H13 Modified High Thermal Conductivity Powder for 3D Printing

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ABSTRACT

Recently, additive manufactured molds with conformal cooling channels have been used to enhance the cooling efficiency of die casting molds. H13 and maraging steel powders are commonly used in 3D printing, but each has its own problems. In case of H13 powder, it is difficult to build without cracking. Maraging powder is less susceptible to cracking during the building process than H13 powder, but due to low thermal conductivity, the thermal stress during casting is higher which promotes cracking from water cooling channels and heat checking on the design surface.

Tackling these problems, new 3D printing powder has been developed by optimizing the chemical composition of H13. As the hardness of the developed powder is lower than that of H13 powder in as-built condition, it is less likely to incur cracking during building. In addition, it has high thermal conductivity which reduces thermal stress during casting. In this paper, the properties such as formability and heat checking resistance of the built specimens are reported.

INTRODUCTION

Molds manufactured by 3D printing have been attracting attention in recent years. One of the reasons why is that it is possible to place conformal cooling channels inside the mold, which was not possible with conventional machining. The conformal cooling channels can significantly improve the cooling capacity of the mold and can cool parts that could not be cooled in the conventional mold, which is effective in shortening the cycle time, reducing the product defect rate, and reducing mold damage such as heat checking and soldering.

Selective laser melting (SLM), which is superior in dimensional accuracy and part density, is often used for additive manufacturing of die casting molds. For mold applications, H13 and maraging steel powders are mainly used in SLM, but each has its own problems.

H13 is a steel that is commonly used for die casting molds. However, H13 powder is not suitable for the SLM process and is easy to crack during building. This is because high thermal stress generated by the process consists of repeated melting and solidification of the powder layers and H13 has a hardness of more than 50 HRC in the as-built condition [1, 2] and deteriorates toughness.

Maraging steel, on the other hand, is less susceptible to cracking during the process because it has a hardness of about 35 HRC in the as-built condition and the subsequent heat treatment increases its hardness.[3] For this reason, it is widely used as a 3D printing powder for molds. But due to low thermal conductivity, the thermal stress during casting is higher which promotes cracking from water channels and heat checking on the design surface.

In addition to H13 and maraging steel, other 3D printing powders have been developed that are less prone to cracking during the process than H13 and have sufficient mechanical properties [4], but they have lower thermal conductivity than H13.

Thus, until now, there has been no powder that is suitable for 3D printing process and also has excellent performance in die casting. Therefore, we have developed new 3D printing powders based on H13. The composition of the powders has been adjusted to reduce cracking during building and to increase thermal conductivity compared to H13.

In this study, to evaluate whether the powders are suitable for 3D printing die casting molds. Cracking during building, mechanical properties and heat check resistance of the built parts were investigated.

EXPERIMENTAL

MATERIALS

Two kinds of the developed powders with different carbon content were alloy designed on the basis of H13 chemistry. The chemical compositions are listed in Table 1. The Carbon (C) content of both powders has been reduced compared to H13, which is expected to suppress cracking by lowering the hardness during building. The Carbon content of Steel A is higher than Steel B and the hardness can be higher.

Relationship between the amount of Silicon (Si) content and thermal conductivity is shown in Figure 1. It is found that decreasing Si content improves thermal conductivity. Therefore, Si content of both developed powders were reduced to attain high thermal conductivity.

The developed powders were produced by gas atomization. The particle size ranges from 25 to 53μm and the morphology of the powder is in a spherical shape. The flowability of these powders are high enough to be able to smooth the surface roughness of the powder bed.

In this study, the evaluation of cracking during building made a comparison with gas atomized H13 powder. As to the mechanical properties and heat check resistance, in order to compare the build parts with those of common mold steel, conventionally H13 steel produced by casting and forging was prepared, referred as 'forged H13' hereafter.

