Alloy Design and Innovative Manufacturing Technology of High-Strength Ni-base Wrought Alloy for Efficiency Improvement in Thermal Power Plants

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Mitsubishi Hitachi Power Systems, Ltd. (MHPS) has established an alloy design method capable of reducing the time and cost required to develop Ni-base superalloys used in thermal power plants, as well as mitigating the risks resulting from the trial manufacturing of large items. By using this method, we have developed a highly-manufacturable material available for 800°C-class steam turbines, and large Ni-base disk material used for gas turbines. An examination of their applicability to actual equipment is now under way. By controlling their metallographic structure, we have also developed a manufacturing process to dramatically improve the manufacturability of high-strength superalloys. Based on this process, the applicability of high-strength wrought alloy for aircraft engines to thermal power plants is presently under examination.

1. Introduction

Thermal power plants are always required to raise the operating temperature in order to improve efficiency. MHPS has developed heat-resistant materials used for the high-temperature component of thermal power plants, thereby contributing to the improvement of efficiency. Ni-base wrought superalloys have excellent high-temperature strength and toughness, but are poor in manufacturability (specifically in terms of casting, forging and machining). These materials are widely used in aircraft engine components, but are not easily applied to thermal power plants with large components. MHPS has established an alloy design method that allows the mechanical properties and manufacturability to be predicted through computer simulation, as well as laboratory-scale experiment, and has developed Ni-base wrought alloys that can be applied to steam turbine rotors and gas turbine disks. We have also developed a manufacturing process that dramatically improves the workability of high-strength Ni-base alloys, which are not easily applied to aircraft engines from the perspective of workability. This report introduces the aforementioned development technology and developed materials.

2. Establishment of alloy design method that makes both strength characteristics and manufacturability compatible

2.1 Alloy design based on phase diagram calculation

Ni-base alloys have acquired high strength by γ' phase precipitation. The γ' phase has the L12 structure, which is the ordered FCC (face-centered cubic) lattice structure, and precipitates with a coherent interface in the matrix γ phase (FCC structure). The strength of Ni-base alloys is governed by the amount and morphology of γ' precipitates. The amounts of γ' and other phases can be predicted, using a CALPHAD (calculation phase diagram) approach (Thermo-Calc, etc.). **Figure 1** exemplifies the results of calculations using Thermo-Calc and Ni-Data[(1)], proving that the strength can be inferred from the amount of γ' phase at operating temperature. Since the γ' phase improves the strength, but if allowed to precipitate during forging, reduces ductility to cause cracks

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and other defects, it is possible to determine the hot-forging temperature from the solvus temperature of the γ' phase. Furthermore, if σ and other harmful phases appear, this reduces long-term creep strength and toughness, the solvus temperature of these phases can be an indicator of long-term reliability. But the conventional calculated phase diagram could not predict the macro segregation (gravity segregation), raising a problem when a large ingot is manufactured. Ni-base alloys are prone to macro segregation since they contain many elements different from Ni in specific gravity, becoming a bottleneck to the manufacture of large items.

