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HIGH TEMPERATURE PROPERTIES OF Ni-38Cr-3.8Al WITH HIGH HARDNESS AND HIGH HOT CORROSION RESISTANCE

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ABSTRACT

Ni-38Cr-3.8Al has high hardness and high corrosion resistance with good hot workability, and therefore, it has been applied on various applications. However, in order to expand further application, it is important to understand the high temperature properties. Then, this study focused on the high temperature properties such as thermal phase stability, hardness, tensile property, creep property and hot corrosion resistance. As the result of studies, we found that the thermal phase stability of (γ/α-Cr) lamellar structure and the high temperature properties were strongly influenced by the temperature. Although the high temperature properties, except for creep property, of Ni-38Cr-3.8Al were superior to those of conventional Ni-based superalloys, the properties were dramatically degraded beyond 973 K. This is because the lamellar structure begins to collapse around 973 K due to the thermal stability of the lamellar structure. The hot corrosion resistance of Ni-38Cr-3.8Al was superior to that of conventional Ni-based superalloys, however, the advantage disappeared around 1073 K. These results indicate that Ni-38Cr-3.8Al is capable as a heat resistant material which is required the hot corrosion resistance rather than a heat resistant material with high strength at high temperature.

Keywords: Ni alloy, lamellar structure, high hardness, hot corrosion resistance

INTRODUCTION

Discontinuous precipitation (DP) is observed in a lot of types of alloy systems. The mechanism of DP reaction was reported by some researchers [1-3]. Ni-Cr binary alloys containing high amount of Cr precipitate the Cr-rich phase (α-Cr) with the body-centered cubic (bcc) structure, forming the lamellae structure with the γ phase with face-centered cubic (fcc) structure by the DP which proceeds from a grain boundary to interior grain. As previous investigations, the DP reaction is caused by supersaturated Cr in the γ phase [4-5]. Ni-40Cr-4Al (mass%) shows superior high hardness and high corrosion resistance without ferromagnetism. Al addition to Ni-based alloy with high Cr concentration brings on Ni consumption in the matrix by the precipitation of the γ′ (Ni_3Al) phase with the $L1_2$ structure. Therefore, Cr supersaturation dramatically increases in the γ phase. The lamellae structure in Ni-Cr binary and Ni-Cr-Al ternary alloys are also known with the Kurdjumov-Sachs relationship of $\{111\}_\gamma//\{110\}_\alpha$ and $<110>_\gamma//<111>_\alpha$ between the γ phase and the α-Cr [6]. The kinetics of the complex DP in Ni-38Cr-3.8Al and Ni-38Cr-3.8Al-X alloys were studied based on the Aaronson and Liu model [5,7-8].

Ni-38Cr-3.8Al was developed through an optimization of Cr and Al concentrations for hot workability [9]. It was reported that Ni-38Cr-3.8Al with high hardness and excellent hot corrosion resistance has been applied on various applications, such as automotive components, exhaust valve for marine engine [10], medical parts and a die for hot forging. In order to clarify a possibility for further applications as a heat resistant material, it is necessary to understand the high temperature properties which are thermal phase stability, hardness, tensile property, creep property and hot corrosion resistance. Therefore, in the present study, the high temperature properties of Ni-38Cr-3.8Al were investigated.

EXPERIMENT

Ternary Ni-38Cr-3.8Al (mass%) alloy was prepared in 50 kg ingot by an induction melting technique in vacuum. The chemical composition of the alloy was showed in Table 1. The ingot was homogenized at 1403 K for 16 hrs and subsequently hot forged below the solidus temperature of the α-Cr phase into bars 20 mm in diameter. The hot forged bars were subjected to the solution heat treatment and aging treatment in various conditions.

The microstructures after the solution and aging treatment were observed by an optical microscopy (OM), a scanning electron microscopy (SEM) and a scanning transmission electron microscopy (STEM). The alloys after aging treatment were evaluated the thermal phase stability, the hardness, the tensile property, the creep property and the hot corrosion resistance at high temperatures.

Table 1 : Chemical composition of Ni-38Cr-3.8Al in mass%.

