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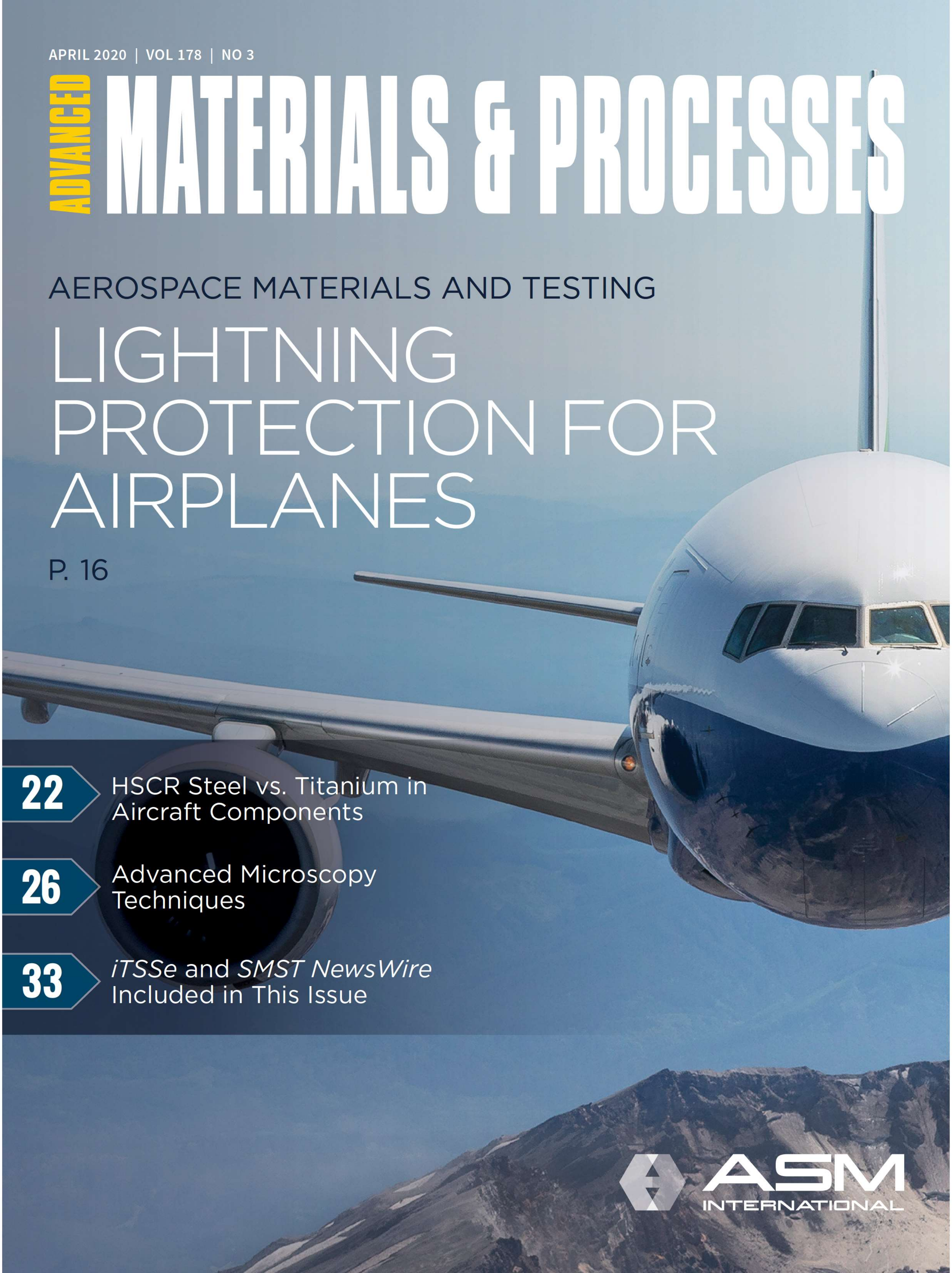
ADVANCED MATERIALS & PROCESSES



AEROSPACE MATERIALS AND TESTING

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COST-EFFECTIVE ALTERNATIVE TO TITANIUM FOR AIRCRAFT PARTS

High-strength, corrosion-resistant steel is a cost-effective alternative to titanium alloys due to its high specific strength, high fatigue strength, good toughness, and corrosion resistance.