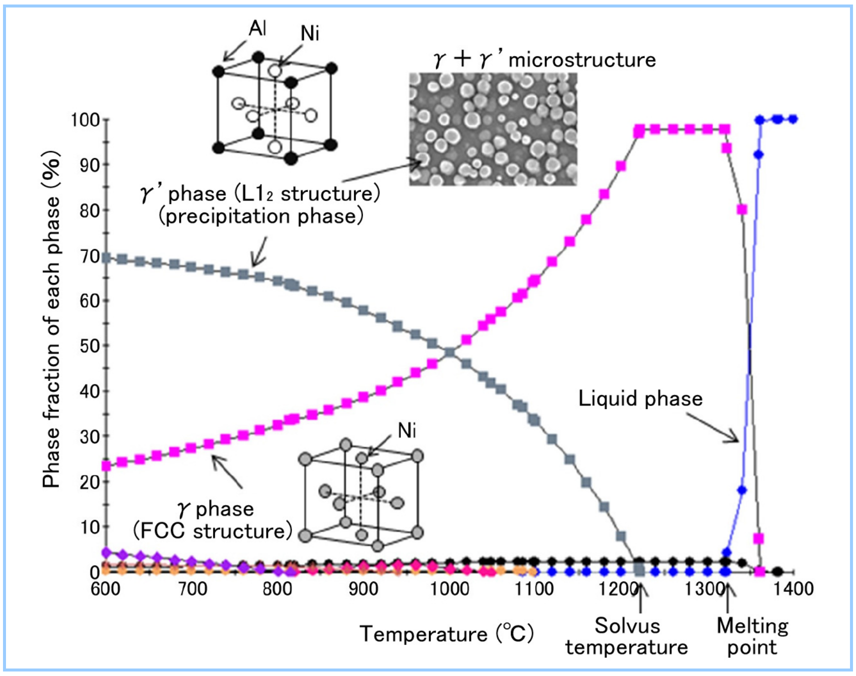

Figure 1 Example of Ni-base alloy phase equilibrium calculation results

Figure 2 is a schematic illustration of the solidification test piece and a solid-liquid interface during the solidification. As solidification advances, solute elements concentrate within molten alloy dependent upon the solid-liquid equilibrium, causing a density difference ($\Delta\rho = \rho_0 - \rho$) within molten alloy. It has been construed that, with this density difference as the driving force, molten alloy starts flowing to cause segregation(2). The density of molten alloy can be calculated from composition and temperature, while the density of the enriched molten phase near the solid-liquid interface can be estimated by considering the distribution behavior of each solute element. The calculation of density also takes into consideration the decrease in temperature until a solid phase is formed and the liquid phase ceases to flow. This computational approach has enabled the determination of a candidate composition that has both large ingot manufacturability and high-temperature strength.

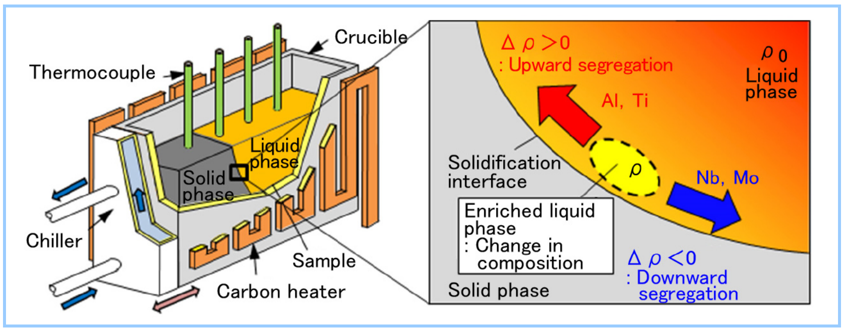

Figure 2 Large ingot-simulator and segregation mechanism

2.2 Evaluation using large ingot-simulator

To evaluate the validity of the calculations, we developed the large-ingot simulator to reproduce solidification conditions equivalent to those of the commercial melting furnace. After candidate compositions were narrowed down through the calculation, some test pieces with solidification conditions that simulate those of an ingot exceeding 10 tons was made of roughly

10-kg of material to investigate whether segregation occurs, thereby enabling the manufacturability of a large ingot to be assessed. If temperatures and working histories similar to those of large forging are applied to this test piece, large forging-simulated characteristic evaluation is applicable. This narrowing down of compositions through a computer aided alloy design method and laboratory-scale test simulating large items have enabled the mitigation of risks resulting from the trial manufacturing of large items, as well as the contraction of the development period.

In the following sections, alloys developed for several applications based on the present alloy design method are explained.

