

Development of Heat-resistant Nickel-based Super Alloy for Exhaust Valve

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ABSTRACT

A heat-resistant super alloy, NCF5015, which has lower nickel content than a conventional high nickel heat-resistant alloy, was developed for use in a highly heat-resistant valve. This alloy has reliable high-temperature strength, abrasion resistance, and phase stability after long-term heating.

These characteristics were obtained by increasing the amount of gamma-prime phase that contributes to precipitation-hardening and the amounts of molybdenum and tungsten that contributes to solid-solution within the range that hot formability is not impaired in order to recover strength by reducing nickel.

1. Introduction

In general, high-manganese heat-resistant steel 21-4N (SUH35) has been widely used for the exhaust valves of 4-wheel vehicles. However, this material does not have adequate strength and hardness at high temperatures, so in high performance engines, hard-facing is used on the valve seat face as necessary. Since 1979, all of the exhaust valves of Honda's 4-wheel vehicles have been made of nickel-based heat-resistant alloy without hard-facing, from the viewpoints of cost reduction and process simplification.

The reasons for using nickel-based heat-resistant alloy for the exhaust valves of 4-wheel vehicles are as follows.

- (1) It eliminates the necessity of hard-facing the valve seat face.
- (2) It has reliable high-temperature strength, and enables the valve stem to be made thinner.
- (3) It has reliable oxidation resistance.

In particular, because of the demand to reduce the cost of the valves, NCF3015 (30Ni-15Cr) has been used in mass-produced vehicles, and high-nickel heat-resistant alloy NCF440 (70Ni-19Cr) has been used in high performance engines. In recent years, lean burning is being adopted to meet the increasingly severe exhaust gas regulations and realize enhanced fuel economy, resulting

in increasingly high exhaust temperatures. Thus, in mass-produced vehicles as well, the needs for exhaust valves that have high-temperature strength are increasing. On the other hand, the requirement for cost reduction remains large. Consequently, a new nickel-based heat-resistant alloy NCF5015 was developed. This new alloy, based on current high-nickel heat-resistant alloy NCF440, contains less nickel in order to reduce cost, and also has the same high-temperature strength and abrasion resistance characteristics.

2. Development Goals

In the development of a high-strength, low-nickel valve, each characteristic was made the same as that of the high-nickel heat-resistant alloy. Also, regarding the following six development goals, the material was set identical to the current material.

- (1) Hardness at normal temperatures
- (2) High-temperature hardness at 800°C
- (3) High-temperature fatigue strength at 800°C
- (4) Value of impact energy after heating to 800°C for 400 hours
- (5) Oxidation resistance
- (6) Forgeability

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Table 1 Nominal chemical composition

Material	Composition (mass %)												Theoretical amount (atomic %)
	C	Si	Mn	Ni	Cr	Fe	Mo	W	Ti	Al	Nb	Others	γ' Ni ₃ (Al, Ti, Nb)
NCF5015-D	0.05	0.1	0.1	50	15	26	1.0	1.5	2.5	1.4	1.3	0.004 B 0.003 Mg	26.7
NCF5015-H	0.03	0.1	0.1	55	16	20	3.7	—	2.1	1.8	1.2	0.004 B 0.004 Mg	27
NCF440	0.05	0.1	0.1	70	19	3	1.0	1.5	2.5	1.4	1.3	0.004 B 0.003 Mg	26.9
Inconel751	0.05	0.1	0.1	72	16	7	—	—	2.3	1.2	1.0		23.4
NCF3015	0.03	0.1	0.1	32	16	47	—	—	2.7	1.2	0.8	0.004 B	23.6

NCF5015-D (Developed material with Daido Steel Co., Ltd.)

NCF5015-H (Developed material with Hitachi Metal, Ltd.)