Table1- Chemical composition of the developed and conventional powders (mass%)

	C	Si	Mn	Ni	Cr	Mo	V	Co
Steel A	0.23	0.1	0.4	-	5.3	1.2	0.4	-
Steel B	0.13	0.1	0.4	-	5.3	1.2	0.4	-
H13	0.40	1.0	0.4	-	5.3	1.2	1.0	-
18%Ni Maraging steel	-	-	-	18.5	-	4.8	-	9.0

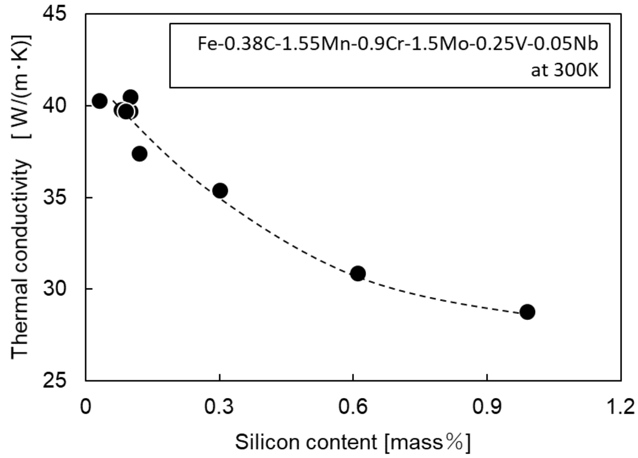

Figure 1- Effect of Si content on thermal conductivity.

BUILDING CONDITIONS

The specimens in this study were built by using a GE Additive Concept Laser M2 machine. To determine the optimal building conditions, the relative density of the built samples by various conditions were investigated. The building conditions are as follows.

The samples sized 12×12×12mm were built by using laser spot diameter of 180μm, layer thickness of 50μm, and hatch spacing of 0.13 μm. The laser parameters including laser power, scanning speed were optimized in the range of 200 - 300 W, 300 - 1200 mm/s, respectively. The relative densities were measured by the ratio of defect-free areas in the optical micrograph of the vertical (building) direction after polishing. The cross sectional images and measured relative densities of samples are shown in Figure 2. Optimized condition to achieve relative density of more than 99.95% was laser power of 300W and scan speed of 600mm/s and it was used to various tests samples built in this study.