3. 800°C-class steam turbine materials with good manufacturability

3.1 Alloy design achieving both high-temperature strength and hot forgeability

The steam temperature in coal-fired thermal power plants exceeds 600°C and is approaching the operating temperature limit of the heat-resistant ferritic steel used thus far. This is why efforts are under way toward A-USC (advanced ultra-super critical) for raising steam temperatures to 700°C using Ni-base alloys with higher strength than heat-resistant ferritic steels. Although Alloy 617 and Alloy 263 are candidate materials for 700°C-class A-USC, high-strength materials available at higher temperatures are expected to not only further efficiency improvement, but save material costs by reducing the thickness of components.

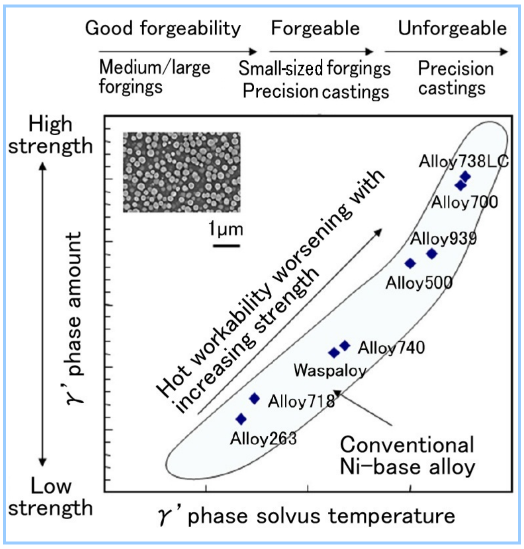

Figure 3 Correlation between solvus temperature and γ' phase amount at 700°C

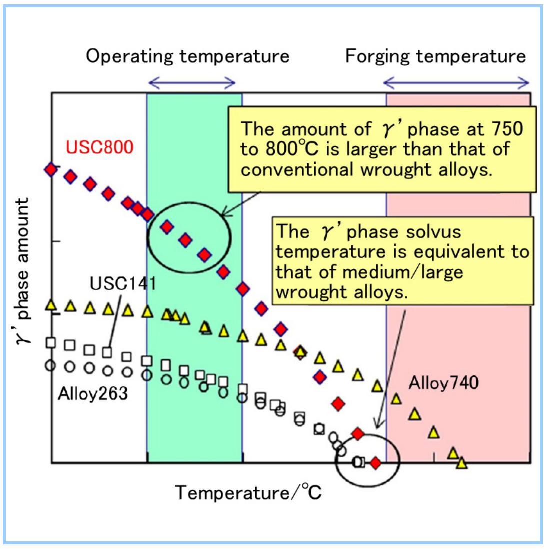

Figure 4 Temperature dependence of γ' phase amount

For higher strength, an increase in the amount of γ' phase precipitation is effective as noted above, but the solvus temperature of the γ' phase rises to worsen forgeability, since the γ' phase remains stable even at forging temperatures (**Figure 3**). The authors analyzed the influence of alloy elements on γ' phase stability using calculated phase diagrams, and found that by stabilizing the γ' phase only with Al instead of adding the Nb, Ta, and Ti that are added to conventional Ni-base alloys as γ'-formers, the amount of γ' phase precipitates can be increased at the operating temperature, even while keeping the solvus temperature low. Based on this finding, the prototype composition of a new Ni-base alloy (USC800) was determined. **Figure 4** shows the amount of γ' phase in various alloys calculated as a function of temperature. USC800 is expected to have both excellent forgeability and high-temperature strength, since the γ' phase solvus temperature of USC800 is equivalent to that of Alloy 263 widely used as a wrought superalloy, and the amount of γ' phase precipitates at operating temperature is at least twice as large.

3.2 Alloy design to improve the manufacturability of large ingots

Figure 5 shows the molten alloy density difference (Δρ) of the USC800 composition, using the method described in the preceding section. In the case of prototype composition, since Δρ is large in the positive direction, it was judged that upward segregation defects would occur during the solidification of a large ingot. As a result of examination, it was found that the Δρ can be minimized by adjusting the amounts of upward segregation-promotive W and downward segregation-promotive Mo content. The final USC800 composition was determined to optimize the W/Mo ratio to suppress the occurrence of macro segregation without changing the γ' phase precipitates at the operating temperature and the solvus temperature, thereby achieving the manufacturability and forgeability of a large ingot and high-temperature strength at the same time. As shown in Figure 5, evaluation using a large ingot-simulator revealed that the prototype composition caused some upward segregation defects, while the final composition caused no such defects.