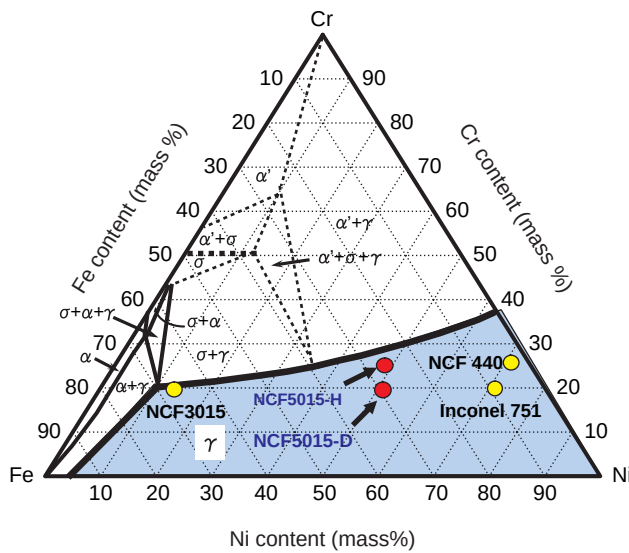


Fig. 4 Phase diagrams of matrix after heat treatment at 800 °C

reliable high-temperature strength and oxidation resistance and can also maintain high strength when used over a long period, was carried out. Table 1 shows the component set values of the developed materials containing reduced nickel. From Fig. 4, it can be seen that both developed materials belong to the structurally stable austenite zone.

4. Phase Stability

4.1. Impact Value

The impact value is a characteristic value that indicates the toughness of the valve stem. When structure is unstable, impact characteristics may fall after prolonged use at high temperatures, leading to valve breakage. Figure 5 shows the impact value after the valve was heated to 800°C for 400 hours. The impact values obtained for the developed materials were superior to the

impact values of the target high-nickel heat-resistant alloy NCF440 and Inconel751.

4.2. Structure

Figure 6 shows photograph of the structure after solution heat treatment, aging treatment, and over-aging of the developed material at 800°C for 400 hrs. From this structure photograph, it was found that after over-aging at 800°C for 400 hrs there was no trace of the harmful

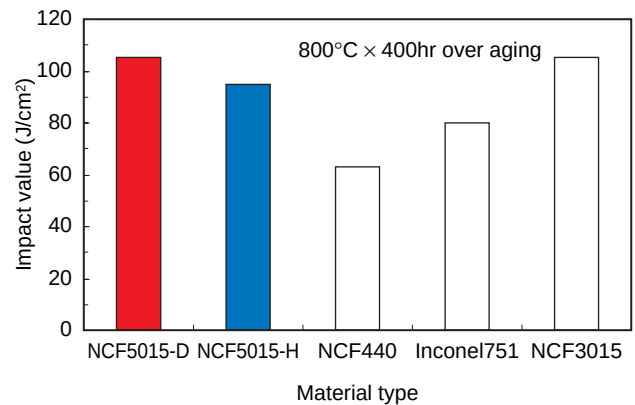
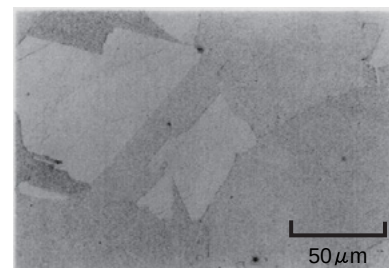
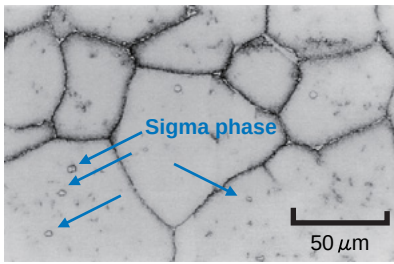


Fig. 5 Impact value of each material type



NCF5015-H after solution heat treatment, aging treatment, and over-aging at 800 °C x 400 hr

Fig. 6 Microstructure of developed materials



Trial material after solution heat treatment, aging treatment, and over-aging at 800 °C × 400 hr

Fig. 7 Microstructure of sigma phase

sigma phase sludge, shown in the example of Fig. 7, which reduces strength.

5. Material Characteristics

5.1. High-temperature Hardness

The high-temperature hardness is an important characteristic value that indicates the abrasion resistance of the valve seat face. Figure 8 shows the hardness of NCF5015 at room temperature and at high temperature. At a high temperature of 800°C, the developed materials had the same degree of hardness as the hardness of the target high-nickel heat-resistance alloy NCF440. In particular, the high-temperature hardness at 600°C or higher, which is the temperature zone of the valve face, was of the same level as that of NCF440 (70Ni-19Cr), and was higher than that of Inconel751 (72Ni-16Cr). Consequently, it can be said that the developed materials