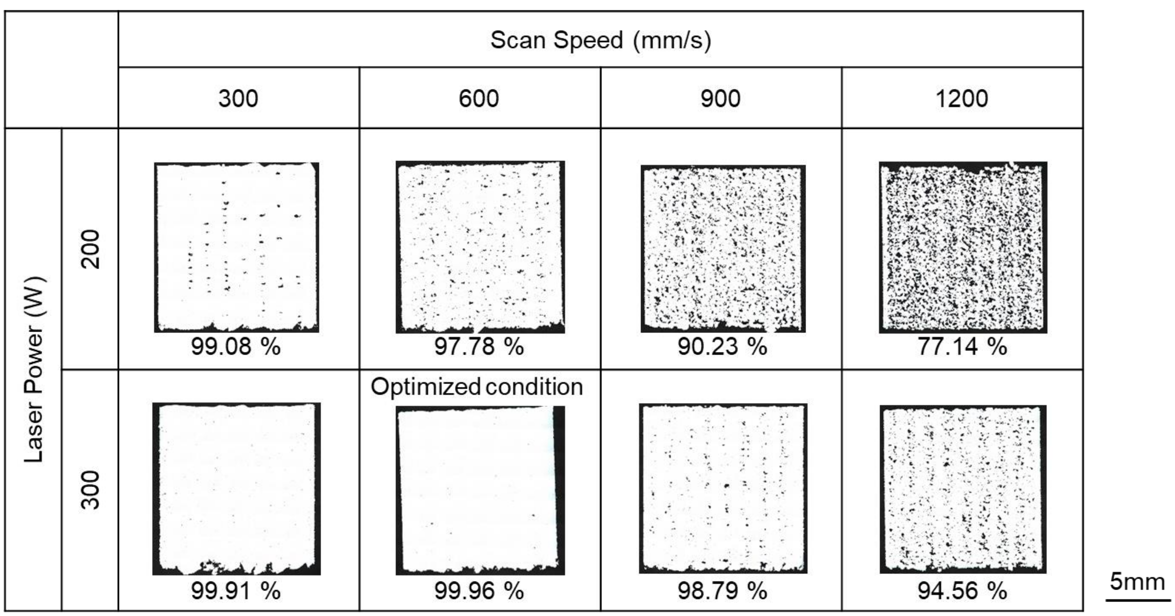

Figure 2- Cross sectional images and relative densities of built samples

FORMABILITY TEST

In order to evaluate the cracking resistance during building, notched specimens changing the height from 20 to 30mm were built by using H13 and steel A with preheating at 473K(392ºF). The reason for changing the height of the specimen is that the more layers are built up, the more thermal stress accumulates [5] and the more likely cracks are to occur. The notch of specimens was at 7.5mm above the base plate and the angle is 90 degrees and the depth is 5mm.

THERMAL CONDUCTIVITY

Steel A were built to be sized 15×15×100mm and tempered at 843K (1,058 ºF) for 1 hour and then were machined to specimens sized 10mm dia. and 2mm thick. The thermal conductivity was measured by the flash method.

TEMPERING HARDNESS

To improve the homogeneous and thermal stability of the microstructure, the built specimens were subjected to the post heat treatment. The relationship between tempering temperature and hardness was investigated. As-built specimens with 15×15×100mm size were cut and each tempered twice at 673~953K (752 ~ 1,256 ºF) for 1 hour and the hardness was determined by Rockwell hardness test. Tempering conditions were decided from this relationship between tempering temperature and hardness. The built specimens in the tests described below tempered to 40 to 50 HRC. Forged H13 specimens were quenched from 1,303K(1,886ºF) by rapid cooling rate and then tempered to the same hardness range.

MECHANICAL TESTS

Charpy impact test and tensile test were conducted to evaluate the toughness, strength and ductility of the built specimens. The preparation procedure and schematic illustrations of the specimen shape are shown in Table.2 and Figure 3, respectively. The Charpy impact values at room temperature of Steel A and B were compared with those of forged H13. (ISO 148-1:2016) Tensile test was conducted to evaluate 0.2% proof stress, tensile strength, elongation and reduction of area at room temperature. (ISO 6892-1:2009)

Table 2- The preparation procedure of mechanical tests specimen

Test	Size of built samples	Condition	
	x, y, z /mm	Steel A	Steel B
Charpy impact test	15×60×15	tempered to 45~50HRC	as-built(43HRC) tempered to 44HRC
Tensile test	15×100×15	tempered to 45~50HRC	as-built(43HRC) tempered to 44HRC

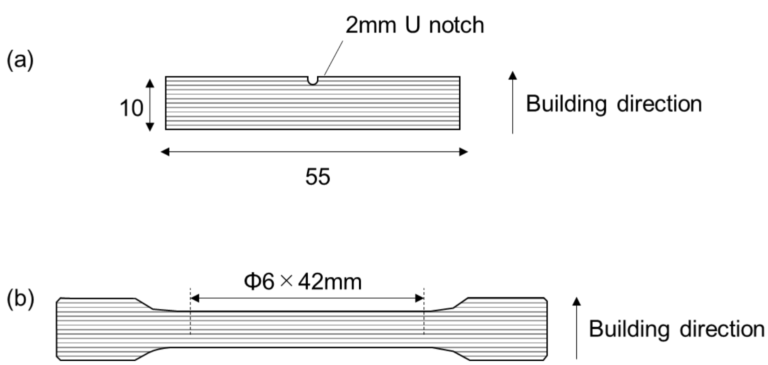

Figure 3- Schematic illustrations of the specimen shape of (a)Charpy impact test and (b)Tensile test.

HEAT CHECKING TEST

Heat checking resistance is one of the most important properties for die casting molds. This is because heat checking accounts for about 78% of the damage modes of die casting molds.[6] Heat checking was tested by the method schematically shown in Figure 4. The size of the heat checking test specimen was 72mm dia. and 50mm thick. A notch with a depth of 1 mm and R6 was made on the test surface to fix the location where the heat checking occurs. In case of steel A, the upper 18 mm of the specimen was built, and the hardness of the built part was tempered to 48.9 HRC. The forged H13 for comparison was quenched and tempered to 47.6 HRC. In the test, the surface of the specimens was heated to 853K (1,076ºF) by induction heating followed by water jet cooling. This was a cycle taking 17 sec. in total. For each 1000 cycles the surface was observed to evaluate the heat checking pattern severity.

