Development of Steel Matrix Composites Used for Metal Die

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Abstract. In this study, we show the development of the steel matrix composites used for metal die. Matrix used is 40CrMoV5 (ISO standard) steel, which is used as press and die-casting dies. The dispersants used are vapor grown carbon nanofiber (VGCF), which is one of carbon nanofiber (CNF) and titanium die-bride (TiB2) particle powder. After mixing 40CrMoV5 powder and the dispersants by ball milling, the composites was prepared by spark plasma sintering (SPS) process. For VGCF, 1.9 and 3.8 vol. % was added to 40CrMoV5 powder in order to obtain the composites. The thermal conductivity of the VGCF/40CrMoV5 alloy composites improved about 20% compared with the 40CrMoV5 monolithic alloy. The tensile strength of the composites with 1.9 vol. % VGCF is about 1980 MPa, which is higher than the monolithic alloy with 1250 MPa. For TiB2 particle, 4.0, 8.0 20.0 vol. % powders was added to 40CrMoV5 powder. By adding 8.0 vol. % TiB2, the thermal conductivity improved about 40% compared with the monolithic alloy, but tensile strength decreased to 612 MPa in 8.0 vol. % VGCF composites, which are caused by the aggregation of TiB2 powders. It seems the strength of the composites will improve by controlling the dispersibility of TiB2 powders.

Keywords: Steel composites, Sintering, Thermal conductivity, Mechanical property, Microstructure

1. Introduction

Die-cast process is used in the automobile industry mainly because of high dimensional accuracy, smooth casting surface, high productivity and easy casting process. Above all, the aluminum alloy die-casting accounts for 95% of total amount of die-casting production. On the other hand, Al products used in vehicle has been substituted from wrought product to casting product because of high cost performance in recent years. Especially, die-cast process has been grate-watched, because the die-cast process is able to make high performance products. Die-cast process is as follows; after coating the die surface by lubricant, die was clamped. Then the molten metals was poured in cavity with high pressure. After cooling and opening the mold, we can obtained the cast products. Repeat of rapid cooling and heating of metal die generate the thermal stress. The extrusion pressure and mold clamping lead the mechanical stress to metal die. The degradation of life time of die-cast mold and surface quality of die-cast products is caused by the defect such as the heat check, the crack and the melting generated during operation. In order to improve the productivity, cost performance and stability of the product quality for die-cast process, the improvement of the life time is important. In order to improve
the lifetime of die, the improvement of the thermal conductivity and the mechanical properties is required because of the degradation of thermal stress and the toughening.

The objective in this study is to relax the thermal stress generated in metal die and to improve the lifetime of metal die by using the metal matrix composites (MMC). Especially, we try to improve the thermal conductivity without the degradation of mechanical properties for conventional steel die. We used the dispersant with high thermal conductivity and small size under sub-micron for composites. Small sized dispersants seems to affect to the improvement of the strength and toughness of metal die because of the refinement of the microstructure and the improvement of grain boundary strength.

2. Experimental Procedure

Two type of carbon nanofiber (CNF) and ceramic particle dispersed steel composites was prepared in this study. Starting material used as matrix is 40CrMoV5 steel alloy powder with average diameter 70\(\mu\)m (Mitsubishi steel MFG Co., Ltd.). Table 1 shows the chemical composition of 40CrMoV5 used in this study. Dispersants used are vapor grown carbon nanofiber (VGCF) and TiB\textsubscript{2} particles. VGCF is one of carbon nanofiber (CNF), which was developed by Showa Denko Co., Ltd. in Japan and forms 150 nm in diameter and 10-20 \(\mu\)m in length. VGCF has high thermal conductivity as 1200 W/mK along fiber direction. TiB\textsubscript{2} particle forms equiaxial with average diameter 2.62 \(\mu\)m, which is developed by Japan New Metals Co., Ltd. Then, these powders was mixed by V shape type ball mixer, which is conventional mixing method. Each powders was inserted in stainless vessel with ethanol and mixed under 50 rpm in rotational speed of mixer. Volume fractions of VGCF were 1.9 and 3.8 vol. %. Volume fractions of TiB\textsubscript{2} were 4.0, 8.0 and 20.0 vol. %. After mixing, the composites were prepared by spark plasma sintering (SPS) process under the condition of 1173K and 1273K in sintering temperature, 50 MPa in applied pressure, 0.6ks in keeping time of pressure and \(<10^{-2}\)Pa in atmosphere. Relative density and microstructure of the composites was evaluated by Archimedes method, optical microscopy, SEM and EPMA. Thermal conductivity and tensile strength were measured by steady state method and tension tester, respectively.

