master alloy [6] instead of pure Mg as an alloying element remarkably improved the oxidation resistance of Al-Mg alloy by a Ca/Mg-enriched protective oxide layer [7]. In this study, a trace amount of Ca is added in the Al-10mass%Mg alloy to reduce Mg oxidation during melting process using Mg+Al_2Ca master alloy as a Mg additive. A SKD61 cylinder with 30 mm in diameter and 10 mm in thickness was immersed for 1 and 3 h in the three Al melts held at 700°C, which is considered a common casting temperature.

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After the immersion test, the dipped samples were air-cooled under an ambient atmosphere and sectioned for microstructural characterization. The samples was grinded, micro-polished for observation of the microstructure. Scanning electron microscope (SEM) was performed on the as-cast samples, operating at 20 kV using backscattered electrons (BSE) imaging mode. Energy dispersive X-ray spectroscopy (EDS) was used to perform composition measurement of intermetallic compound regions in the interface. Equilibrium products of the interfacial reaction between SKD61 and Al melts were predicted using *FactSage 7.3* [8]. To simplify the calculation, Al, Fe and one main alloying element were used as variable reactants.

3. Results and discussion

Fig. 1 displays SEM images of interfacial layers in the diffusion couple at 700°C depending on holding time. Analyzed compositions of the numbered areas in Fig. 1 by EDS are shown in TABLE 1. Partial separation of the reaction layers from SKD61 was found, but overall soldering between Al melts and tool steels was observed. Pure aluminum and Al-10mass%Mg alloy showed relatively simple interfacial layers, whereas thicker, multi-layered reaction bonds were found in the diffusion couple of A380 alloy, indicating that Si as main element led to a strong interaction of Al melt and tool steel. As shown in the EDS results in TABLE 1, a number of Al-Fe intermetallic particles in pure Al matrix near the interfacial layer were observed. This is attributed to the diffusion of a large amount of Fe into Al matrix from the interfacial layer. The soldering layer seems to consist of two separated areas with different Fe-Al based intermetallic phases containing a trace of Cr as shown in the analyzed compositions of Area 2 and 3. Because SKD61 has approximately 5mass%Cr as a main alloying element, Cr possibly dissolved in the intermetallic layer. The diffusion couple of Al-10mass%Mg alloy showed a similar intermetallic layer as can be seen in the compositions of Area 7 and 8. This indicates that 10mass%Mg in the Al melt rarely affected the formation of Al-Fe intermetallic layers. However, A380 alloy showed much expanded soldering area. It can be divided into 3 regions containing Si depending on Fe content, indicating that Al-Fe-Si ternary intermetallic compounds are formed. Therefore, the existence of Si in the alloy would increase die soldering due to strong interaction between Fe and Si. Fig. 2 shows the measured thickness of intermetallic