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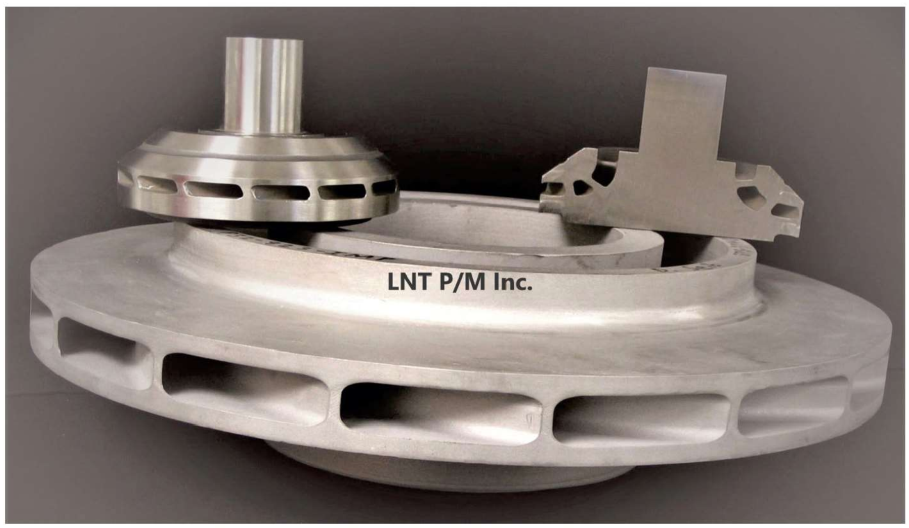
Aircraft landing gear and structural components, as well as turbomachinery components that are used at moderate temperatures, are regularly subjected to severe loading, corrosion, and adverse environmental conditions. They also have complex shapes varying from thin to thick sections. Materials such as high-strength titanium alloys and high-strength steels are widely used for these critical components. The main criteria for selecting these materials include their specific strength (tensile strength to density ratio), fatigue strength, toughness, and corrosion resistance.



High-strength titanium alloys Ti-6Al-4V, Ti-10V-2Fe-3Al, and Ti-5Al-2Sn-2Zr-4Cr-4Mo are excellent candidates for use in critical components due to their high specific strength and fatigue strength, toughness, and excellent corrosion resistance. However, high cost along with machining issues limits application of these alloys.

Near net shape (NNS) powder metallurgy-based hot isostatic pressing (PM HIP) is well verified for numerous critical applications in aerospace and turbomachinery. This technique is considered an advanced shaping and consolidation process for manufacturing critical components from high-strength titanium alloys.

This article proposes using a high-strength, corrosion-resistant steel (HSCR steel) as an alternative material for manufacturing critical aerospace and turbomachinery components. HSCR steel is a low-cost substitute for titanium alloys due to its high specific strength, high fatigue strength, good toughness, and corrosion resistance.

ADVANTAGES OF HSCR STEEL

HSCR steel[1] and high-strength titanium alloys are both used in critical components, yet each has some advantages as well as shortcomings. Premium-quality HSCR steel ingots are produced by vacuum melting whereas HSCR steel powder is produced through atomization, including vacuum atomization. Critical components can be manufactured from HSCR steel by the following processes:

1. Hot working (HW) of premium-quality ingots by forging, rolling, and pressing, followed by machining and hardening.
2. Powder metallurgy-based, hot isostatic pressing to near net shapes, followed by finish machining and surface quality improvement, if necessary, and hardening.
3. Additive manufacturing (AM) followed by finish machining and surface quality improvement if necessary, along with heat treatment.
4. Casting, including precision investment casting and vacuum casting, then hot isostatic pressing, followed by finish machining and surface quality improvement, if necessary, and hardening.

Hardening of HSCR steel consists of austenitizing and rapid cooling, optional refrigerating, and tempering at low, medium, and high temperatures (secondary hardening) that depend on the required properties.

Formation of near net shapes by PM HIP allows manufacturing various types of complex-shaped aircraft components[2]. The process enables precise geometry of complex shapes, blanks up to 55 inches in diameter, and properties close to forgings.

The cost of critical components made by PM HIP is generally higher than the cost of the same components made by HW. However, small batches of large-section complex-shape articles are economically feasible to produce by PM HIP rather than HW, especially for NNS products. NNS critical components made by PM HIP are cost-effective due to minimal waste. They also have a significantly lower buy-to-fly ratio than HW components.

Fig. 1 — Impeller for gas compressor made by PM HIP from Ti-6Al-4V alloy powder. Courtesy of LNT PM Inc.

Figure 1 shows an example NNS part made by PM HIP from Ti-6Al-4V alloy powder (impeller for gas compressor working in a corrosive environment).

However, the high cost of titanium powder, its affinity to oxidation, and issues with machining limit the application of critical components made by PM HIP from powder.

