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# Corrosion Behavior of Inconel 600 Ni-based Alloy

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**Abstract**

A study on the oxidation behavior of inconel 600 alloy was conducted at elevated temperature from 700°C to 1000°C for 1~12 hours. It was found that corrosion rate was increased with increasing temperature and time. In addition, weight was gained dramatically at 1100°C as well as above 6 hours. The results of EDS analysis of inconel 600 alloy heated at 1100°C for 12 hours confirmed that the oxide layer was composed of Cr and Fe oxide and that Cr oxide was formed first and Fe oxide was formed thereafter.

**Keywords:** Inconel, Oxidation, Corrosion, Oxide layer, Alloy

## INTRODUCTION

The inconel alloy is a heat-resistant Ni-based alloy containing 15% of chromium, 6~7% of iron, 2.5% of titanium, and 1% or less of aluminum, manganese and silicon. It has excellent heat resistance; does not oxidize even in an oxidation stream (oxidation stream) of 900°C or above; and is not immersed in an atmosphere containing sulfur. Its properties such as elongation, tensile strength and yield point do not change much to about 600°C, exhibiting its excellent mechanical properties. In addition, it is not corroded by organic matters and saline solutions.

Inconel 600 alloy is marked as UNS Alloy N06600 or Inconel 600 by US Inco International. UNS, the abbreviation of the Unified numbering system, is a nomenclature for the materials commonly used in North America and is compatible with many standards such as ASTM, ASME and ASW. UNS consists of a prefix designating the constituent material and five digits. UNS Alloy N represents nickel and nickel alloys, and the following five numbers do not include material specifications.[1-5)]

Inconel 600 among nickel alloys is a solid solution strengthened alloy composed of elements such as nickel, chromium, and iron. It has excellent heat resistance and corrosion resistance. In particular, it does not show chloride corrosion cracking phenomenon that appears in the stainless steel. This is because the addition of nickel makes it resistant to acidic, alkaline, organic and inorganic substances, and the chromium of Inconel 600 improves its resistance to sulfides and acidic substances in a corrosive environment. It also has mechanical properties and strength, facilitates cold/hot working, and is weldable, so it is widely applied in various industries. Especially, it has excellent heat resistance and plasticity at a high temperature up to 700°C, so it is used for the distiller and condenser for fatty acid treatment; the wall for the rolling heat furnace, the furnace material and tray in the heat treatment industry; and the abiotic acid processing equipment for making pulp for paper.[6-8)] Table 1 given below shows the composition and mechanical properties of commercially-available Inconel 600 Ni-based alloy.

**Table 1.** Chemical composition of Inconel 600 alloy.

| Element | Ni | Cr | Fe | C | Mn | Si | Cu | P | S |
|---|---|---|---|---|---|---|---|---|---|
| Content (wt. %) | 72 | 14~17 | 6~10 | 0.15 | 1 | 0.5 | 0.5 | 0.015 | 0.015 |

**Table 2.** Mechanical properties of Inconel 600 alloy.

| Tensile Strength(σb/MPa) | Yield Strength(σp0.2/Mpa) | Elongation(σ5/%) |
|---|---|---|
| 585 | 240 | 30 |

The metal, which is commonly used in our everyday life, is refined by applying a lot of energy to the material which is an ore in its natural state, so it is unstable from a thermodynamic point of view. Therefore, the metal has an instinct to return to a stable natural state through the process of corrosion. In this process, the corrosion, which is the process of making oxides by oxygen, is called oxidation. The oxidation of metal takes place in two phased: the diffusion of oxygen to the metal surface and the formation of an oxide layer. The rate of oxidation is governed by the transport properties of oxygen and metal constituent elements in the oxide layer. In the inconel, a stable Cr oxide film is formed at room temperature or at a high temperature of 700°C or lower to prevent the further metal oxidation, thereby maintaining its mechanical properties even at high temperatures. However, at a temperature of 700°C or higher, the molecular activity of Cr oxide increases due to heat, thereby failing to fulfill its role as a stable oxide. In addition, unstable oxidation progresses and a thick oxide layer is formed, thereby deteriorating the inherent mechanical properties. Inconel 600 alloy is mainly used in heat-resisting facilities such as ultra-high-temperature electric furnaces and ceramic baking furnaces. Therefore, it is essential to research the oxidation behavior and mechanical properties at high temperatures to evaluate its stability, and there are, in fact, many studies conducted on its oxidation behaviors at high temperature.

