High-strength, corrosion resistant steel for power generation turbines

Developed for aircraft, HSCR steel can be used in high-stress applications.

By **Dr. Gregory Vartanov**

Highly stressed components of a power generation turbine, including impellers, shafts, discs, etc. are subjected to severe loading, oxidation, corrosion. High-strength titanium alloys and high strength nickel-based alloys are widely used for those components. The main criteria for choosing materials are strength, specific strength (tensile strength to density ratio), fatigue strength, toughness, and corrosion and oxidation resistance. Ti-6Al-4V alloy and the alloy 718 fit these criteria. However, high cost and machining issues limit their application.

Initially developed for high stressed aircraft landing gears components [1-2], a high strength corrosion resistant steel ("HSCR steel") is applicable for manufacturing of high stresses components for natural gas-fueled and hydrogen-fueled turbines. HSCR steel is a low cost substitution of alloy 718 at temperature up to 930°F/500°C and Ti-6Al-4V alloy.

NATURAL GAS-FUELED TURBINES

The natural gas-fueled high stressed turbine components can be manufactured from HSCR steel by the following four processes:

- Hot working (HW) of ingots by forging or rolling followed by machining and hardening.
- Powder metallurgical-based, hot isostatic pressing (PM HIP) to the near net shapes (NNS) followed by finish machining, and hardening (NNS PM HIP).
- Additive manufacturing (AM) followed by surface finishing and heat treatment.
- Vacuum casting followed by hot isostatic pressing, finish machining, and hardening (Casting + HIP).

Hardening of HSCR steel consists of austenitizing and rapid cooling, optional refrigerating, and tempering at low, medium, and high temperatures (secondary hardening) depending on the required properties. Formation of NNS by PM HIP enables manufacturing of various complex-shaped components. The process provides precise geometry and properties close to the forgings. Also, PM HIP supplies a homogeneous microstructure through any cross section. The cost of components made by PM HIP is generally higher than the same products made by HW. However, small batches of large-section complex products are economically feasible by PM HIP rather than HW (Figures 1A and B).

COST-EFFECTIVE

NNS components made by PM HIP are cost effective due to waste minimization and their buy-to-fly ratio (the mass of raw material to the mass of the product) being significantly lower than HW components.

The high cost of titanium alloy and nickel-based alloy powders, as well as issues with machining, limit their applications. Critical components made by PM HIP from HSCR steel powder are a good alternative to those made from titanium nickel-based alloys due

SOURCE: LNT PM

PICTURE 1A: Gas compressor impeller made by PM HIP from Ti-6Al-4V alloy powder (A).

SOURCE: LNT PM

PICTURE 1B: Gas compressor impeller made by PM HIP from Inconel alloy 625 powder.

ABOUT THE AUTHOR

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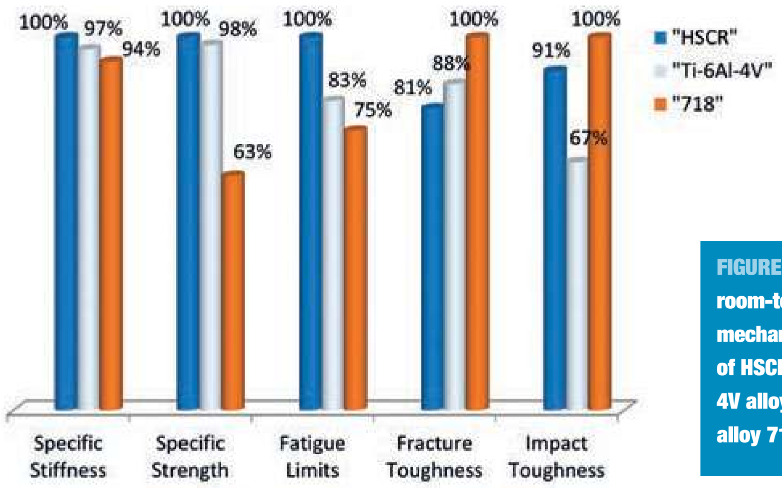

FIGURE 2: The room-temperature mechanical properties of HSCR steel, Ti-6Al-4V alloy and Inconel alloy 718.

to lower cost and better machinability for the same lifetime and durability.