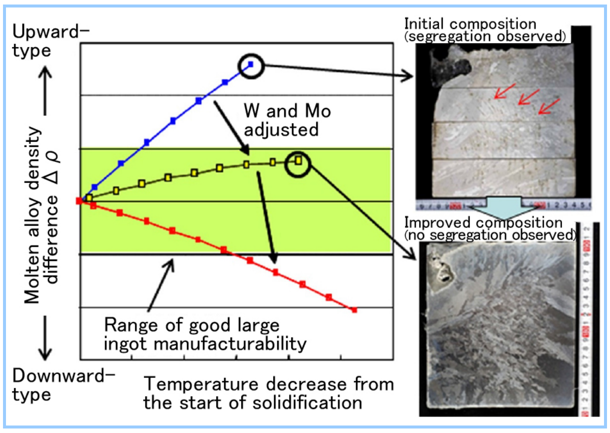

Figure 5 Transition of density difference (Δρ) of molten alloy due to adjustment of Mo and W amount

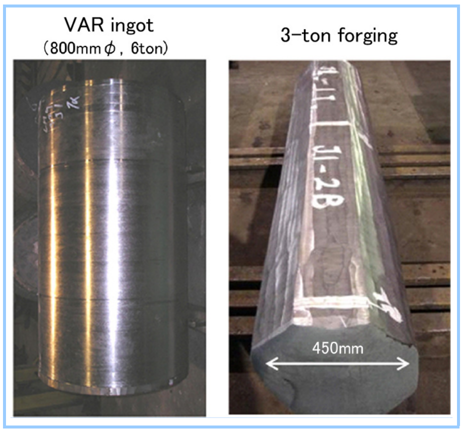

Figure 6 Trial manufacturing results of USC800

3.3 Evaluations of trial materials

Figure 6 shows the external appearance of a trial-manufactured large ingot (with an outside diameter of 800mm) of USC800, and 3 tons of forging from this ingot. The forgeability of the developed material proved to be good, and no macro segregation was observed in the cross section of these items. **Figure 7** shows the creep characteristics and low-cycle fatigue properties of USC800. With the creep-resistant capable temperature (at 100MPa for 10^5 hours) reaching 800°C and the creep strength at 700°C estimated to about 250MPa, the creep strength is about twice as large as that of Alloy 617 and Alloy 263. Moreover, it has a low-cycle fatigue life 5 to 10 times longer than that of Alloy 263 used for gas turbine combustors, so USC800 can be expected to be used for gas turbine components for which fatigue strength is important. It is found that die-forging, pipes, tubes, bolts, sheets, bars and wires can be easily formed from trial-manufactured forging, proving the applicability of such forged material not only to steam turbines, but also to various parts in thermal power plants.