Ni	Cr	Al	C	B
Bal.	38.0	3.8	0.01	0.003

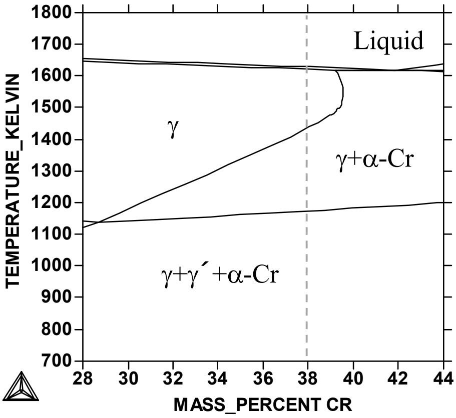


Figure 1 : Calculated phase diagram of Ni-xCr-3.8Al by thermo-calc software.

RESULTS AND DISUCCSION

Microstructure

Figure 1 shows the phase diagram calculated by the thermo-calc software. Ni-xCr-3.8Al alloy exhibit three phases: the γ phase, the γ´ phase and the α-Cr phase. The solidus temperatures of the γ´ phase and the α-Cr were approximately 1123 K and 1433 K, respectively. The solution treatment temperature is important to obtain the appropriate properties, especially, the ductility degrades in coarse γ grain. Figure 2 shows the microstructures taken by OM after various solution treatments above or below the solidus temperature of the α-Cr phase. The γ grain size depended strongly on the solution treatment condition above or below the solidus temperature of the α-Cr phase. In general, it is recommended that the solution treatment is conducted below the solidus temperature of the α-Cr phase to enhance the ductility [11]. Figure 3 shows the microstructures taken by OM and the lamellar morphology taken by STEM after the aging treatment. Although

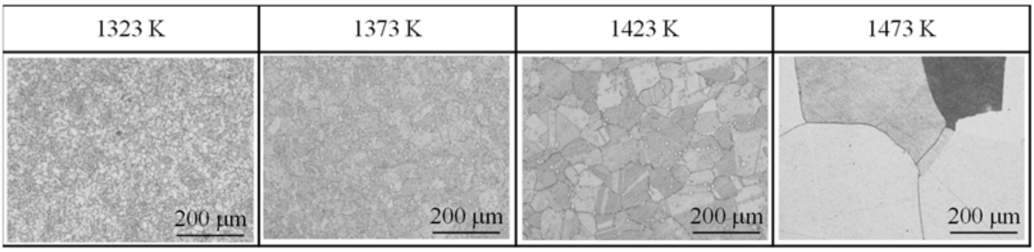
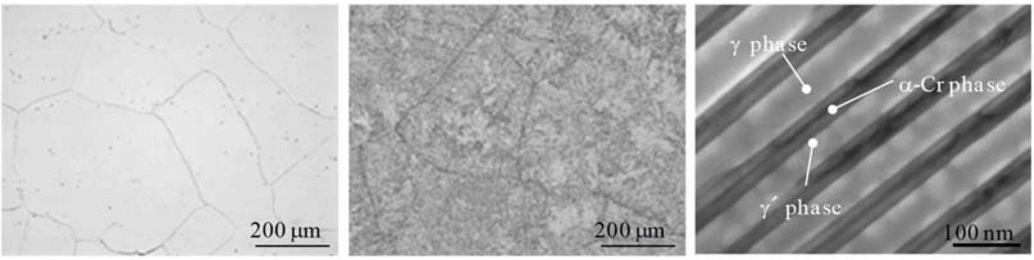


Figure 2 : Microstructure after various solution treatment for 1 h of Ni-38Cr-3.8Al obtained by optical microscopy.

the γ single phase was obtained after the solutionization, the lamellar structure covered all grains after aging. The interlamellar spacing between the α-Cr lamellae after the aging treatment was less than 100 nm.



(a) Solution treated (b) Fully lamellar structure (c) STEM image of lamellar structure

Figure 3 : Microstructures of (a) γ single phase by solution treatment at 1453 K for 1hr followed by water cooling and fully lamellar structure after aging treatment at 973 K for 16 hrs followed by air cooling by OM (b) and STEM (c).