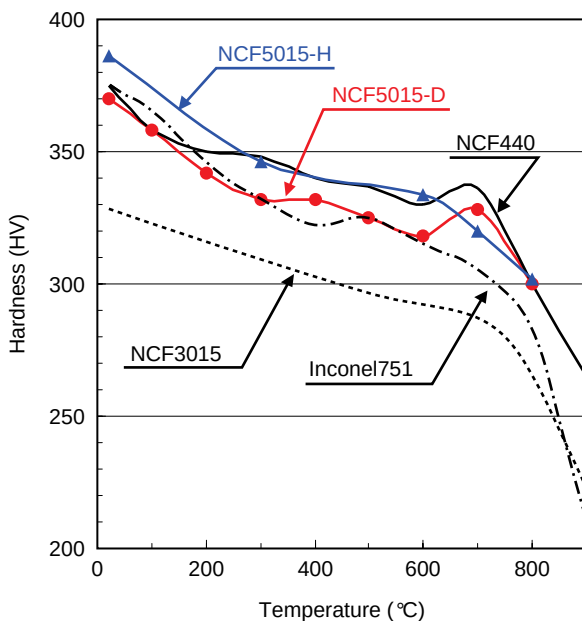


Fig. 8 Hardness at elevated temperature

have the same order of abrasion resistance as that of high-nickel heat-resistant alloy.

5.2. Tensile Strength

The tensile strength is a characteristic value that determines the strength of the valve stem. The valve stem temperature reaches a temperature of at least 800°C, and when the valve is seating, a tensile stress is generated together with a bending stress. In the case of a high output high-speed engine, an excessively large stress is generated during over-revving⁽²⁾. Figure 9 shows the tensile characteristics of the developed materials at room temperature and at high temperature. The tensile strength of the developed materials is the same level as that of the high-nickel heat-resistance alloy NCF440 (70Ni-19Cr), and is higher than that of Inconel751 (72Ni-16Cr) at temperatures of 500°C and higher.

5.3. Fatigue Strength

The high-temperature fatigue strength is an important characteristic value that indicates the fatigue strength of

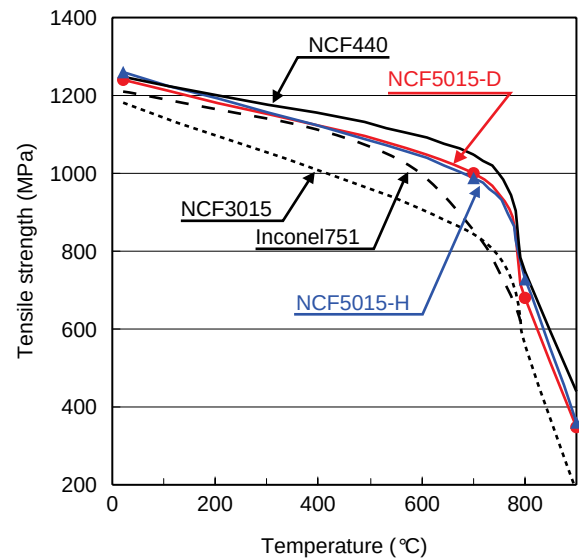


Fig. 9 Tensile properties at elevated temperature

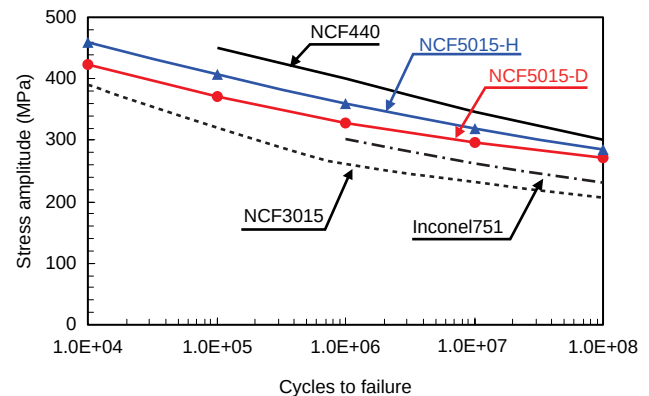


Fig. 10 Fatigue strength at 800 °C

the valve stem. Figure 10 shows the results of the rotary bending fatigue test at 800°C. The developed materials had a fatigue strength of roughly the same as that of the target high-nickel heat-resistant alloy NCF440 at 800°C.

5.4. Oxidation Resistance

The exhaust valves are used under the valve seat contact conditions, and are used under a thermo cycle accompanying a high-temperature oxidation environment and engine acceleration and deceleration load change. Oxidation of the valve generates abrasive scale, which increases abrasion and sometimes causes leakage from the valve face. Figure 11 shows the increase by oxidation after the valve is heated at 850°C for 400 hrs. The developed materials have the same oxidation resistance as that of high-nickel heat-resistant alloy NCF440 (70Ni-19Cr), and have reliable oxidation resistance to Inconel751 (72Ni-16Cr). It is thought that the addition of aluminum caused the Al_2O_3 oxide film to function even more efficiently with respect to Inconel751.

