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High Strength Corrosion Resistant Steel for Aircraft Landing Gears and Structures

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Abstract

High stressed aircraft landing gear and structural components are subjected to severe loading, corrosion and adverse environmental conditions. Materials such as high strength steels and high-strength titanium alloys are widely used for those critical components. The main criterions for choosing the materials are their strength and fatigue strength, toughness and ductility.

300M steel is widely used for high stress aircraft landing gears and structures; however, this steel is not corrosion-resistant and requires protective coatings.

Cobalt-free, quenched and tempered high strength corrosion resistant steel alloy ("HSCR steel") provides the same strength, ductility, and toughness as the 300M steel and while it possesses corrosion resistance in salt spray test. HSCR steel has showed no rust after the standard salt spray test in accordance with ASTM B117 using a 5% NaCl concentration, natural pH, at 95°F, for 200 hours test duration.

Aircraft applications of the wrought HSCR steel include landing gear components, rotatable shafts, actuators, flap tracks, slat tracks, fasteners, and others.

Besides forging, the aircraft components can be manufactured from HSCR steel powders by:

- Powder metallurgical-based hot isostatic pressing (PM HIP) to the near net shapes

(NNS) followed by finish machining/surface finishing and heat treatment

- Additive manufacturing (AM) followed by surface finishing and heat treatment.

Modification of the HSCR steel is applicable for vacuum and investment casting of aircraft hydraulic fluid system, motion control and actuation system, cargo system, and flight safety components.

HSCR steel is a low cost alternative of Ti-6Al-4V alloy. The components made from Ti- 6Al-4V alloy can be substituted by the same weight components made from HSCR steel due to HSCR steel possesses slightly higher specific stiffness and specific strength (ratio of modulus elasticity and ultimate tensile strength to density) and slightly lower ductility and toughness compared to Ti-6Al-4V alloy.

Industrial production of HSCR steel is underway.

Introduction

Aircraft landing gears and structures have stringent performance requirements. They are subjected to severe loads, corrosion, and adverse environmental conditions, and have complex shapes which vary in thickness. The 300M steel is widely used for high stress aircraft landing gears and structures. This steel is not corrosion-resistant and it requires protective coatings.

Recently, a new non-toxic zinc-nickel coating is being developed; however, neither zinc-nickel coating nor toxic cadmium coatings do not solve the corrosion problem if it cracks. Ultimately, the use of stainless steel delivers a more robust solution, reducing maintenance time and cost of repairs caused by corrosion.

Cobalt-free, quenched and tempered high strength corrosion resistant steel alloy ("HSCR steel") possesses the same strength, ductility, and toughness as the 300M steel while it holds corrosion resistance in the ASTM standard salt spray test.

Advantages of the HSCR steel compared to the 300M steel are as follows:

- Corrosion resistance in salt-spray test
- Higher impact and fracture toughness
- Higher stress corrosion cracking resistance.

The corrosion resistance of the HSCR steel allows avoiding protective coatings that increase robust of landing gears and reduce the cost of manufacturing.

Comparison of the HSCR steel with the well-known high strength corrosion resistant alloy Ferrium S53 shows that the HSCR steel has:

- Better corrosion resistance in salt spray test
- The same strength and fatigue strength
- Higher impact toughness and slightly lower fracture toughness

- More than 2.5 times lower the projected manufacturing cost and more than 1.5 times lower the projected heat treatment cost.

This proposed HSCR steel is a material for manufacturing of the aircraft landing gears and structure components ("Components") and the same time that material is a low-cost substitution of Ti-6Al-4V alloy due to its high specific strength, high fatigue strength, good toughness, and corrosion resistance.

Description

Chemical Composition

The table below shows a chemical composition (wt.%) of HSCR steel [1].