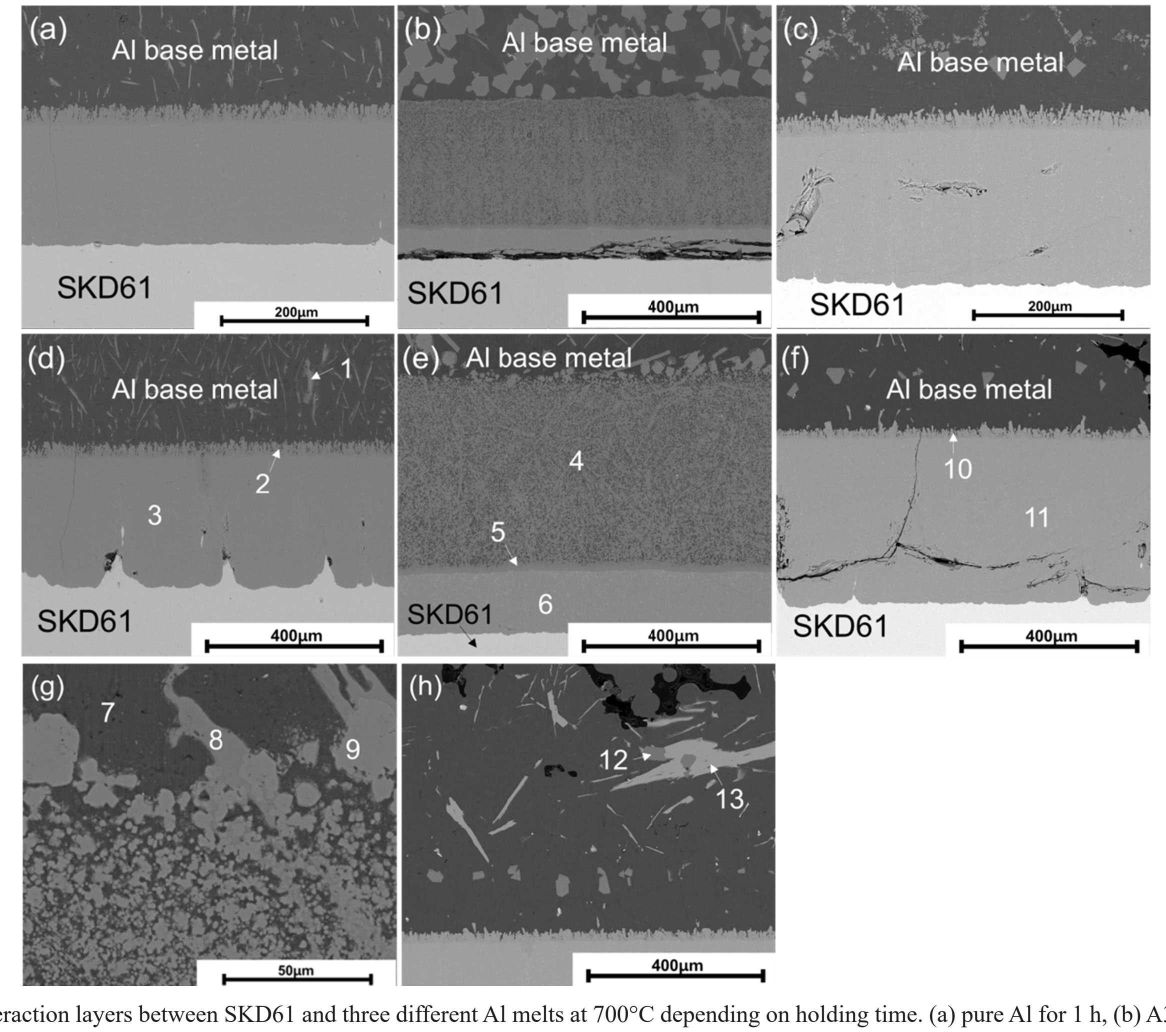

Fig. 1. Interaction layers between SKD61 and three different Al melts at 700°C depending on holding time. (a) pure Al for 1 h, (b) A380 for 1 h, (c) Al-10mass%Mg for 1 h, (d) pure Al for 3 h, (e) A380 for 3 h, and (f) Al-10mass%Mg for 3 h. Intermetallic particles on Al matrix side near interaction layers between SKD61 and (g) A380 and (e) Al-10mass%Mg alloy melts at 700°C after 3 h

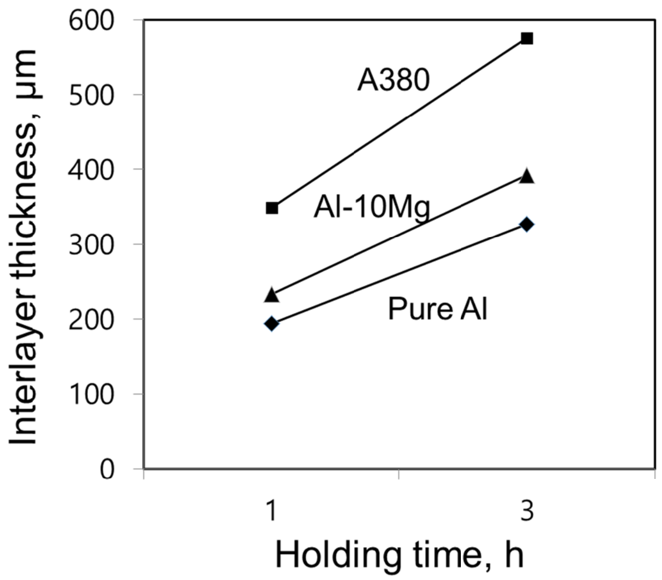

Fig. 2. Thickness of interaction layers between SKD61 and three different Al melts at 700°C depending on holding time measured from the images in Fig. 1

