New alloy for aerospace applications

High Strength Precipitation Hardening Stainless Steel Alloy for Turbines

The technical article below was kindly provided by Dr. Gregory Vartanov, a chief engineer at Advanced Materials Development Corp, a Toronto-based company that develops new high strength steels and alloys with a focus on aerospace, defence, and turbomachinery applications. Dr. Vartanov holds an M.S. and a Ph.D. in materials science and metallurgy and he was granted six US patents in high-strength steels and alloys.

A-286 alloy is a commonly used material for turbine applications. High performance of the alloy is accomplished through special alloying composition and heat treatment. High Ni concentration stabilizes the face-centered cubic (fcc) austenitic matrix (γ-matrix) and the small quantity of additive elements Ti, Mo, Al, and V do not affect it. Stability of its γ-matrix is important for high temperature corrosion and oxidation resistance and mechanical properties. A γ'(gamma prime)-Ni_3 (Al, Ti) phase with an ordered face-centered cubic structure is a key strategy for hardening at high temperatures - the precipitated γ' phase exhibits a thermal stability at temperatures <700°C. At temperatures >700°C, the γ' phase does not remain stable for a long time and it transforms into a η(eta) - Ni_3Ti phase with the hexagonal close packed crystal (hcp) structure, and the η phase is not coherent with the γ-matrix. The exposure at >700°C for prolonged time at stressed conditions can lead to degradation of the stress rupture, creep resistance, and corrosion resistance of A-286 alloy when the η phase forms in excessive quantity [1-2].

The newly developed high strength precipitation hardening stainless steel alloy for turbine applications ("PHSS-T alloy") possesses high performance that is accomplished through formation of a special microstructure consistiing essentially of the γ-matrix, primary carbides, and two different intermetallic phases precipitated by aging. PHSS-T alloy possesses good corrosion resistance at ≤800°C, and good oxidation resistance at ≤950°C. The alloy was designed as a new material for high temperature applications such as aircraft turbine discs, shafts, wheels blades, frames, casings, afterburner parts and fasteners; also, it is applicable for industrial turbines.

Aircraft and turbine components can be manufactured from PHSS-T alloy by vacuum melting of ingots followed by hot forging and hot rolling (hot working), machining, and heat treatment or by hot isostatic pressing of the PHSS-T alloy powder followed by surface finishing and heat treatment. Also, the components can be additive manufactured from PHSS-T alloy powder followed by heat treatment.

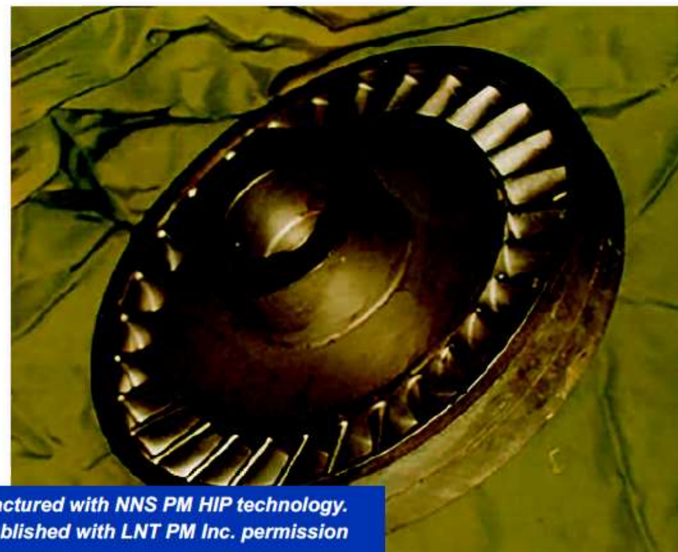
Description

PHSS-T alloy is a Fe-Ni-Cr composition with additions of V, Al, Mo, and Ti. A concentration of Ni >25wt.% stabilizes its γ-matrix, while two precipitated intermetallic phases supply high rupture strength and creep resistance at high temperature. A concentration of Cr >15wt.% supplies good corrosion and oxidation resistance at ≤800°C and oxidation resistance at ≤950°C.

The alloying composition of PHSS-T alloy differs from A-286 alloy by higher concentration of V>1.8 wt.%, and lower concentration of Ti< 1.0 wt.% and Al<0.1wt.%.

PHSS-T alloy is strengthened by precipitated small particles of primary carbides and two intermetallic phases after solution annealing followed by aging.

Primary carbides are TiC and/or (Ti, Me) C, wherein Me is mostly V; also, Cr, Mo, and other transition metals can be a part of the complex carbide. It should be noted that nitrides and carbonitrides can be formed if nitrogen presents in the alloy. The carbides are formed during solidification or high temperature hot working. Carbides TiC and (Ti,Me)C have a cubic crystal structure similar to the NaCl structure with symbol B1 ("B1 crystal structure"), dissolution temperatures >1,200°C, and values of enthalpy of formation (ΔHc)~ -340 kJ/mol to -300 kJ/mol.