Critical components made by PM HIP using HSCR steel powder are a lower-cost alternative to components made with titanium alloy powder using the same process. The HSCR steel components offer the same lifetime and durability as high-strength titanium alloy parts, but at a much reduced cost. It should be noted that among the four previously mentioned processes, only the PM HIP process results in components with a unique homogenous microstructure observable at any of their cross sections.

Near net shape components made by AM from the powder of high-strength titanium alloys have a buy-to-fly ratio that is comparable to the PM HIP process. However, the high cost of titanium powder required for AM, high energy consumption, and issues with machining limit the practicality of using AM to make components from high-strength titanium alloys.

The lowest cost process for making critical components out of the four processes described above involves casting + HIP, including precision investment casting and vacuum casting, followed by HIP, finish machining, and surface quality improvement (if necessary) and hardening. The combination of casting and HIP results in slightly less strength compared to the HW process. The combination of vacuum investment casting and HIP is a feasible option for

TABLE 1 – MECHANICAL PROPERTIES OF HSCR STEEL AND Ti-6Al-4V ALLOY

Processes	HW + Hardening		PM HIP+ Hardening		SLM + Annealing		Casting + HIP	
Materials	HSCR	Ti-6-4	HSCR	Ti-6-4	HSCR	Ti-6-4	HSCR	Ti-6-4
Density (ρ), lb/in³	0.280	0.160	0.280	0.160	0.280	0.160	0.280	0.160
Modulus Elasticity (E), ksi	30100	16670	28900	16000	29800	16500	28200	15000
Specific Stiffness (E/ρ)	**107500**	**104160**	**103210**	**100000**	**106430**	**103130**	**100700**	**93750**
Tensile Strength (UTS), ksi	294	165	290	159	291	162	275	140
Specific Strength (UTS/ρ)	**1050**	**1030**	**1037**	**994**	**1039**	**1013**	**980**	**875**
Yield Strength (YS), ksi	226	151	220	145	223	148	210	125
Fatigue Limits (S) at 10^7 Cycles, ksi	120	100	116	90	117	90	90	-
Elongation (El), %	10	10	10	9	10	10	8-10	5-10
Reduction of Area (RA), %	36	34	40	30	34	30	32-34	-
Fracture Toughness (K_{1C}), ksi√in	65	70	65	75	60	65	60	-
Charpy V-Notch Impact Toughness Energy (CVN), ft-lb	22	16	20	14	16	14	15	-

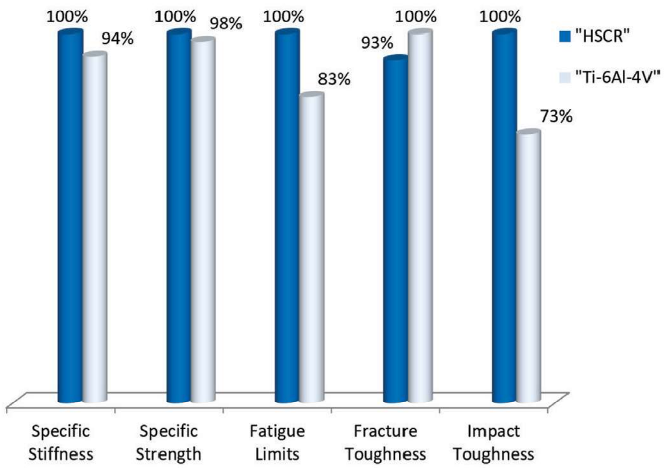


Fig. 2 — Summary comparison of key properties of the HW + hardening of HSCR steel and HW + hardening of Ti-6Al-4V alloy. Also see Table 1.

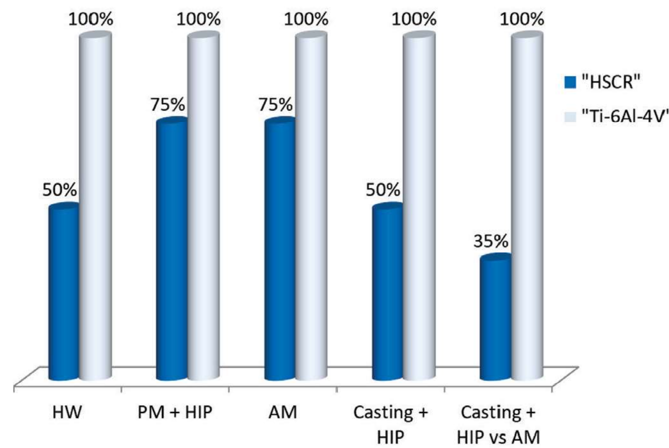


Fig. 3 — Summary comparison of projected cost reduction of components made from HSCR steel by HW, PM HIP, SLM, and casting + HIP.

manufacturing components from HSCR steel and has the following advantages: minimized formation of oxide and nitride inclusions; low losses of alloying elements by oxidation; very close compositional tolerance; precise temperature control; removal of undesired trace elements with high vapor pressure; and removal of dissolved gasses, such as hydrogen and nitrogen.