TABLE 1

C	N	Ni	Mn	Cu	Cr	Mo	W
0.20-0.45	<0.05	3.5-7.0	<1.0	<1.0	10.0-14.5	0.50-2.0	<1.0
Σ*	Al	Si	Ce		Fe	Σ**	
0.1-1.30	<0.25	<1.20	<0.01		Balance	<27.0	

Σ* is a sum of at least one element from V, Ti, Nb, and Ta
Σ** is a sum of all alloying elements (except Fe)

Manufacturing Processes of Components

HSCR steel and the components made from it can be manufactured by the following four processes [2, 3]:

1. The vacuum melted ingot is hot worked by forging and/or rolling followed by machining and hardening ("HW process").
2. Powder metallurgical-based, hot isostatic pressing ("PM HIP") to the near net shapes (NNS), followed by finish machining and hardening ("PM HIP process").
3. Additive manufacturing followed by surface finishing and heat treatment ("AM process").
4. Vacuum casting and hot isostatic pressing followed by surface finishing and hardening ("Casting+HIP process").

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 shape (NNS) by the PM HIP process allows manufacturing various types of the complex-shaped components [4]. The process provides precise geometry of the complex shape components; however the mechanical properties are lower compared to the HW process.

Modern AM process allows manufacturing the complex-shaped components with the lowest "buy-to-fly" ratio (the ratio of the mass of raw material to the mass of the product); nevertheless, the ductility and toughness are lower compared to the HW process.

The Casting+HIP process supplies less strength compared to the strength of the HW process; however, simplicity of that process is very attractive.

Mechanical Properties

Table 2 shows a comparison of the room temperature ASTM standard test results of HSCR steel manufactured the by the HW process (industrial-scale) and PM HIP, AM, and Casting+HIP processes (lab-scale).

Table 3 shows a comparison of the room temperature ASTM standard test results at of HSCR steel, 300M steel, and FerriumS53 alloy manufactured by VIM-VAR melting, hot forging, and followed by hardening.

Corrosion Resistance

The HSCR steel shows no rust after the ASTM B 117 standard salt spray test in 5% NaCl solution at 95°F for more than 200 hrs. HSCR steel possesses better corrosion resistance than FerriunS53 alloy while 300M steel requires a corrosion protective coating.

Cost

The manufacturing costs of the components have crucial meaning. Cost of the components made by the PM HIP

TABLE 2

Properties/Processes	HW+ Hardening	PM HIP+ Hardening	AM+ Annealing	Casting+HIP Hardening
Modulus Elasticity (E) x10^{-3}, ksi	30	28.5	30	27.5
Tensile Strength (UTS), ksi	295	285	295	265
Yield Strength (YS), ksi	225	215	225	200
Fatigue Limits (S) at 10^7 cycles, ksi	110	100	110	70
Elongation (El), %	10	10	5	5
Reduction of Area (RA), %	40	35	30	30
Fracture Toughness (K_{1C}), ksi$\sqrt{in}$	60	55	50	50
Charpy V-Notch Impact Toughness Energy (CVN), ft-lb	20	15	10	10

TABLE 3

Properties/Steels	HSCR	300M	S53
Modulus Elasticity (E) x10^{-3}, ksi	30	29	29.5
Tensile Strength (UTS), ksi	295	280	290
Yield Strength (YS), ksi	225	235	225
Fatigue Limits (S) at 10^7 cycles, ksi	110	100	115
Elongation (El), %	10	10	15
Reduction of Area (RA), %	40	35	55
Fracture Toughness (K_{1C}), ksi$\sqrt{in}$	60	50	65
Charpy V-Notch Impact Toughness Energy (CVN), ft-lb	20	18	18

process is generally higher than the cost of the same components made by the HW process; however, small batches of the large-section complex shape articles are economically feasible to produce by the PM HIP process rather than the HW process, especially, for the NNS products. The NNS components made by the PM HIP process are cost-effective due to its waste minimization and they have the "buy-to-fly" ratio significantly lower than the components made by the HW process. The components made by the Casting+HIP process have the lowest cost and the components made by the AM process have the highest cost.