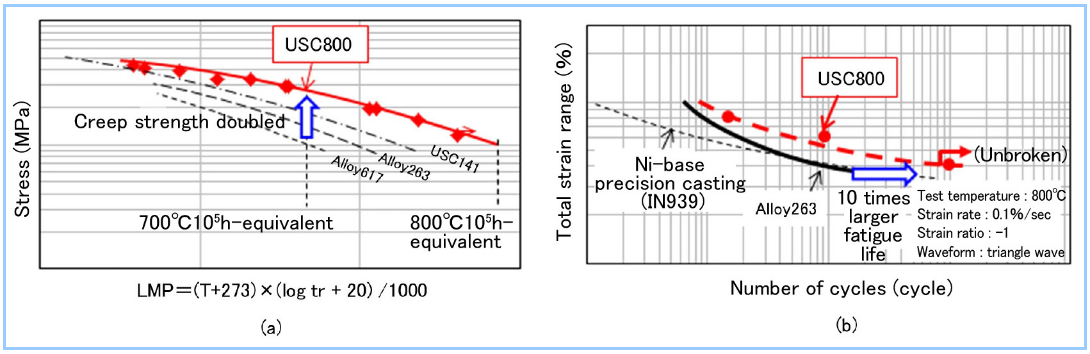

Figure 7 (a) Creep and (b) low-cycle fatigue properties of USC800

4. High-strength Ni-base superalloy for large gas turbine disks

Although highly manufacturable steel forging such as ferritic steel has predominantly been used for industrial gas turbine disks, Ni-base wrought alloys usable at high temperatures are utilized in some high-efficiency high-combustion temperature equipment. Alloy 718, which is widely used in aircraft engines and small gas turbines, has excellent mechanical properties as material for gas turbine disks. However, Alloy 718 is available only for the manufacturing of small ingots and products due to its formation of macro segregation while casting. MHPS has, using the alloy design method mentioned in Section 2, modified the composition of Alloy 718 and developed a new Ni-base disk material (FX550) which enables large disks to be manufactured without degrading the mechanical properties.

As shown in **Figure 8**, in the case of Alloy 718, the molten alloy density difference (Δρ) occurring during solidification is large in the negative direction to form downward segregation. On the other hand, FX550 in which amounts of Mo and W have been adjusted, the density difference become close to 0, specifically a level equivalent to that of Alloy 706 now in use for large gas turbine disks. Furthermore, evaluation using a large-ingot simulator has resulted in the prospective potential that a large ingot equivalent to Alloy 706 can be manufactured. **Figure 9** shows the results of phase fraction calculation for the stable phases of Alloy 718 and FX550. To acquire equivalent mechanical characteristics, the phase fractions of the γ', γ'' phases (precipitation strengthening phases) and δ phase (contributing grain size control) are equalized to those of Alloy 718. **Figure 10** shows the trial disk made of FX550 and a macro slice of the billet used to manufacture disks. Observation of the macro slice found no macro segregation and a cut up examination of the disk found strength characteristics equivalent to or better than those of Alloy 718.

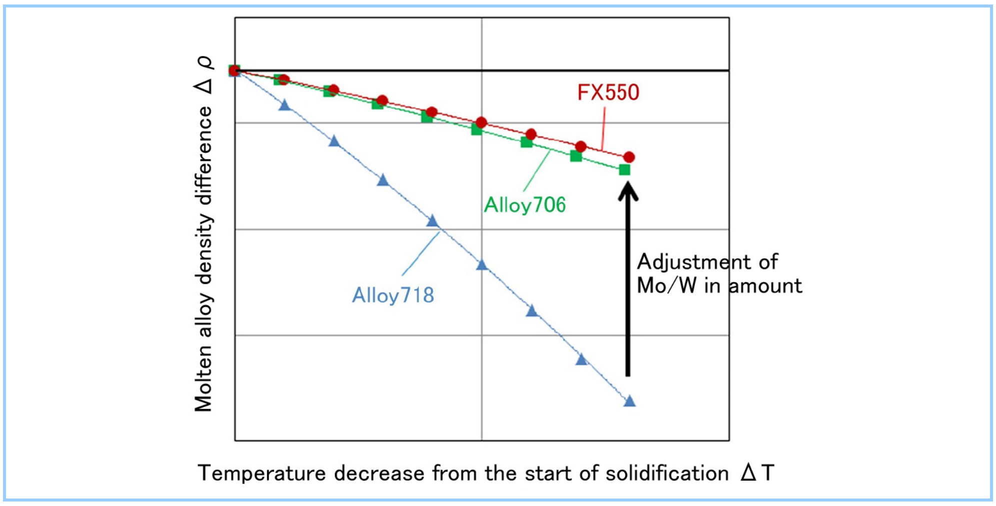

Figure 8 Improvement of molten alloy density difference (Δρ) through adjustment of Mo/W in Amount