In this study, the high temperature oxidation behavior of Inconel 600 alloy, which is the most basic and commercially available alloy among the inconel alloys, was observed. More specifically, the changes in weight and oxide layer thickness were measured by varying the holding time at 1~10hrs in the temperature range of 700~ 1100°C in air atmosphere. The change of weight for the alloy that went though respective heat treatment conditions were measured using a microbalance, and the oxide layer thickness and oxide layer composition were analyzed using scanning electron microscopy (SEM) and energy dispersive spectrometry (EDS).

## MATERIALS

Inconel 600 nickel alloy plate was used in this study. The size of the plate, which was ordered for test, was following; width × length × length = 0.1 mm × 200 mm × 200 mm. The composition of Inconel 600 alloy was: Ni > 72%, Cr: 14-17%, Fe: 6-10%, Mn <1%, C, 0.15% and Density=8.42g/cm$^3$. To facilitate SEM/EDS analysis, the sample was cut to the size of 2×3 cm and its oxidation behavior was observed at high temperature. The equipment used to oxidize Inconel 600 alloy plate is an electric furnace and the equipment setup is shown in Figure 1 below.

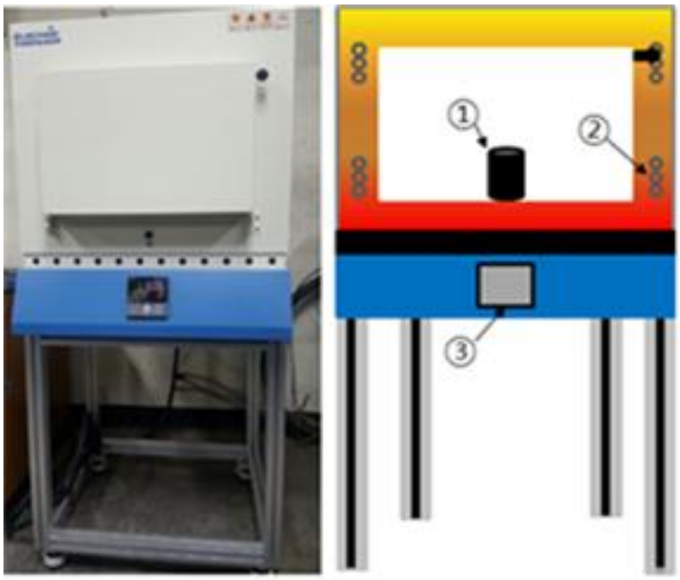


**Figure 1.** Schematic diagram of the electric furnace used in this study.

In the above Figure 1, the photo on the left is the electric furnace used in this study, and the figure on the right is the structure of the furnace. First, ① is an alumina crucible to contain Inconel 600 alloy. It is mainly composed of $Al_2O_3$ with a trace of $SiO_2$ or $Fe_2O_3$. The alumina crucible is stable at high temperature up to 1800°C and has the advantage of being a fine grained structure, which is less reactive to the sample. ② is the SiC heater, the heat source of the furnace. SiC is resistant to electricity to an extent that until the surface temperature of the hot zone reaches 1050±50 ℃, the resistance range is 600-1400 Ω mm$^2$/M. Therefore, when electricity flows from the equipment to the SiC heater, heat is generated by its resistance to electricity, so that the temperature can be raised to the temperature zone that satisfies the test conditions, and the SiC is stable up to 1500°C in air atmosphere.③ is the control unit of this equipment. The temperature can be adjusted from room temperature to 1100°C and its heating rate also can be adjusted.

Test was conducted at 700, 900, and 1100°C. The weight changes were measured after the holding time of 1 hour, 6 hours, and 12 hours in each temperature zone, and the weight change per unit volume was measured to determine the degree of oxidation. The oxide layer thickness and oxide layer composition were analyzed using SEM / EDS.

## RESULTS AND DISCUSSION

In this study, the weight change and surface oxide layer behavior of Inconel 600 were observed at high temperature. An alumina crucible having a diameter of 3 cm and a height of 5 cm was used. Since the Inconel 600 sample was heated in an alumina cubicle, it was necessary to cut the sample to the proper size of 2×3 mm. Table 1 below shows the weight changes of Inconel 600 alloy sample measured by varying holding time at each temperature, and Figure 2. graphs the weight changes of sample measured by varying holding time and temperature. It shows that the weight increases when the sample is kept at high temperature for a longer time. The results show that the oxidization of Inconel 600 ally proceeds much more, thereby forming a thick oxide film when it is maintained at a high temperature for a longer time.