Thermal stability of lamellar structure

Thermal stability of the lamellar structure is important characteristics to consider the application temperature limit. Figure 4 shows the SEM micrographs after long-term exposure. The initial aging treatment condition was at 973 K for 16 hrs. The lamellar structure exposed at 873 K was almost stable even after 1000 hrs. The collapse of lamellar structure was not significant even at 973 K, while a few spherical α-Cr precipitates are observed at the initial γ grain boundary and interface between the lamellar cells. In contrast, the lamellar structure exposed at 1073 K collapses even after 100 hrs. Moreover, the interlamellar spacing increases with increasing

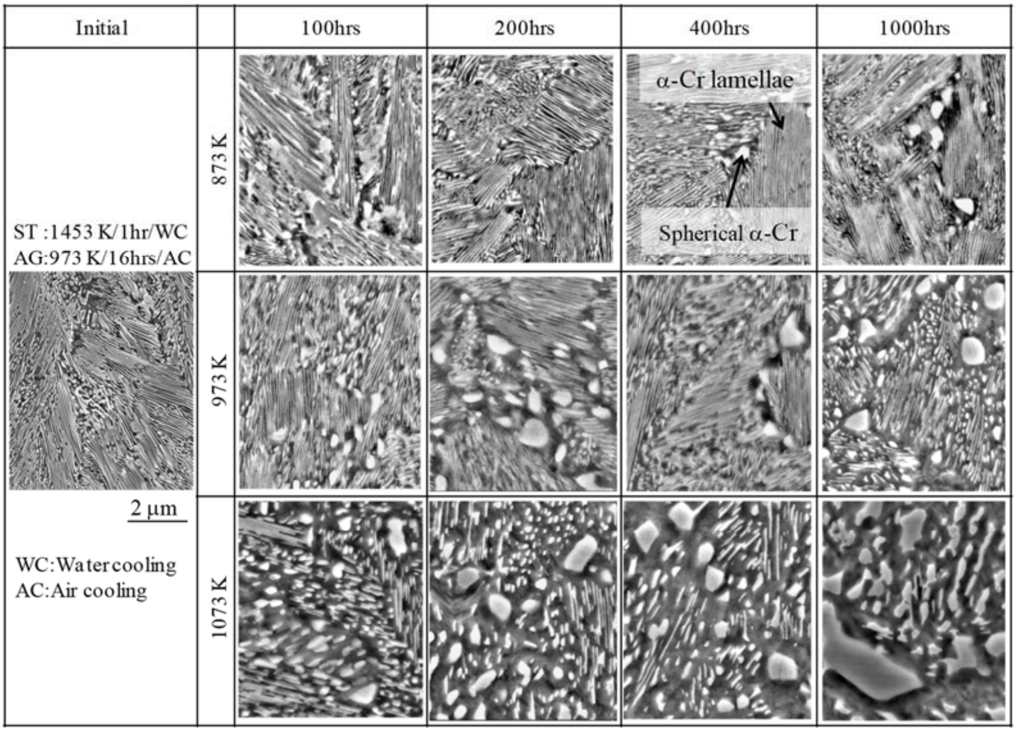
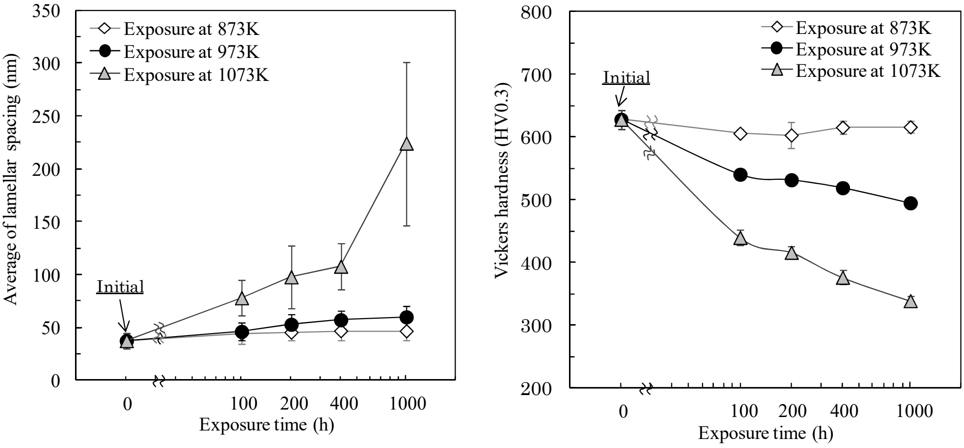


Figure 4 : SEM images of lamellar structures after long-term exposure at 873, 973 and 1073 K for 100, 200, 400 and 1000 hrs.

exposure time. Figure 5 shows (a) the interlamellar spacing and (b) the hardness after long-term exposure at 873, 973 and 1073 K. At and below 973 K, an increase of interlamellar spacing with exposure time was insignificant, while it increased dramatically at 1073 K. Also, the hardness decreased with increasing exposure time (i.e. interlamellar spacing). It was reported that the properties of Ni-38Cr-3.8Al is influenced by the lamellar structure [9, 11]. Therefore, this result indicates that the high temperature properties might be different between 873 K and 1073 K.