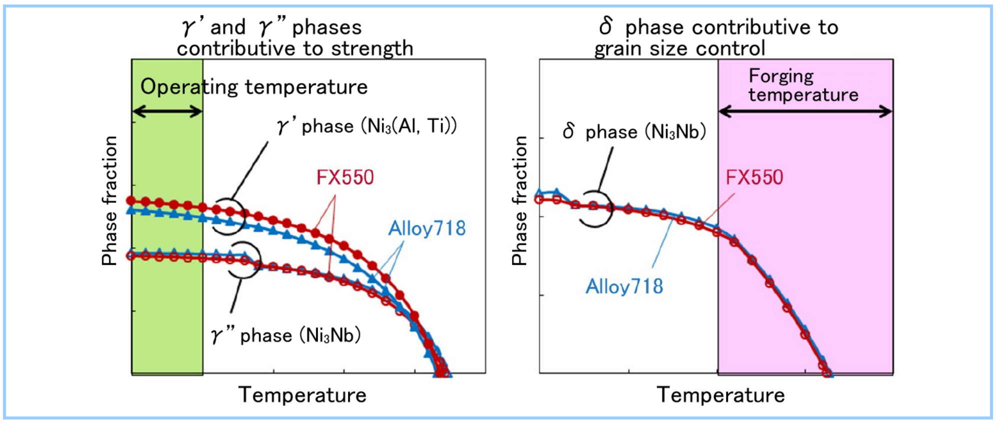

Figure 9 Phase fractions of precipitation strengthening phases and δ phase in FX550

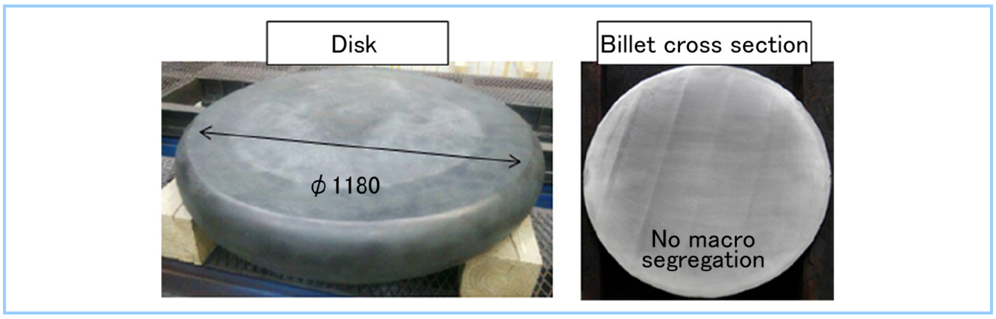

Figure 10 External appearance of FX550 disk and macro slice of the billet

5. Innovative process of manufacturing high-strength Ni-base superalloys

Figure 11 shows the mechanism of precipitation strengthening of Ni-base superalloys. It is known that the coherent interface between the γ phase-γ' phase contributes to the strength (Figure 11(a)). The authors found that strengthening capability can be lost by changing the γ phase-γ' phase interface from coherent to incoherent as shown in Figure 11 (b), and using this principle, the workability of high-strength Ni-base superalloys for aircraft engine disks, for which the amount of γ' phase exceeds 40%, can be remarkably improved. It was also found that the same initial strength is obtained by heat treatment at the end of processing due to the precipitation of the coherent γ' phase. **Figure 12** shows the external appearance of test pieces after the tensile test conducted at 920°C for Ni-base wrought superalloy (AD730[4]) with a level of high-temperature strength 1.5 times or higher than that of Alloy 718. Figure 12(a) illustrates the conventional process and Figure 12(b) shows the results of the aforementioned process. Rupture occurred with almost no deformation in the conventional process, while in the case of the weakened specimen as noted above, substantial deformation took place before rupture, thus indicating much better workability. Other tests have also confirmed that hot forgeability can be improved to a level equivalent to that of Alloy 718, and it is possible through cold processing to manufacture sheets and wires. The utilization of the developed process realizes application to gas turbine and steam turbine members of aircraft engine-dedicated high-strength Ni-base wrought superalloys, which has so far been difficult to apply to thermal power plants in view of its manufacturability.