The components made by AM have a buy-to-fly ratio lower than the components produced by PM HIP. However, the high cost of powder for AM, high-energy consumption, and issues with machining limit applications of the AM processes.

Casting+HIP is the lowest cost of the manufacturing processes. But it supplies lower strength compared to HW, PM HIP and AM. A combination of Casting+HIP is feasible for manufacturing of components from HSCR steel. The projected cost reduction of critical components is 65% (even more when compared to the same weight of components made by AM from powders of Ti-6Al-4V alloy and alloy 718).

The various processes used produce different mechanical properties (Figure 2).

Figure 2 shows a comparison of the mechanical properties of the vacuum melted, forged, and hardened HSCR steel, Ti-6Al-4V alloy, and Inconel alloy 718 (HW + hardening). HSCR steel possesses higher specific stiffness (E/ρ) and specific strength (UTS/ρ), higher fatigue limits (S), lower fracture toughness (K1c) and higher impact toughness (CVN) compared to Ti-6Al-4V alloy. Additionally, HSCR steel has a higher elevated temperature strength at up to 950°F compared to alloy 718 and a higher elevated temperature strength at up to 1200°F compared to Ti-6Al-4V alloy.

WORKABILITY, MACHINABILITY

HSCR steel also has greater workability and machinability, and better wear resistance. Alloy 718 and Ti-6Al-4V alloy have better corrosion and oxidation resistance compared to HSCR steel; nevertheless, HSCR steel has no rust after the standard salt spray test in accordance with ASTM B117 using a 5% NaCl concentration, natural pH, at 95°F, for

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more than 200 hours test duration.

Given its mechanical properties, critical components made by HW, PM HIP, and AM processes from Ti-6Al-4V alloy and alloy 718 can be replaced by HSCR steel without sacrificing stiffness, durability or lifetime (Table 1 see the Attachment 1).

In terms of cost, HSCR steel is an attractive alternative (Figure 3). There is a significant reduction in cost for components made by HW, PM HIP, and SLM using HSCR steel. At the same time, utilization of HSCR steel reduces dependency on Ti, Ni, Mo, and Nb.

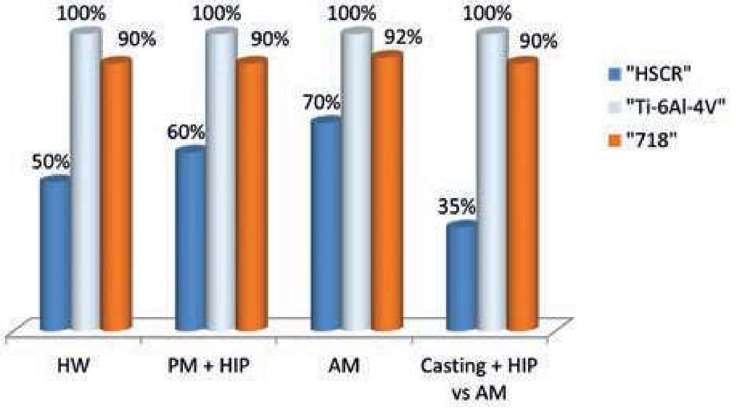

FIGURE 3: Cost comparison between HSCR steel, Ti-6Al-4V alloy and alloy 718.

HYDROGEN-FUELED TURBINES

Efforts by Siemens Energy, GE Power, Mitsubishi Hitachi Power Systems (MHPS), Ansaldo Energia and others to develop hydrogen-fueled gas turbines have shifted into high gear.