(a) Interlamellar spacing

(b) Hardness

Figure 5 : Influence of long-term exposure at 873, 973 and 1073 K on (a) interlamellar spacing and (b) hardness.

High temperature Hardness

Figure 6 shows the room temperature hardness after various aging treatments with different solution treatments. A maximum hardness of HRC60 was obtained, which is comparable to martensitic stainless steel, and the hardness decreased with increasing aging temperature. However, the hardness remains high, compared with conventional Ni-based superalloys, Alloy718 (Fe-53Ni-19Cr-3Mo-5Nb-0.9Ti) strengthened by precipitation of $\gamma' + \gamma''$ phases. Figure 7 shows the high temperature hardness after various aging treatments with solution treatment at 1373 K. The high temperature hardness was influenced by aging temperature as well as the hardness at room temperature up to 973 K. However, the hardness drastically decreased beyond 973 K and they become close in every aging treatment conditions. This is due to the

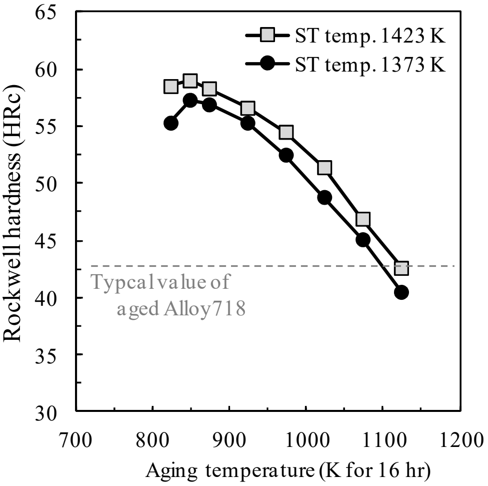


Figure 6 : Hardness after various aging treatment of Ni-38Cr-3.8Al at room temperature.

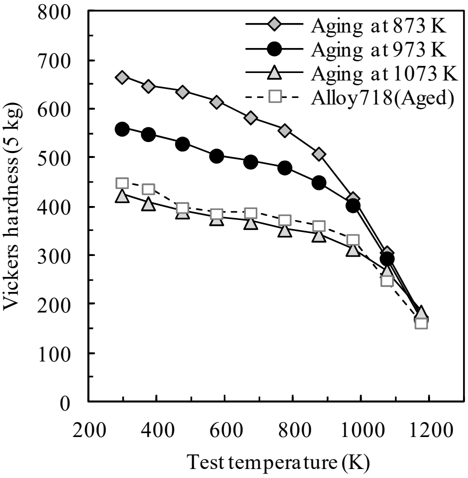


Figure 7 : Hardness after various aging treatment of Ni-38Cr-3.8Al at elevated temperature.

thermal stability of the lamellar structure, as shown in Fig. 4. In addition, the high temperature hardness of Ni-38Cr-3.8Al was remarkably higher than that of Alloy718 up to 973 K in some aging treatment conditions. However, it become close over 1073 K.

Tensile property at high temperatures

Figure 8 shows the 0.2% proof stress and the tensile strength of the specimens aged at 973 K for 16hrs and then pulled at elevated temperatures up to 1173 K. The 0.2% proof stress and the tensile strength of the specimens at room temperature were 1692 MPa and 1847 MPa, respectively. Basically, the strength decreased gradually up to 673 K, and then dropped significantly over 873 K. As the comparison to Alloy718, the strength of Ni-38Cr-3.8Al less than 673 K was higher than that of Alloy718. However, the decrease of strength of Ni-38Cr-3.8Al was significant, compared with Alloy718 at high temperature.

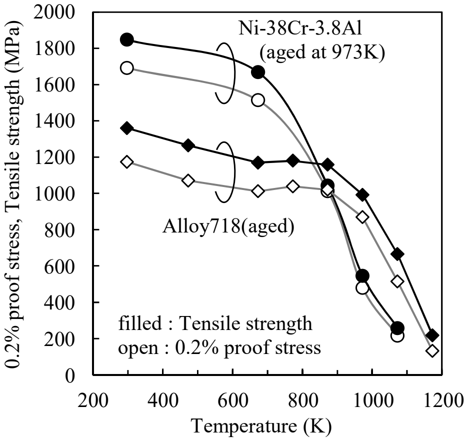


Figure 8 : 0.2% proof stress and tensile strength after aging treatment at 973 K for 16 hrs followed by air cooling at elevated temperature.