5.5. Physical Characteristics

Among the various physical characteristics, the coefficient of thermal expansion affects the elongation, that is, the tappet clearance, the thermal conductivity affects the heat reducing ability of the valve, and the specific gravity affects the weight of the valve. In general, the coefficient of thermal expansion should be small, to reduce thermal stress and minimize the effect on the tappet clearance; the thermal conductivity should be large, to enhance the heat reducing ability; and the specific gravity should be small from the viewpoint of lightness⁽³⁾. Figure 12 shows the coefficient of thermal expansion, Fig. 13 the thermal conductivity, and Table 2 the specific gravity. The coefficient of thermal expansion and the thermal conductivity of the developed materials exhibit the same characteristics as those of high-nickel heat-resistant alloy, and the specific gravity has become smaller due to the reduction of the amount of nickel.

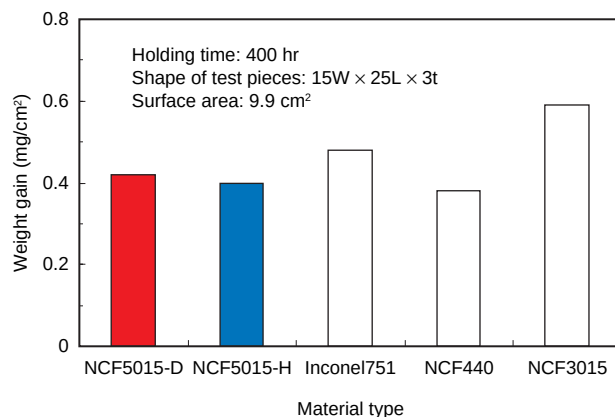


Fig. 11 Oxidation resistance at 850 °C

Table 2 Specific gravity

g/cm ³				
NCF5015-D	NCF5015-H	NCF440	Inconel751	NCF3015
8.09	8.17	8.24	8.25	7.90

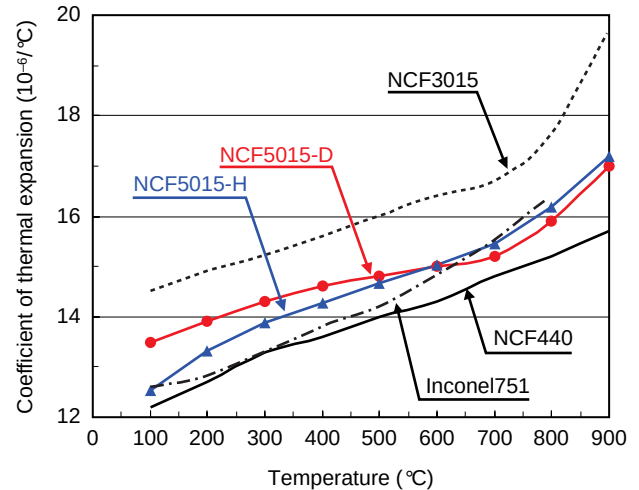


Fig. 12 Coefficient of thermal expansion

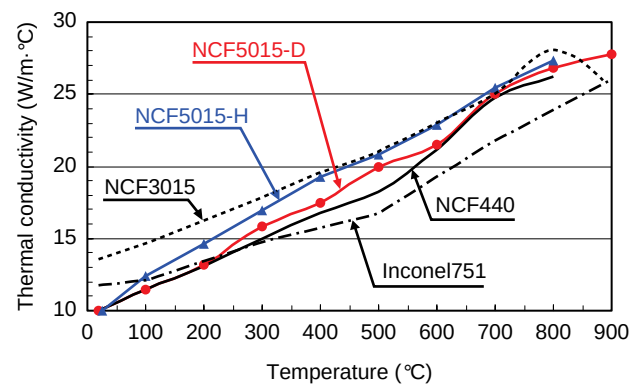


Fig. 13 Thermal conductivity

6. Part Unit Characteristics

6.1. Hot Formability

Hot formability is used to evaluate the forming ability of the valve. Figure 14 shows the results of performing a hot high-speed tension test using a Grebl examination machine. In general, the temperature region in which a contraction of area of at least 50% can be obtained in the Grebl test is the formable range. The temperature range over which the contraction of area of the developed materials is at least 50% has a temperature of at least 250°C, and has the hot formability of the current material.

6.2. Part Unit Characteristics

Figure 15 shows the results of the valve sliding examination. The developed materials have the same

frictional resistance as that of the high-nickel heat-resistant alloy NCF440. The abrasion is no more than one half that of the current mass production material NCF3015.