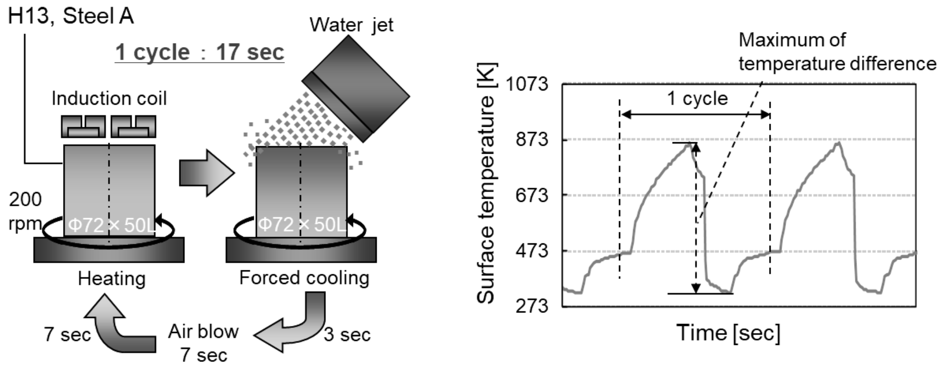

Figure 4- Heat checking test procedures

RESULTS AND DISCUSSION

FORMABILITY

Figure 5(a) shows the schematic illustration of sample shape and (b) shows appearance of the specimen comparing the cracking of H13 and Steel A during building.

Gross cracking was observed at the notch at all specimen heights in H13. It has been reported that H13 is prone to cracking during building when the preheating temperature is less than 573K(572°F) [7], which is consistent with this results.

On the other hand, no cracks were observed at the notch of Steel A in appearance and even after checked by dye penetrant test. Thus, it was obvious that cracking was suppressed due to the reduction of hardness during building by reducing the Carbon content. It is suggested that the toughness during building has been improved because the hardness of the as-built specimen shown in Figure 5 was lower than that of H13. In addition, Steel B has a lower hardness than Steel A, so it is less likely to crack during building than Steel A. Also, since the yield stress decreases with hardness, it is possible that the thermal stress during building was reduced by plastic deformation. The details of the mechanism by which cracking was suppressed should be further examined.