**Table 3.** Weight increase of Inconel 600 ally according to temperature and holding time.
(Unit : milligram)

| | 1 hour | 6 hours | 12 hours |
|---|---|---|---|
| 700°C | 0.03 | 0.013 | 0.6 |
| 900°C | 0.12 | 0.08 | 0.7 |
| 1100°C | 0.72 | 1.73 | 1.73 |

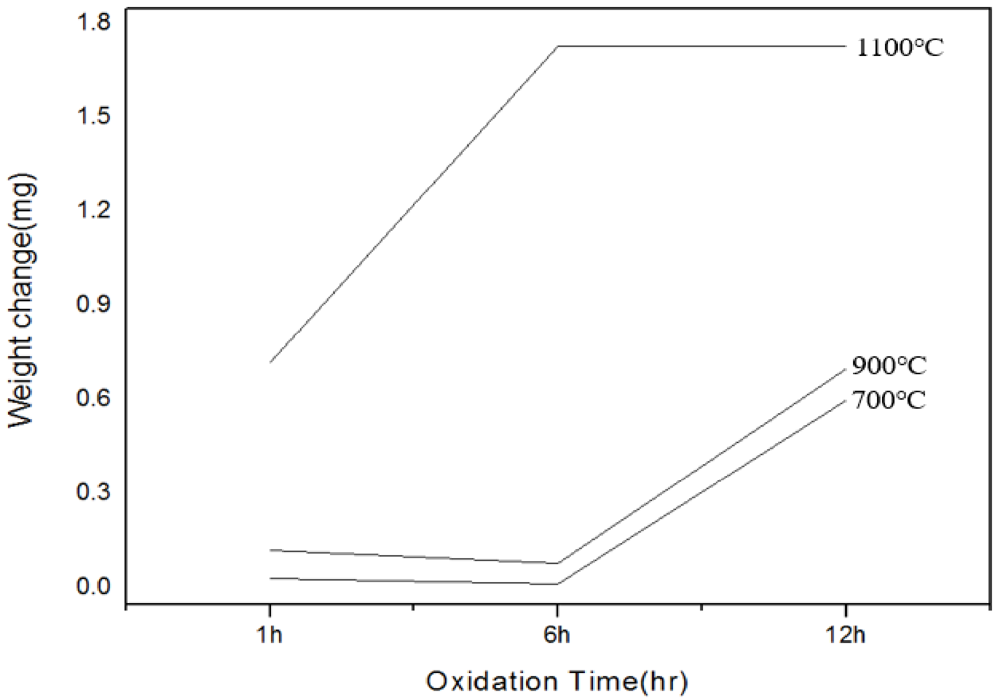


**Figure 2.** Weight increase of the specimen according to temperature and holding time.

As can be seen from the above results, Inconel 600 shows a very small weight increase even in a high temperature atmosphere. In particular, the weight increase is extremely small in an atmosphere below 900°C or lower. When the Inconel 600 sample is maintained at a temperature of 1100°C for a long time, it shows a comparatively large change in weight at 1~6 hours, but does not show a large weight change at a longer time. It seems that the thickening of oxide layer with time forms a layer that protects, the metal inside, thereby preventing the progress of the oxidation.

Figure 3. below shows SEM photograph of Inconel 600 Ni-based heated at 700~ 1100°C for 12hrs. As can be seen from the SEM photo, when Inconel 600 alloy is heated at each temperature for 12 hours, an oxide layer having a depth of about 2 to 3 μm is formed: about 2~3μm at 700°C, about 5μm at 900°C and about 10μm at 1100°C.