layers shown in Fig. 1. Pure Al and Al-10mass%Mg alloy were thought to have similar thicknesses, but Al-Si alloys exhibited much increased thickness. As shown in Fig. 1(g) and (e), in the Al base material, ternary intermetallic compound particles were found in the matrix of A380 alloy, and it is considered that the entire amount of Si is dissolved in the matrix from the composition of Area 9. As that of pure Al, Al-Fe-based compounds were found in the Al-Mg alloy matrix, and intermetallic particles containing various elements from the SKD61 were also observed because of the presence of a trace amount of Ca contained in the alloy. Shirzadi et al. [1] studied diffusion bonding between Al-6 mass%Mg alloy and stainless steel. Their results indicated that the diffusion bonding of Al-6 mass%Mg alloy to stainless steels was difficult because of high concentration of Mg at the joint interface, low melting point of Al-Mg alloys, and formation of Mg oxide on the faying surfaces [1]. The reasons mentioned above may be related to the difficulty of diffusion bonding, but in this study, the change in diffusion behavior in case of alloying a large amount of Mg with Al was investigated using phase diagrams.

TABLE 1

Analyzed compositions of numbered areas in Fig. 1 by EDS

Sample	Area	Analyzed composition (mass%)							
		Al	Fe	Si	Mg	Cr	V	Ca	Mn
Pure Al for 3 h	1	76.35	23.65	—	—	—	—	—	—
	2	60.33	36.85	—	—	2.82	—	—	—
	3	55.13	42.52	—	—	2.35	—	—	—
A380 for 3 h	4	66.31	18.60	11.40	—	3.70	—	—	—
	5	57.12	28.85	11.72	—	2.31	—	—	—
	6	51.33	42.82	3.27	—	2.58	—	—	—
	7	85.11	—	14.89	—	—	—	—	—
	8	56.43	26.17	17.40	—	—	—	—	—
	9	58.76	24.74	10.34	—	3.43	—	—	2.73
Al-10Mg for 3 h	10	61.54	38.46	—	—	—	—	—	—
	11	54.93	42.64	—	—	2.43	—	—	—
	12	74.46	—	—	7.77	6.85	7.04	3.87	—
	13	62.02	37.98	—	—	—	—	—	—

Fig. 3 shows the phase diagrams plotted for Fe versus main elements (Si or Mg) in Al at 700°C. The solubility of Fe in liquid Al increased significantly with increasing Si content up to approximately 5mass%, and then gradually increased thereafter. AlFeSi_alpha phase appeared over apploximately 5mass%Si. Therefore, the increased Fe solubility and the appearence of Al-Fe-Si ternary intermetallic phase in A380 alloy cannot lead only to the formation of a number of Fe based intermetallics in Al matrix after the solidification, but also to increased die-soldering and erosion of the die. However, in the case of 10mass%Mg addition, the Fe solubility gradually decreased with increasing Mg content. This implies that the increase of Mg content in Al alloy casting can reduce the entrainment of Fe into Al melt from the contact with steel base materials.

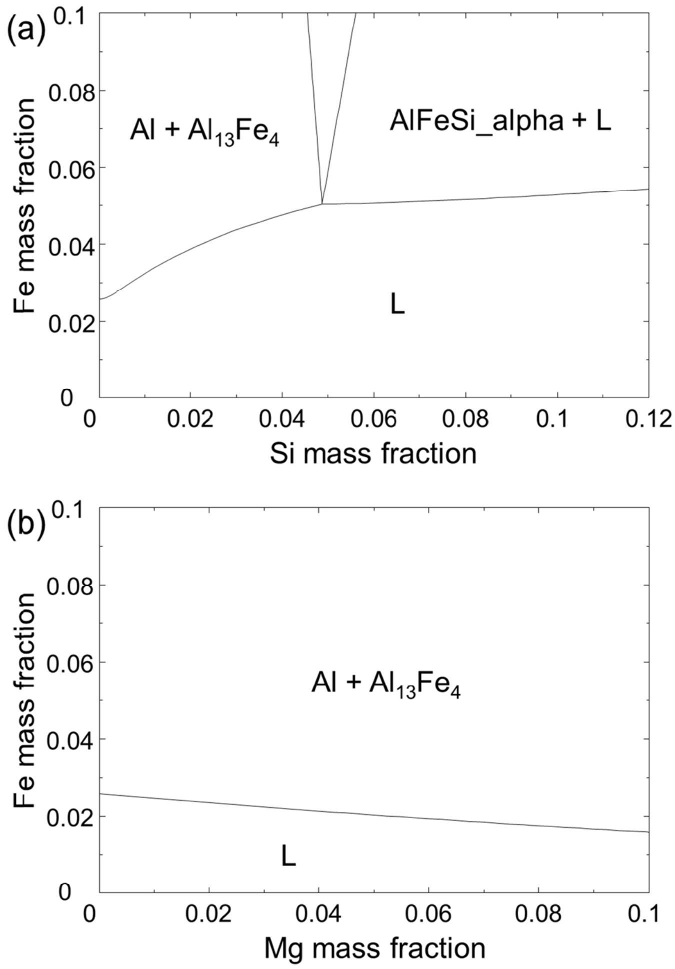

Fig. 3. Phase diagrams plotted for (a) Fe versus Si and (b) Fe versus Mg at 700°C calculated by *FactSage 7.3*.