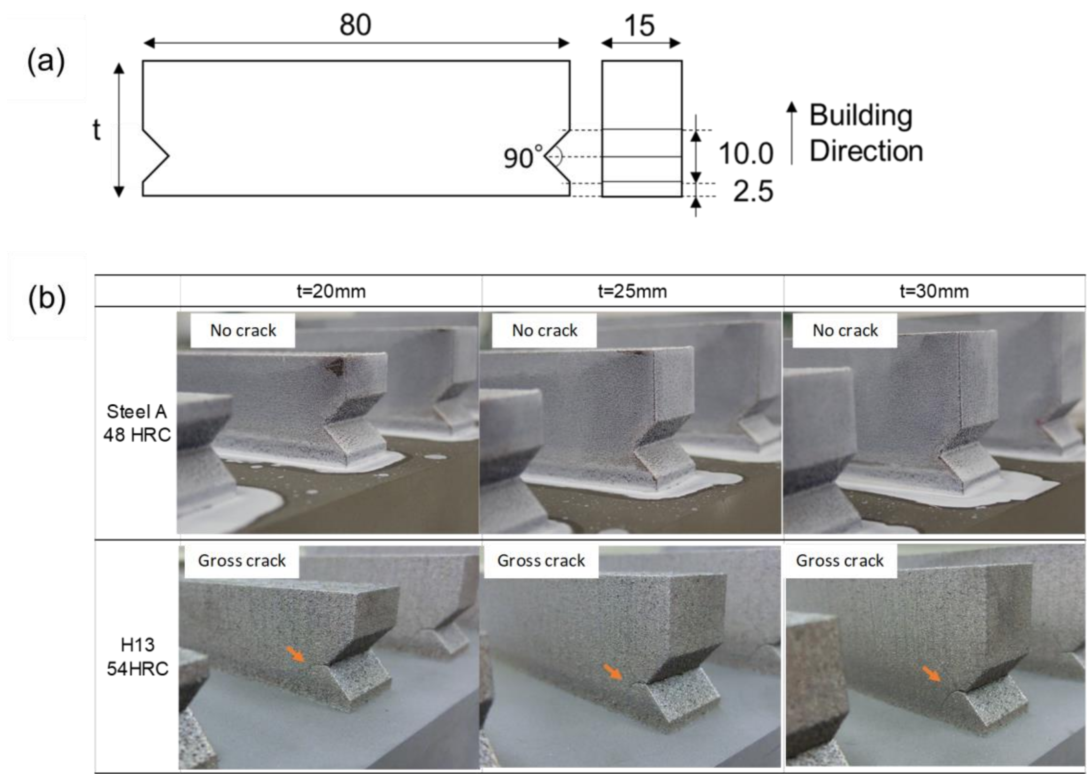

Figure 5- Formability test results (a) Schematic illustrations of the specimen shape (b) Specimen appearance comparing the cracking during building.

THERMAL CONDUCTIVITY

The thermal conductivities of Steel A and forged H13 and forged maraging steel measured by flash method are shown in Figure 6. Because of the lower silicon content, the thermal conductivity of Steel A is higher than that of H13.

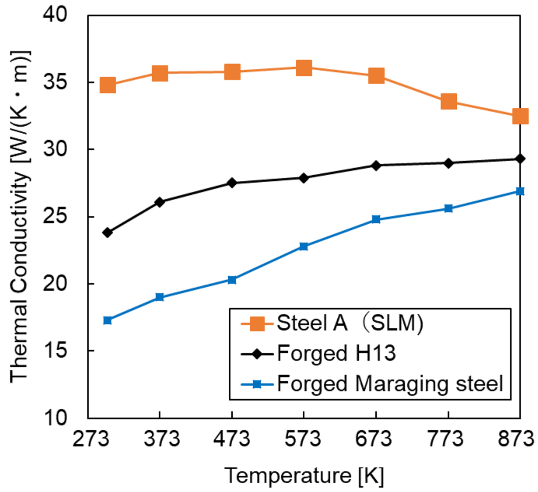

Figure 6- Thermal conductivity of mold steels

TEMPERING HARDNESS

The hardness measured after heat treatment of built Steel A and B is shown in Figure 7.
The as-built hardness of Steel A is 48 HRC and that of Steel B is 43 HRC. The as-built hardness of both steels are lower than that of H13, which is 54 HRC shown in Fig.5. Both Steels A and B show secondary hardening by heat treatment at 773 to 823K (932 - 1,022°F), similar to that of forged H13 after quenching, and they hardened up to 50 HRC and 45 HRC, respectively.

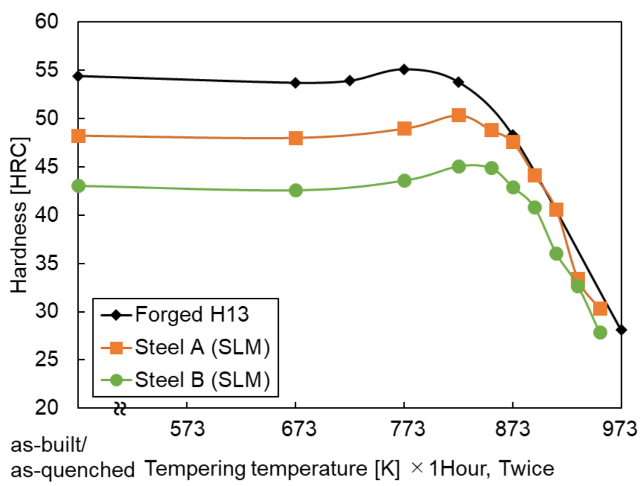

Figure 7- Hardness after heat treatment

NITRIDING HARDNESS

Nitriding is often used in die casting molds to reduce heat checking, soldering, and erosion. In order to confirm whether nitriding treatment is possible for the developed steel, Steel A and the forged H13 were tempered to 43 HRC by heat treatment, and then gas nitrided at 783K(950ºF) for 3 hours. The cross-sectional hardness distribution of the specimens after nitriding treatment was measured by Vickers hardness test.
The cross-sectional hardness distribution from surface of the nitrided specimens is shown in Figure 8. Before nitriding, built Steel A and forged H13 were tempered to 43 HRC. The hardness at 0.02 mm depth was about 1,100 HV with the nitride layer of about 0.1mm deep. Thus, the surface hardness distribution after gas nitriding is equivalent for Steel A and forged H13.