| Chemical composition of 40CrMoV5 steel powders used in this study. |
|------------------|---|---|---|---|---|---|---|---|---|---|
| C               | Si  | Mn  | P   | S   | Cu  | Ni  | Cr  | Mo  | V  | Fe   |
| 40CrMoV5 (wt.%) | 0.51 | 1.09 | 0.06 | 0.008 | 0.007 | 0.03 | 0.03 | 4.63 | 1.03 | 1.06 |

3. Results and Discussion

Fig. 1 shows the microstructure of VGCF dispersed 40CrMoV5 steel composites and TiB\textsubscript{2} particle dispersed 40CrMoV5 steel composites. Fig. 1 (a) is 1.9 vol. % VGCF/40CrMoV5 steel composites. Dark dots and lines were observed at the boundary of sintered steel particle, which is aggregation of VGCFs. Fig. 1 (b) and (c) is 4.0 vol.% and 8.0 vol. % TiB\textsubscript{2}/40CrMoV5 steel composites, respectively. Dark area in these figs. is traces of falling particles by polishing. It seems the dispersed nanofibers or particles segregated at the boundary of sintered steel particle. Sintered steel particle forms equiaxed, which forms maintain the as-received particle. As VGCF and TiB\textsubscript{2} may react with Fe thermodynamically, we have to check the reactivity of the composites during sintering. Fig. 2 shows the mapping of C, Fe and Cr element around the dark dots in fig. 1 (a) observed by EPMA, which is 1.9 vol. % VGCF/40CrMoV5 steel composite. The composites was fabricated at 1173K in sintering temperature. The density of the composites was over 98%. Fe and Cr elements was not detected in the area shown strong carbon element. It means VGCF did not react with Fe and Cr to form these carbides. This composites prepared by sintering at 1173K. But, most VGCF react with Fe in the composites
prepared by sintering at 1273K. It seems 1173 K is suitable temperature to obtain dense composites without reaction between VGCF and Fe.

Fig. 1 Microstructure of (a) 1.9 vol. % VGCF/ 40CrMoV5 steel composites, (b) 4.0 vol. % TiB$_2$ / 40CrMoV5 steel composites and (c) 8.0 vol. % TiB$_2$ / 40CrMoV5 steel composites.

Fig. 2 EPMA mapping of 1.9 vol. % VGCF/ 40CrMoV5 steel composite.

Fig. 3 Equilibrium phase diagram between 40CrMoV5 alloy and TiB$_2$ [2].
Fedrizzi et al. [1] shows TiB$_2$ react with iron element in 40CrMoV5 alloy as following reaction.

$$\text{TiB}_2 + \alpha-\text{Fe(C)} \rightarrow \text{TiC} + \text{Fe}_2\text{B} + \alpha-\text{Fe(C)} \tag{1}$$