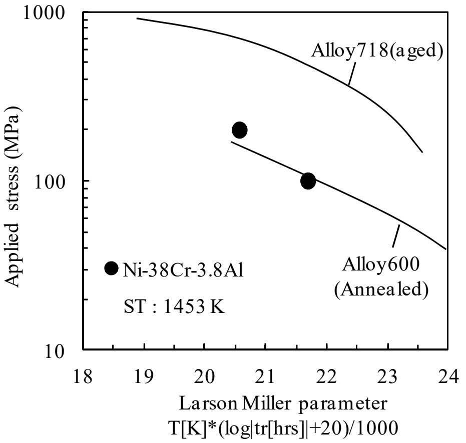
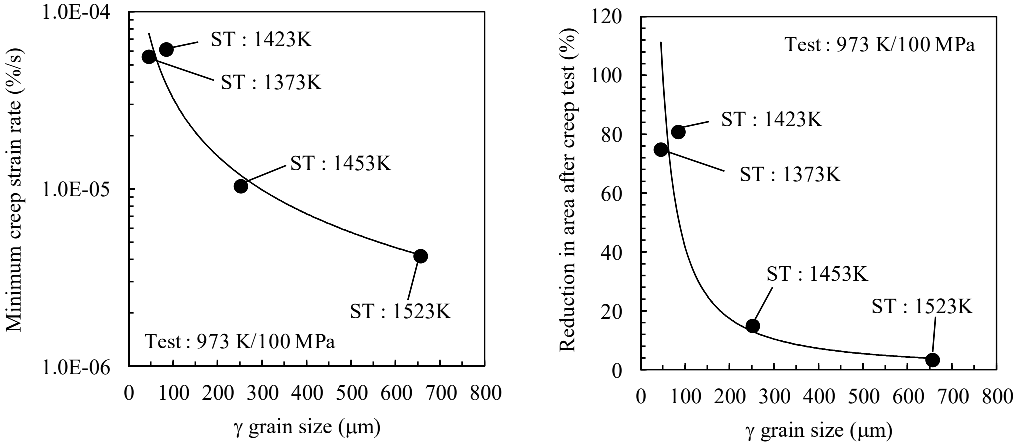


Figure 9 : Creep rupture property after aging treatment at 973 K for 16 hrs followed by air cooling.

Creep property

The creep property was evaluated at 973 K at a constant load of 100 and 200 MPa. Figure 9 shows the creep rupture properties in comparison with conventional Ni-base superalloys which



(a) Minimum creep strain rate

(b) Reduction in area

Figure 10 : Influence of g grain size on (a) minimum creep strain rate and (b) reduction in area after aging treatment at 973 K for 16 hrs followed by air cooling.

are Alloy718 and Alloy600 (Ni-16Cr-7Fe) strengthened by solid solution. The creep rupture property of Ni-38Cr-3.8Al was extremely lower than that of Alloy718 and it was similar to that of Alloy600 despite Ni-38Cr-3.8Al precipitates the γ' phase. This is associated with the thermal stability of the lamellar structure, as shown in Fig. 4. Moreover, it is well known that grain size influences creep strength. In general, the grain coarsening is effective in the improvement of creep property. However, the influence of γ grain size on creep strength in Ni-38Cr-3.8Al is unclear. Therefore, the effect of γ grain size on the creep property was investigated. Figure 10 shows the influence of the γ grain size on the minimum creep strain rate and the reduction in area after creep rupture. The γ grain size was controlled by the change of the solution treatment temperature. The minimum creep strain rate became slow with increasing γ grain size. The reduction in area dramatically increased with increasing γ grain size. These results indicate that the creep property of Ni-38Cr-3.8Al is influenced by γ grain size, similar to common materials. However, it must be considered the balance of properties because the ductility degrades in the case of coarse γ grains.