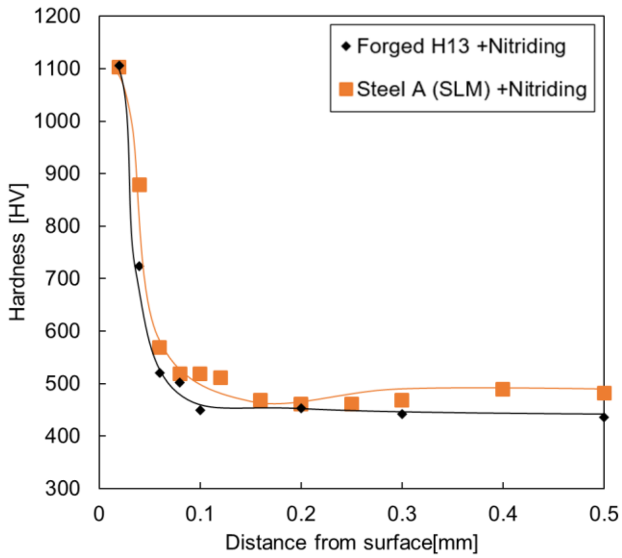

Figure 8- Hardness distribution after nitriding

MECHANICAL PROPERTIES

Charpy impact values of built Steel A and B are shown in Figure 9 in comparison with forged H13. Comparing in the same hardness range, the impact values of built Steel A and B are higher than that of forged H13.

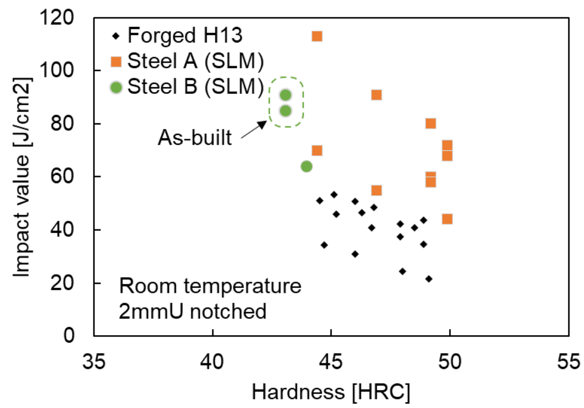

Figure 9- Charpy impact values at room temperature

Figure 10 shows the 0.2% proof stress and tensile strength(a), elongation, and reduction of area(b) of built Steel A and B by tensile test. Steel A and B have comparable tensile strength to forged H13. They were also equal to or better than forged H13 in elongation and reduction of area.