Furthermore, Fedrizzi et al. [1] shows the equilibrium phase diagram between 40CrMoV5 alloy and TiB$_2$ by using Thermo-Calc® software and TCFe3 database [2]. Fig. 3 shows this diagram. Molar fraction of boron in horizontal axis in Fig. 3 for 4 vol. %, 8 vol. % and 20 vol. % TiB$_2$/40CrMoV5 alloy composites are 0.035, 0.069 and 0.15. This diagram shows the stable phase at 1273K in 4 vol. % TiB$_2$/40CrMoV5 alloy composites are $\alpha+\gamma+\text{TiB}_2+\text{Fe}_2\text{B}$, and TiB$_2$ phase is unstable phase. But in 8 vol. % and 20 vol. % TiB$_2$/40CrMoV5 alloy composites, stable phases are $\alpha+\text{TiB}_2+\text{Fe}_2\text{B}+\text{TiC}$, and TiB$_2$ phase remains as stable phase. As the thermal conductivity of TiB$_2$, TiC and Fe$_2$B are 66.4 W/mK, 16.7W/mK and 20.7W/mK, it seems the generation of TiC and Fe$_2$B lead to degrade the thermal conductivity of the composites. Fig.4 shows XRD analysis of 20 vol. % TiB$_2$/40CrMoV5 composites. Two peaks are observed at around 34 degree and 44 degree. The former is TiB$_2$ peak, and the latter is sum of Fe and TiB$_2$ peaks. This results shows many TiB$_2$ remains in composites. It seems TiB$_2$ phase remains in 8 vol. % TiB$_2$/40CrMoV5 composite. But obvious TiB$_2$ was not observed in XRD result of 8 vol. % TiB$_2$/40CrMoV5 composite.

![XRD analysis of 20 vol. % TiB$_2$/40CrMoV5 composites.](image)

Fig. 4 XRD analysis of 20 vol. % TiB$_2$/40CrMoV5 composites.

Fig. 5 shows the thermal conductivity of monolithic 40CrMoV5 alloy, VGCF dispersed 40CrMoV5 alloy composites and TiB$_2$ disperse 40CrMoV5 alloy composites. Thermal conductivity of monolithic 40CrMoV5 alloy is about 20.0 W/mK. By adding 1.9 vol. % VGCF, the thermal conductivity increased to 25.0 W/mK. On the other hand, 4 vol. % TiB$_2$/40CrMoV5 alloy composites was 18.0 W/mK, which is caused by the generation of TiC and Fe$_2$B and dissipation of TiB$_2$ by reaction during sintering. But by adding TiB$_2$ content to 8 vol. %, the thermal conductivity increased to 34 W/mK, which is caused by the remains of TiB$_2$ in composites. Consequently, the addition of VGCF and TiB$_2$ is effective for the improvement of the thermal conductivity of monolithic 40CrMoV5 alloy.

The keeping of strength for composites is important for practical use of metal die. Fig. 6 shows the tensile strength of the monolithic alloy and the composites. By adding 1.9 vol. % VGCF, the tensile strength of the composites improved dramatically from 1250MPa to 1980MPa. It seems the strength of 40CrMoV5 particle boundary in composites was improved by the bridging of 40CrMoV5 particles by VGCF. On the other hand, by adding TiB$_2$, the strength of 40CrMoV5 alloy degraded. For 4 vol. % and 8 vol. % TiB$_2$ addition, the strength of the composites was decreased as 1213 MPa and 612 MPa, respectively. The degradation of the strength seems to be caused by the stress concentration at aggregation area of TiB$_2$ particles.
On the other hand, the elongation of TiB₂/40CrMoV5 is improved by increasing TiB₂ contents, which is caused by the grain boundary strengthening by boron element, which is supplied from the reaction of Fe and TiB₂. In order improve the strength of the composites, the microstructure control is very important.

Fig. 5 Thermal conductivity of monolithic 40CrMoV5 alloy, VGCF dispersed 40CrMoV5 alloy composites and TiB₂ disperse 40CrMoV5 alloy composites

Fig. 6 Tensile strength of monolithic 40CrMoV5 alloy, VGCF dispersed 40CrMoV5 alloy composites and TiB₂ disperse 40CrMoV5 alloy composites.

4. Conclusions

In order to obtain high performance metal die with high thermal conductivity and high strength, 40CrMoV5 alloy based composites was prepared by SPS process. Two type’s materials was investigated as dispersant of the composites, which is VGCF and TiB₂ particles. For VGCF, the
suitable sintering temperature was 1173K because of few reaction and dense composites. The thermal conductivity and the tensile strength of 1.9 vol. % VGCF/40CrMoV5 alloy composites was better than the monolithic 40CrMoV5 alloy block. On the other hand, Addition of 4vol. % TiB₂ degraded the thermal conductivity and tensile strength because of the reaction of Fe and TiB₂, but by increasing TiB₂ contents more, thermal conductivity of the composites increased because of the suppress of the reaction.

5. Acknowledgements

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6. References

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