Hot corrosion resistance

Ni alloy containing high Cr concentration exhibits excellent hot corrosion resistance so that it has been used at severe hot corrosive components. Ni-38Cr-3.8Al contains high Cr concentration, therefore, it is expected to possess the excellent hot corrosion resistance. Figure 11 shows the results of V-attack hot corrosion test from 773 K to 1073 K for 691.2 ks (192 hrs). The V-attack hot corrosion resistance of Ni-38Cr-3.8Al was superior to conventional Ni-based superalloy, Alloy80A (Ni-20Cr-1.4Al-2.3Ti) which has been used for exhaust valve in marine engine up to 973 K. However, the advantage of Ni-38Cr-3.8Al disappeared around 1073 K. The mechanism of the improvement of hot corrosion resistance in Ni-38Cr-3.8Al is well described in our previous paper [10]. The lamellar structure is favorable for not only strengthening for the matrix, but also hot corrosion resistance.

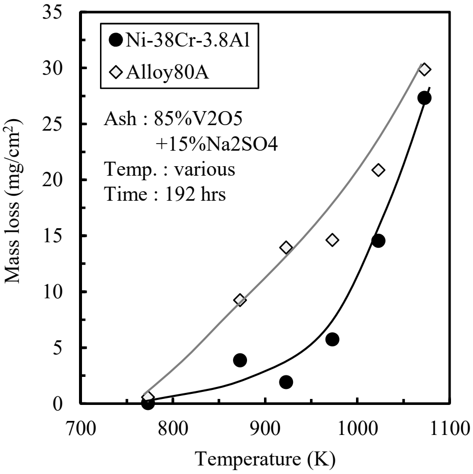


Figure 11 : Mass loss after V-attack hot corrosion test from 773 K to 1073 K for 691.2 ks (192 hrs).

CONCLUSIONS

In order to clarify the further possibility of Ni-38Cr-3.8Al as a heat resistant material, the high temperature properties were evaluated. The following conclusions were reached.

1) Thermal stability of the lamellar structure depended strongly on the temperature. In particular, the lamellar structure rapidly collapsed over 1073 K.
2) The hardness and the tensile properties dramatically changed from 873 K to 1073 K. This is because the lamellar structure begins to collapse around 973 K.
3) The hot corrosion resistance was superior to that conventional Ni-based superalloy. However, the advantage in hot corrosion resistance disappeared around 1073 K.
4) It is expected that Ni-38Cr-3.8Al is appropriate as a heat resistant material with excellent hot corrosion resistance rather than a heat resistant material with high strength at high temperatures.

REFERENCES

[1] C. Zener, "Kinetics of the decomposition of austenite", *Trans. AIME*, Vol. 167, (1946), pp. 550-595.

[2] J. W. Cahn, “The kinetics of cellular segregation reactions”, *Acta Metall.*, Vol. 7, No. 1, (1959), pp. 18-28.

[3] D. Turnbull, “Theory of cellular precipitation”, *Acta Metall.*, Vol. 3, No. 1, (1955), pp. 55-63.

[4] R. Kossowsky, “Cellular precipitation in Ni-51Cr lamellar eutectic and cast Ni-44Cr alloys”, *Metall. Trans.*, Vol. 1, No. 6, (1970), pp. 1623-1627.

[5] W. Gust et al. , “Discontinuous precipitation in Nickel-Rich Ni-Cr alloys”, *Mater. Sci. Eng.*, Vol. 39, (1979), pp. 15-25.

[6] I. Manna et al. , “Discontinuous reactions in solids”, *International Materials Reviews*, Vol. 46, No. 2, (2001), pp. 53-91.

[7] D. B. Williams et al., “Grain boundary discontinuous precipitation reactions”, *International Metals Reviews*, Vol. 3, (1981), pp. 153-183.

[8] S. Komatsu et al., “Microscopic observation of γ' and α-Cr duplex precipitation in 40Cr-4Al-Ni alloy”, *J. Japan Inst. Metals*, Vol. 40, No. 12, (1976), pp. 1208-1215.

[9] N. Takahata et al., “Influence of heat treatment on microstructure and hardness of Ni-Cr-Al alloy”, *Denki Seiko*, Vol. 75, No. 2, (2004), pp. 97-105.

[10] Y. Koyanagi et al., “Hot corrosion characteristics of cellular precipitating Ni-based alloy “DSA®760” with high hardness and high corrosion resistance”, *Denki Seiko*, Vol. 87, No. 2, (2016), pp. 65-73.

[11] S. Ueta, “Material properties of high hardness and high corrosion resistant Ni-based alloy “DSA760””, *Denki Seiko*, Vol. 83, No. 1, (2012), pp. 69-73.