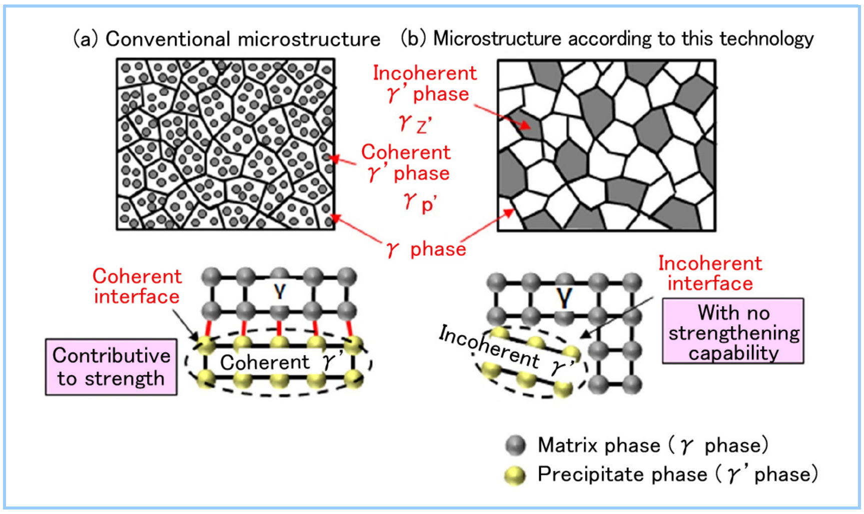

Figure 11 Strengthening mechanism of Ni-base superalloys

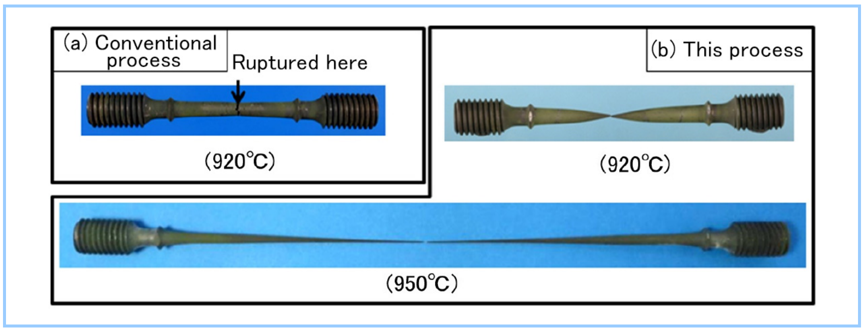

Figure 12 External appearance of tensile test piece for this process-applied AD730

6. Conclusion

MHPS has established a method of designing Ni-base wrought alloys contributive to the higher efficiency of thermal power plants, and using this method, a steam turbine material available at 800°C-class temperature and a gas turbine-dedicated large disk material have been developed. The trial manufacturing and verification of these materials are under way for application to actual equipment. Furthermore, we have developed a manufacturing process that dramatically improves the forgeability of high-strength aircraft engine material, which has the creep strength equivalent to that of precision castings used for rotor blades of gas turbines, as well as tensile and fatigue strengths 1.5 times or higher, assuring the prospective potential to be applied to gas turbine components.

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Reference

1. Saunders, N. et al., J-Ph. Proc. Symp. Materials Design Approaches and Experiences, eds. J.-C. Shao et al., Warrendale, PA, TMS, (2001) p.185-197
2. Koji Kajikawa, et al., "Freckle Formation in Ni-base Superalloys", Tetsu-to-Hagane, Vol.95 No.8 (2009) p.613-619
3. Beardmore, P. et al., Trans. Metall. Soc. AIME, Vol.245 (1969) p.1537
4. Devaux, A. Et Al., Ad730tm - A New Nickel-Based Superalloy for High Temperature
5. Engine Rotative Parts, Superalloys 2012, P.911-919