Fig. 4 exhibits Al-rich portion of Al-Si-Fe ternary phase diagram isothermal at 700°C calculated by *FactSage 7.3* with the compositional points corresponding to analysed areas in TABLE 1. As shown from the dashed line, it can be seen that the diffusion path from the Al-Si alloy side to the Fe side leads to the Al-Fe binary system side through the formation of two types of Al-Fe-Si-based compounds. According to a literature [9], if the die surface temperature reaches the soldering critical temperature, Fe dissolves in the Al melt and Al diffuses into the die if there is no obstacle to diffusion such as a lubricant and coating. And then, intermetallic compound layer would steadily form at the die surface. With increasing Al concentration at the die surface, a fraction of a liquid Al-rich phase is formed. The fraction of the liquid phase changes with the Al concentration and the temperature. During cooling, the Al-rich liquid solidifies and forms a coupled structure of Al-rich and Fe-Al intermetallic phases at the interface. The strength of the bond is dependent on the fraction of the soldering. Therefore, A380 alloy with expanded metallurgical bond area would have a strong bond causing the casting easily sticks to the die. On the other hand, it is considered that the Mg enrichment can minimize problems that may occur due to contact with Fe-based tools.

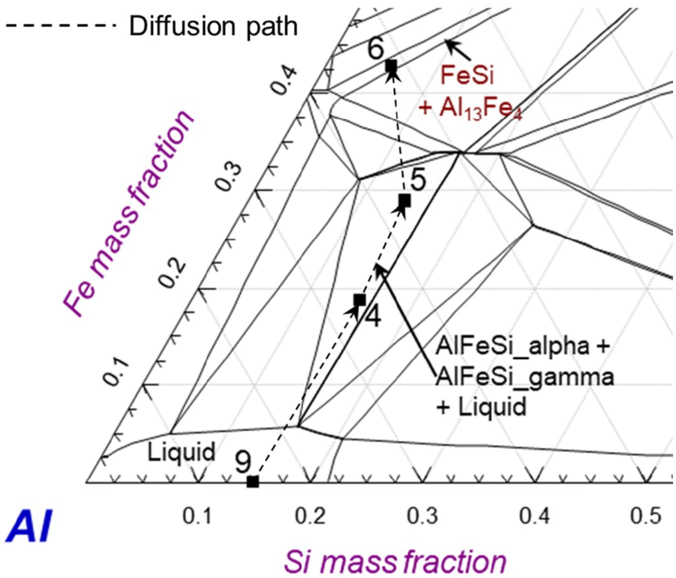

Fig. 4. Al-rich portion of Al-Si-Fe ternary phase diagram isothermal at 700°C calculated by *FactSage 7.3* with the compositional points corresponding to analysed areas in TABLE 1.

4. Conclusions

Pure Al and Al-10mass%Mg alloy showed relatively simple Al-Fe based interfacial layers with tool steel, whereas thicker, multi-layered reaction bonds with binary and ternary compounds were found in the diffusion couple of A380 alloy. The diffusion couple of Al-10mass%Mg alloy showed a similar intermetallic layer as that of pure Al, indicating that 10mass%Mg in the Al melt rarely affected the formation of Al-Fe intermetallic layers. However, A380 alloy showed much expanded soldering area and increased thickness of intermetallic layers. This would be caused by the significantly increased solubility of Fe in liquid Al with increasing Si content and the appearence of Al-Fe-Si ternary intermetallic phase in A380 alloy. Al-Fe binary compounds with various chemical formulas are produced between Al and Fe depending on relative fraction in Al-Fe and Al-10mass%Mg alloy-Fe based on the phase diagrams calculated. However in the Al-12mass%Si alloy, two types of Al-Fe-Si ternary compounds are present on the Al-rich side. A380 alloy with expanded metallurgical bond area would have a strong bond causing the casting easily sticks to the die. On the other hand, it is considered that the Mg enrichment can minimize problems that may occur due to contact with Fe-based tools.

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