Critical components made of HSCR steel by casting + HIP can be a low-cost alternative to PM HIP or AM processes. It should be noted that the mechanical properties of components made by casting + HIP using HSCR steel are slightly lower than the properties of the same components made by the PM HIP or AM processes from HSCR steel powder. Projected cost reduction for critical components made by casting + HIP from HSCR steel is 65% or more compared to the same weight components made by AM from Ti-6Al-4V.

Table 1 shows a comparison of room-temperature mechanical properties of HSCR steel samples and Ti-6Al-4V alloy samples made by the following processes:

1. HW + hardening: The forged HSCR steel is hardened by quenching, refrigerating, and tempering (QRT) and the forged Ti-6Al-4V alloy is hardened by solution treating and aging (STA)[3].
2. PM HIP + hardening: HSCR steel powder consolidated by PM HIP is hardened by QRT and Ti-6Al-4V alloy powder consolidated by PM HIP is hardened by STA.
3. AM + annealing: Built by selective laser melting (SLM) of HSCR steel powder is heat treated by annealing and built by SLM of Ti-6Al-4V alloy powder is heat treated by annealing[4].
4. Casting + HIP + hardening: Vacuum cast HSCR steel is subjected to HIP followed by hardening by QRT, and vacuum cast Ti-6Al-4V alloy is subjected to HIP followed by hardening by STA[5].

Figure 2 shows a comparison of mechanical properties of vacuum melted, forged, and hardened by QRT (HW + hardening) of HSCR steel and the vacuum melted, forged, and hardened by STA (HW + hardening) of Ti-6Al-4V alloy. HSCR steel possesses slightly higher specific stiffness (E/ρ) and specific strength (UTS/ρ), higher fatigue limits (S), slightly low fracture toughness (K_{1C}), and higher impact toughness (CVN). Also, HSCR steel has higher elevated temperature strength, better workability and machinability, and better wear resistance. However, Ti-6Al-4V alloy has better corrosion resistance.

Given the superior material properties of HSCR steel over Ti-6Al-4V alloy, the author concludes that critical components made by HW, PM HIP, and AM processes from Ti-6Al-4V alloy can be substituted with the same weight components made of HSCR steel by the same processes without sacrificing stiffness, durability, and lifetime. Cost of production plays a crucial role in the selection of materials for critical components. The lower cost of HSCR steel makes it a cost-effective alternative to high-strength titanium alloys.

Figure 3 shows a comparison of the projected cost of components made by four different processes. Projected cost reductions for manufacturing components by HW, PM HIP, SLM, and Casting + HIP from HSCR steel are 50% or more, 25% or more, 25% or more, and 50% or more, respectively compared to the same weight components made by the same process using Ti-6Al-4V alloy. Projected cost reduction of critical components made from HSCR steel by casting + HIP is 65% or more compared to the same weight components made by AM from Ti-6Al-4V alloy.

It should be noted that production of critical components made from HSCR steel reduces energy consumption by 25% or more compared to the same weight components made from Ti-6Al-4V alloy. HSCR steel is also well suited for defense applications such as missiles, artillery barrels, military land vehicles, and other applications where high-strength and fatigue limits, good toughness, and corrosion resistance at a reasonable cost are required.

LNT PM Inc. is planning a pilot production of near net shape critical components made by PM HIP from HSCR steel powder as a lower-cost substitute for the same weight components made of high strength titanium alloys.

CONCLUSION

HSCR steel is proposed as a low-cost substitution for high strength titanium alloys in the manufacture of aircraft landing gear and structural components, as well as turbomachinery components used at moderate temperature. HSCR steel possesses specific stiffness, specific strength, and fatigue limits higher than Ti-6Al-4V alloy at the same ductility and toughness. The projected cost of manufacturing these critical components from HSCR steel is significantly lower than the cost of the same weight critical components made of Ti-6Al-4V alloy.

Manufacturing critical components from HSCR steel reduces energy consumption by 25% or more compared to the same weight components made of Ti-6Al-4V alloy. HSCR steel also reduces the aircraft manufacturers' dependency on the handful of titanium suppliers in the world market. **~AM&P**

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