6.3. Durability in an Actual Vehicle

Figure 16 shows the amount of valve face abrasion after 100 hrs of operation at 7100 rpm in a 2.4-liter engine that runs on unleaded gasoline. The developed material has the same abrasion resistance in an actual vehicle as that of the high-nickel heat-resistant alloy NCF440.

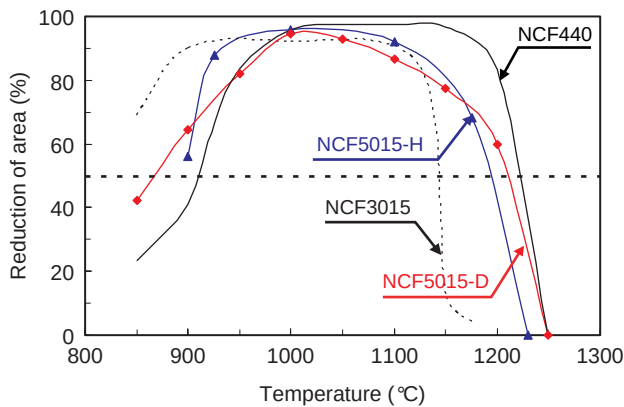


Fig. 14 Hot forgeability

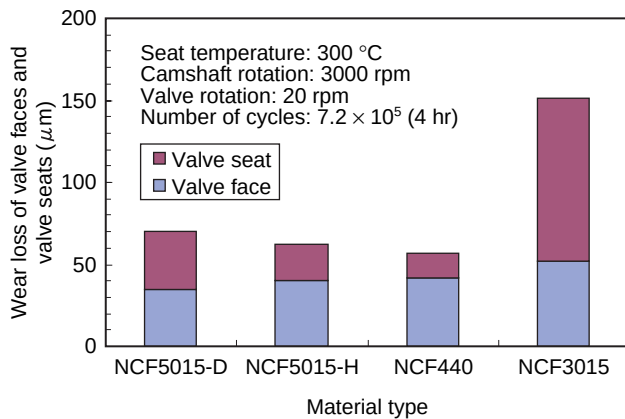


Fig. 15 Valve sliding examination

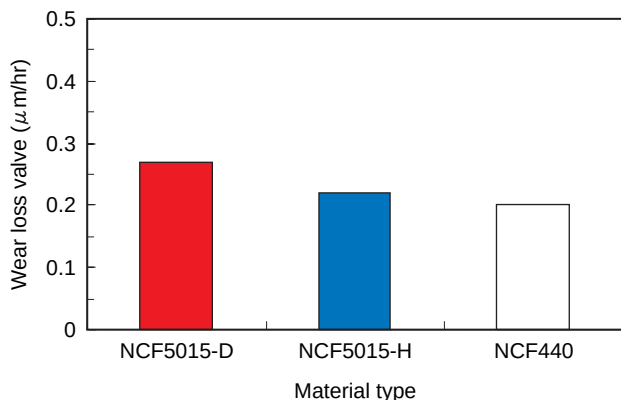


Fig. 16 Wear loss of exhaust valve faces

7. Conclusion

The characteristics called for exhaust valve materials in recent years were reexamined, and a resource-saving low-cost NCF5015 material was developed. A summary of the characteristics of the developed material is set out below.

- (1) The material is a nickel-based high heat-resistant alloy that does not require hard-facing and has phase stability, even after it is heated for a long period.
- (2) The abrasion resistance and fatigue resistance at high temperatures are the same as those of the high-nickel heat-resistant alloy.
- (3) The features of the material are that the amount of gamma-prime phase generated in the range where the hot formability is not allowed to fall is increased, while low-nickel is realized, as well as molybdenum and tungsten, which are elements for strengthening of solid solution, are optimally added.
- (4) As a result of the application of this alloy, a cost reduction of approximately 16% was realized compared to the use of the conventional high-nickel heat-resistant alloy. Mass production of the newly developed material started from the 2008 model year ACCORD.

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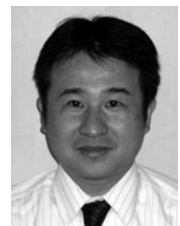
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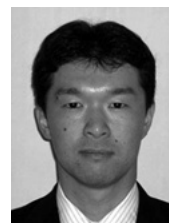
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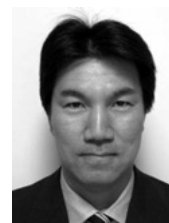
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