Hydrogen embrittlement (HE) of the hydrogen-fueled high stressed turbine components is a critical challenge. The hydrogen environment embrittlement (HEE) rating of materials varies widely. Ti-6Al-4V, Inconel 718, Inconel 625 alloys and HSCR steel should not be utilized for the hydrogen-fueled high stressed turbine components. High-strength aluminum alloys 2000 and 7000 are a better choice; however, their strength up to 70 ksi at 75°F and up to 30 ksi at 400°F limits application. Similarly, Type 316 austenitic stainless steel has a good HEE rating, but possesses strength of only 90 ksi at 75°F and 80 ksi at 400°F. That, too, is not enough for the highly stressed turbines components.

Analysis shows the key mechanisms for resisting of hydrogen embrittlement in steels:

- Diffusion barriers, including ductile Zn-Ni and Zn-Ni-Me coatings, brittle nitrides TiN, VN, oxides Cr2O3, Al2O3, carbides VC, TiC, etc. coatings.
- "Irreversible" traps, including carbides TiC and VC/V4C3 and nitrides TiN and VN, inclusions MnS, etc.
- Absorbers, including retained austenite, fine bainite, ε-carbide, voids, etc.

Experimental research showed that MAX-phase Ti2AlN layer that had not been heated withstood hydrogen 50 times better than untreated steel and heated, with formation of α-Al2O3 layer, withstood hydrogen 3,500 times greater than those of untreated steel.

The experimental developed Al2O3-Al-(Fe–Al) coatings showed excellent resistance to hydrogen entry in pressure of 14.5 ksi/100MPa of hydrogen gas at temperature of 518°F/270°C.

Hydrogen barrier coatings have been developed using aluminized steels produced by a variety of methods, including pack-aluminizing, hot-dipping, and vacuum evaporation. Permeation reduction factors of up to 104 have been realized in this manner. The Ti-based coatings offer an alternative choice to Al but are not as permeation resistant as the alumina-based methods and are not as reproducible in being able to be fabricated.

The authors confirmed that applying the Al2O3, TiC, or TiN coatings on a steel substrate reduced the hydrogen permeation by a factor of at least one order of magnitude compared with uncoated substrates. The Al2O3 films consisting of fine crystal grains, with diameters of about 40 nm or less, provided superior hydrogen-permeation barriers on the test specimens. The test specimens coated with TiN or TiC films, with columnar crystals grown vertically on the 316 stainless steel substrate, tended to exhibit higher hydrogen permeability.

All aforementioned coatings are applicable to prevent hydrogen permeation in components made from HSCR steel and the same time HSCR steel has some advantages over stainless steels and alloys that are commonly used in turbomachinery.

AMD Corp. is developing a complex barrier to prevent hydrogen permeation in high stressed components made from HSCR steel. The first level of the barrier is Ni-Co layer joined with the HSCR steel substrate by diffusion bonding. The second level is 316 stainless steel or similar stainless steel grade layer joined with the first layer by diffusion bonding as well. The diffusion joining of the two layers and the layer and the substrate is accomplished by the HIP cladding technique at 2000-2200°F/1095-1205°C under inert gas pressure of 10ksi/69MPa - 20ksi/138MPa. High temperature and pressure supply the diffusion bonding without any defects that it won't break under stress.

HSCR steel has the following advantages compared to the other metallic materials.

After the HIP cladding followed by normalizing at 1900-2000°F/1035-1093°C, HSCR steel has a microstructure contained fine titanium and vanadium carbides and the steel possesses the room temperature mechanical properties: UTS of more than 260ksi/1800MPa, CVN of more than 22ft-lb/30J, and K1C of more than 65 ksi√in/71MPa√m. To increase durability of the complex barrier, the components could be periodically subjected to an embrittlement relief by removing infused hydrogen into the barrier. The embrittlement relief ("baking') usually consists of heating to 375°F/190°C and higher for 6 hours and more that depend on a thickness of the barrier and turbine operating conditions.

LNT PM and Synertech PM have developed NNS PM HIP technology for critical gas turbine components. Pilot production of the turbine components made by PM HIP from HSCR steel powder is underway. For more information please contact info@amdoncorp.com or visit www.amdoncorp.com ■