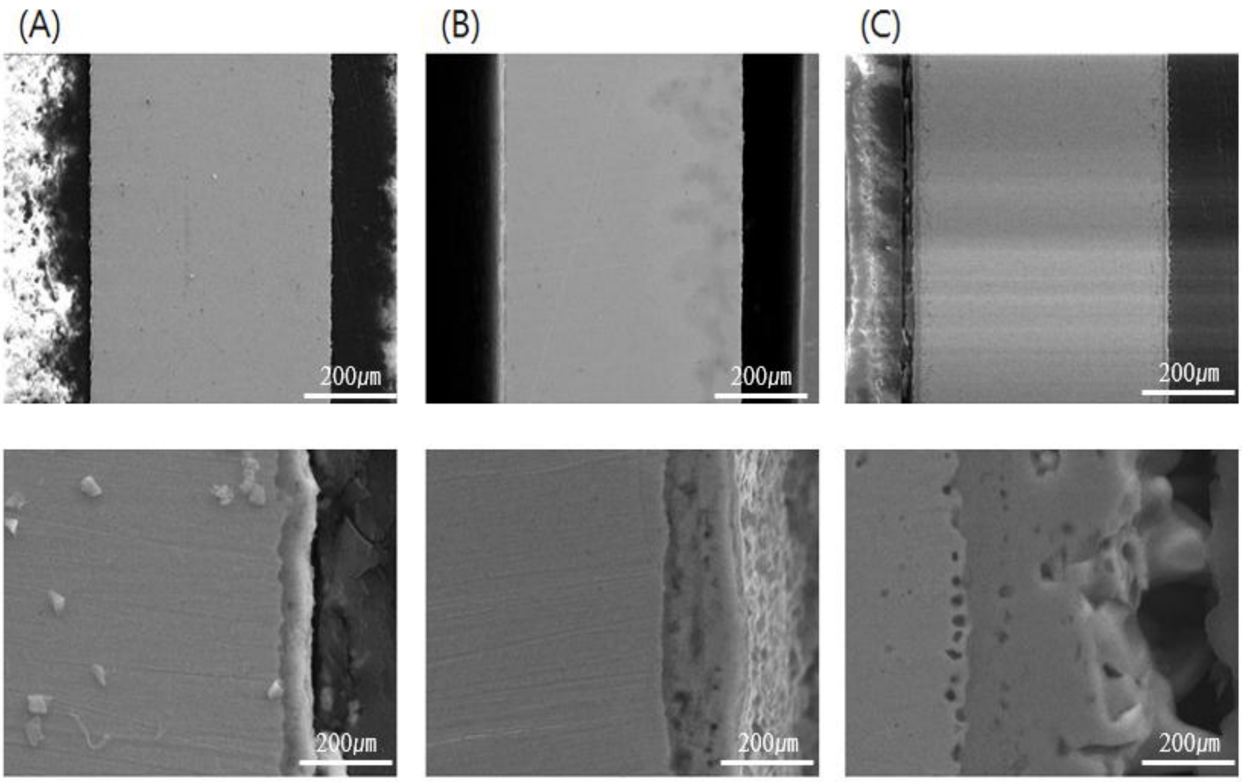


**Figure 3.** SEM picture of Inconel 600 nickel alloy heat treated for 12 hours.

(A)700°C (B)900°C (C)1100°C

Table 4 given below show the EDS analysis results of the oxide layer of Inconel 600 alloy heated at 700, 900, and 1100°C for 12 hours, and Figure 4 shows the results of line-profiling analysis conducted to determine the distribution of the components in the oxide layer.

**Table 4.** EDS analysis results of the oxide layer of Inconel 600 alloy heated at 700~1100°C for 12 hours.

| EDS Results | | | |
|---|---|---|---|
| Element | 700°C | 900°C | 1100°C |
| | wt.% | wt.% | wt.% |
| O | 25.8 | 19.72 | 25.03 |
| Cr | 69.22 | 32.31 | 15.85 |
| Fe | 0.88 | 2.64 | 51.54 |
| Ni | 4.09 | 45.31 | 7.56 |