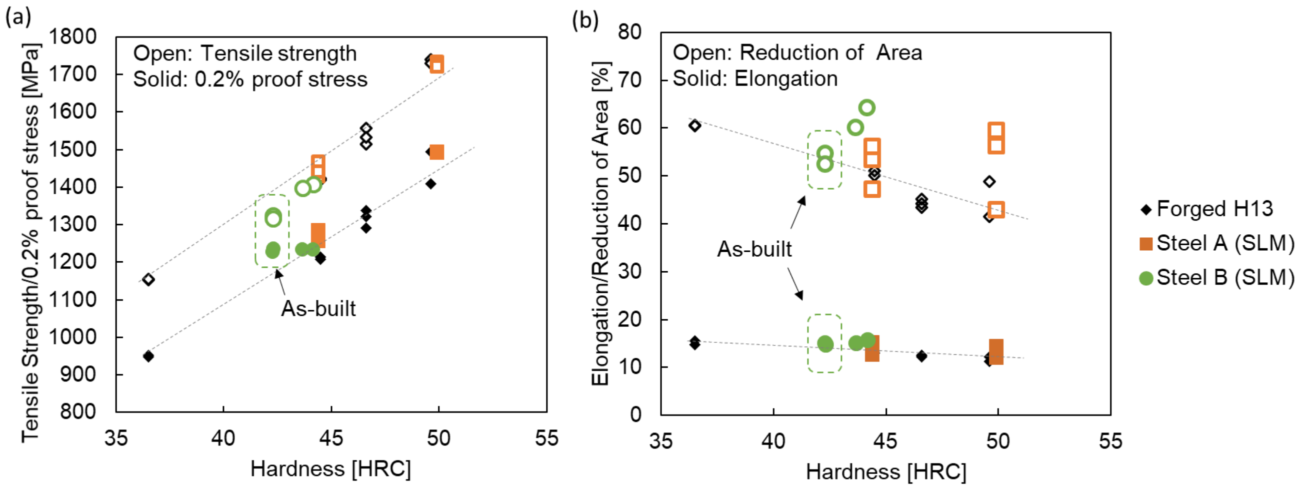

Figure 10- Tensile test results (a) 0.2% proof stress, tensile strength, (b) Elongation, Reduction of area at room temperature.

HEAT CHECKING RESISTANCE

The appearance of the specimen evaluated for heat checking resistance after 4,000 cycles are shown in Figure 11(a,b). The optical microscope image of the cross section at the bottom of the notch are shown in Figure 11(c,d). In both specimens, heat checking occurred at bottom of the notch, but in built Steel A, the area where the heat checking occurred was smaller and the crack depth was about half than that of the forged H13.

It is reported that in case of the same hardness of molds, high thermal conductivity steel shows better heat checking resistance, which was caused by decrease of thermal stress in casting cycles. [8,9] In this heat checking test, the hardness of Steel A is the equivalent as that of forged H13, so the reduction of heat checking in Steel A is considered to be due to high thermal conductivity.

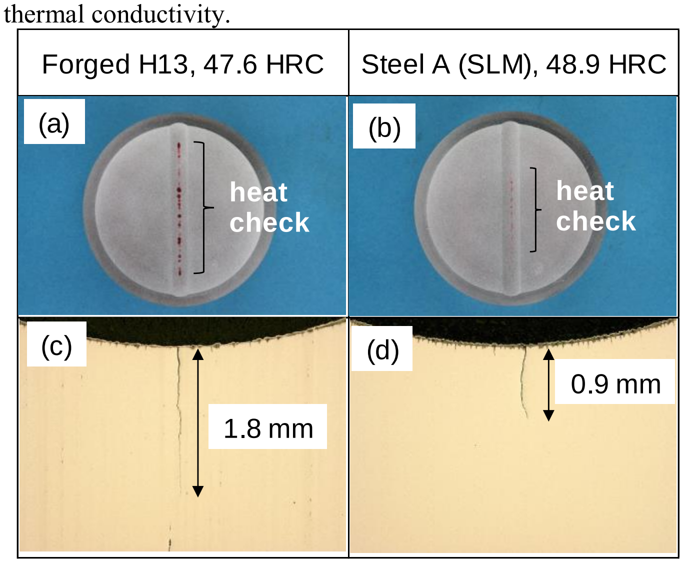

Figure 11- (a)(b) Heat checking observed on the test specimens after 4000 cycles, (c)(d) the optical microscope image of the cross section at the bottom of the notch

CONCLUSIONS

In this study, we developed H13 modified powders to improve formability and thermal conductivity, and examined the developed powders are suitable for 3D printing and are sufficiently durable as a die-casting mold after building.

1) The developed powders suppressed the cracking during building compared to H13.
Cracking was suppressed due to the lower as-built hardness by reducing the Carbon content than H13.
2) The built steels have higher thermal conductivity than H13 so have superior heat checking resistance to H13.

By adopting the developed steels, it is expected to reduce the risk of cracking during building in 3D printing and contribute to shortening the cycle time and improving the mold life by strengthening the cooling capacity of die casting molds.

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