A selectively net shape (SNS) turbine blisk manufactured with NNS PM HIP technology. Photo published with LNT PM Inc. permission

The 1st intermetallic phase is a θ(theta) - Ni_3V binary and Ni_3 (V, Me1) complex phase, wherein Me1 is mostly Ti; also, Cr, Mo, and other transition metals can be a part of the complex phase. The Ni_3V phase has a formation temperature >450°C, a dissolution temperature >1,000°C, an ordered crystal structure with symbol $D0_{22}$ ("$D0_{22}$ crystal structure"), a fcc unit cell, and ΔHc ~ -17.5 kJ/mol. Intermetallic phase Ni_2V with ΔHc~ -22.14 kJ/mol can be precipitated as well; therefore, the intermetallic phase Ni_xV, wherein 2≤x≤3 can be a part of the alloy. The binary and complex intermetallic phases are coherent with the γ-matrix.

The 2nd intermetallic phase is a η- Ni_3Ti binary and Ni_3 (Ti, Me_2) complex phase, wherein Me_2 is mostly V; also, Cr, Mo, and other transition metals can be a part of the complex phase. The Ni_3Ti has a formation temperature of >450°C, dissolution temperature of >1,000°C, ordered crystal structure with symbol D024 ("$D0_{24}$ crystal structure"), hexagonal close packed unit cell ("hcp"), and a value of enthalpy of formation ("ΔHc") of -38.07 kJ/

mol. The binary and complex intermetallic phases are not coherent with the γ-matrix [3-5].

It should be noted that Fe can partially substitute Ni in the binary and complex phases and form $(Ni, Fe)_{3V}$ - $(Ni, Fe)_3(V, Me1)$ and $(Ni, Fe)_3Ti$ - $(Ni, Fe)_3(Ti, Me2)$ phases.

Heat treatment/hardening of PHSS-T alloy consists of solution annealing at 950-1,000°C and rapid cooling followed by the aging at 800-850°C and air cooling.

After the heat treatment, a microstructure of PHSS-T alloy consisted essentially of the γ-matrix, particles of (Ti,V)C carbides with an average diameter <1μm, particles of the precipitated Ni_3 (V, Ti) phase with an average diameter <3μm, and randomly distributed particles of Ni_3Ti phase with an average diameter <10μm.

Experimental tests showed that PHSS-T alloy possesses good corrosion resistance properties at ≤800°C and good oxidation resistance properties at ≤950°C. High temperature short time strength, rupture strength, and creep resistance tests are underway.

Three different technologies can be utilized for production of aircraft and industrial gas turbine components made from PHSS-T alloy.

The 1st technology consists of vacuum melting of ingots by one of VIM-VAR, VIM-ESR, and EAF-VAR techniques. The ingots are hot forged or hot rolled (hot worked) to bars or plates followed by rough machining of the components and heat treating them. Finally, the components are finish machined to obtain the required tolerance. Further, that technology is designated as "vacuum melting + hot working" or "VM+HW". A cost of PHSS

alloy and a cost of production of the components made by VM+HW are equal to the cost of A-286 alloy and the cost of production for the same components by VM+HW.

The 2nd technology is a formation of near net shape ("NNS") by hot isostatic pressing of PHSS-T alloy powder ("PM HIP") followed by surface finishing and heat treatment. The technology allows the manufacture of various types of the complex-shaped gas turbine components for high temperature applications [6]. That technology provides precise geometry of the complex shape components <1,250mm diameter and properties close to VM+HW. Cost of the components made by NNS PM HIP is generally higher than the cost of the same components made by VM+HW; however, small batches of the large-section complex shape products are economically feasible to produce by NNS PM HIP rather than VM+HW. The components made by NNS PM HIP are cost-effective due to its material waste minimization and they have the "buy-to-fly" ratio (the ratio of the mass of raw material to the mass of the product) significantly lower than the components made by VM+HW.

The 3rd technology is additive manufacturing ("AM") that has lower "buy-to-fly" compared to NNS PM HIP; however, the extremely high cost of powder required for AM, high energy consumption, and a limitation of sizes of the components restrict applications of AM technology.

USA, Los Angeles area-based LNT PM Inc has developed NNS PM HIP technology for high temperature turbine components and the company is planning pilot production of such parts from PHSS-T alloy powder.

Conclusion

The new high strength precipitation hardening stainless steel alloy is hardened by two different intermetallic phases. The alloy possesses good corrosion resistance at ≤800°C, and good oxidation resistance at ≤950°C. High temperature short time strength, rupture strength, and creep resistance tests are underway.

The alloy is a new material for aircraft and industrial gas turbine components at ≤780°C. Near net shape hot isostatic pressing technology allows the manufacture of complex-shaped aircraft and industrial gas turbine components from PHSS-T alloy powder. ■

References

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