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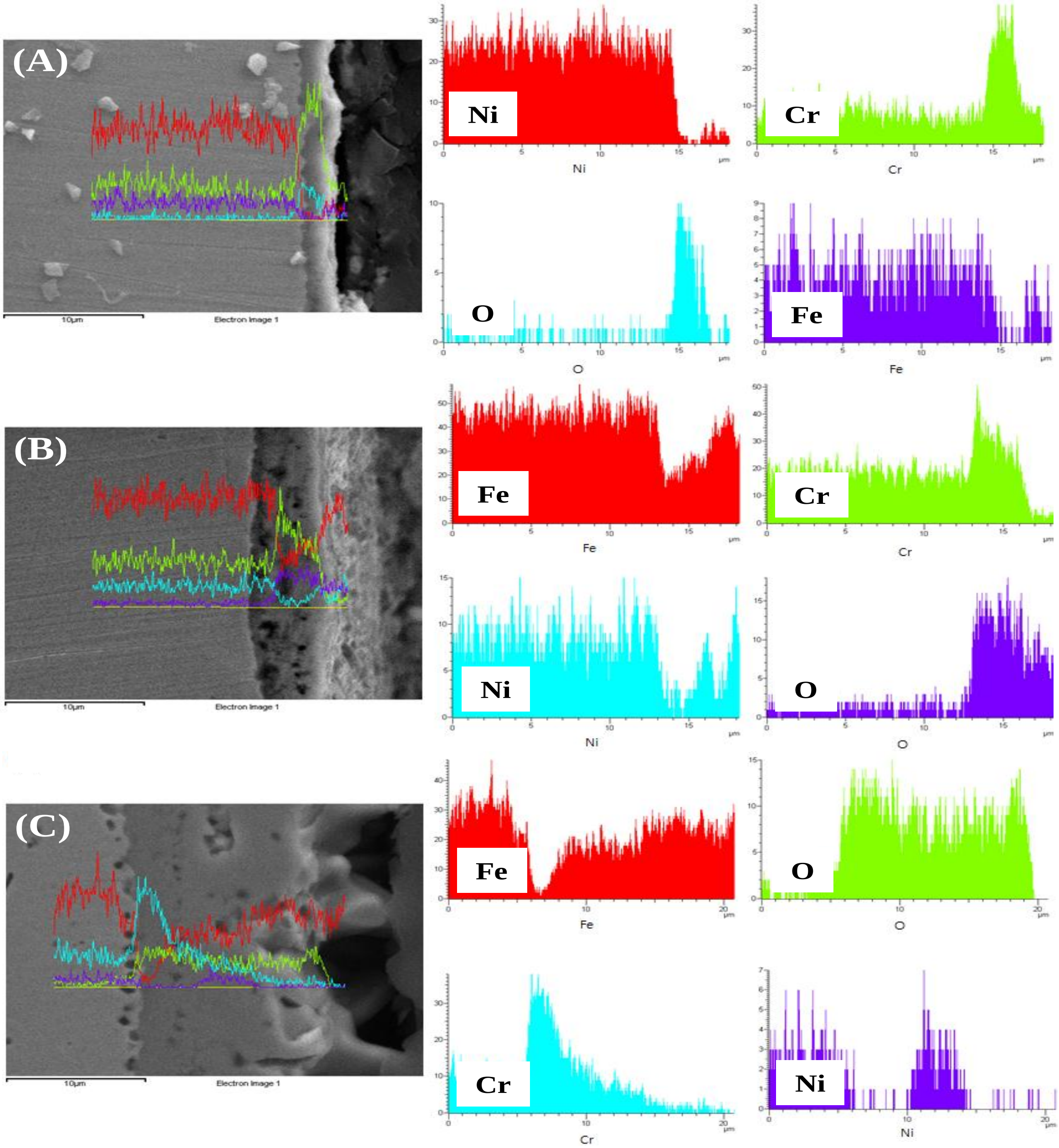


**Figure 4.** Line-profiling analysis results of Inconel 600 Ni-based alloy heated at 700, 900, and 1100℃ for 12 hours. (A) 700°C (B) 900°C (C) 1100°C

In the Inconel 600 Ni-based alloy heated at 700°C for 12 hours, the oxide layer is mostly composed of Cr oxides with a trace of Fe and nickel. Therefore, it can be confirmed that the inconel alloy forms a stable chromium oxide film at a temperature of 700°C to protect the base metal. Compared with at 700°C, the content of Cr decreases and the content of Ni and Fe increases at 900 ℃. From the line-profiling results, it can be seen that the Cr content is predominant at the boundary between the base metal to, whereas the content of Fe and Ni increases to the outward direction. In Inconel 600 alloy heated at 1100 ℃ for 12h, the oxide layer is composed mostly of Fe oxide and a trace of Cr oxide. The results of analyzing the distribution of oxide layer components show that Cr content sharply increases at the boundary between the base metal and the oxide layer to form an oxide layer; whereas Fe content is very high in the base metal, but decreases sharply at the boundary between the base metal and the oxide layer, and then increases gradually thereafter. Based on these results, it can be deduced that Cr oxide is generated first to protect the base metal when Inconel 600 nickel alloy is oxidized at a high temperature, whereas Fe is deposited under the extreme oxidation conditions at a certain temperature or higher. In contrast, Ni content irregularly changes. These results indicate that nickel itself has excellent corrosion resistance, and Ni itself is not significantly affected in oxidation atmosphere because Cr and Fe oxide are formed first.

## CONCLUSION

In this study, to analyze the high-temperature oxidation behavior of Inconel 600 alloy, heat treatment was carried out at 700, 900, and 1100°C for 1~12 hours.

1. Inconel 600 nickel alloy showed almost no weight change in air atmosphere under the conditions of 900°C or lower for 6h or less.
2. At 1100°C, the weight change was relatively large up to 6hrs, but there was no significant weight change after the heat treatment of 6 hours or longer.
3. EDS analysis results of Inconel 600 alloy heated at 1100°C for 12 hours confirmed that the oxide layer was composed of Cr and Fe oxide and that Cr oxide was formed first and Fe oxide was formed thereafter.

## ACKNOWLEDGMENT

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