Figure 1 shows a comparison of the projected manufacturing costs (%) of the same components made by the aforementioned four processes.

Figure 2 shows a comparison of the projected manufacturing cost of the VIM-VAR melted and forged bars of HSCR steel and the manufacturing cost of 300M steel and FerriumS53 alloy (USD/lb).

HSCR Steel vs. Ti-6Al-4V Alloy

High-strength Ti-6Al-4V alloy is excellent candidate for aircraft landing gears and structures due to its high specific strength, high fatigue strengths, good toughness, and excellent corrosion resistance [5]. However, high cost limits applications of that alloy. The proposed HSCR steel is a low-cost substitution of Ti-6Al-4V alloy due to its high strength, high fatigue strength, good toughness, and corrosion resistance [6, 7].

Table 4 shows the room temperature ASTM standard test results of the hardened HSCR steel and the hardened

FIGURE 1

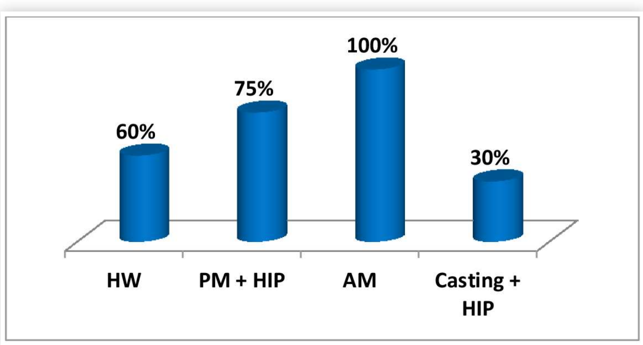


FIGURE 2

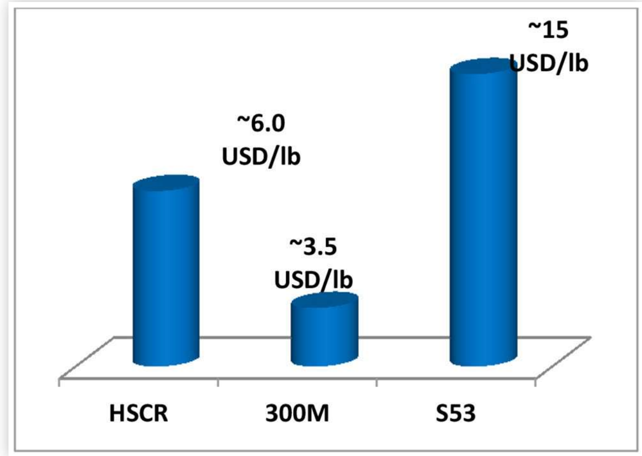


TABLE 4

Material	HSCR	Ti-6Al-4V
Density (ρ), lb/in^3	0.280	0.160
Modulus Elasticity (E) x10^{-3}, ksi	30	16.6
Specific Stiffness (E/ρ) x10^{-3}	107	104
Tensile Strength (UTS), ksi	295	165
Specific Strength (UTS/ρ)	1055	1030
Yield Strength (YS), ksi	225	150
Fatigue Limits (S) at 10^7 Cycles, ksi	110	80
Elongation (El), %	10	10
Reduction of Area (RA), %	40	35
Fracture Toughness (K_{1C}), ksi$\sqrt{in}$	60	70
Charpy V-Notch Impact Toughness Energy (CVN), ft-lb	20	15

Ti-6Al-4V alloy manufactured by VIM-VAR melting and hot forging.

A comparison of the mechanical properties of the Table 4 is summarized in Figure 3 where it is shown that HSCR steel has slightly higher specific stiffness (E/ρ) and specific strength (UTS/ρ), higher fatigue limits (S), slightly lower fracture toughness (K_{1C}), and higher impact toughness (CVN) compared to Ti-6Al-4V alloy.

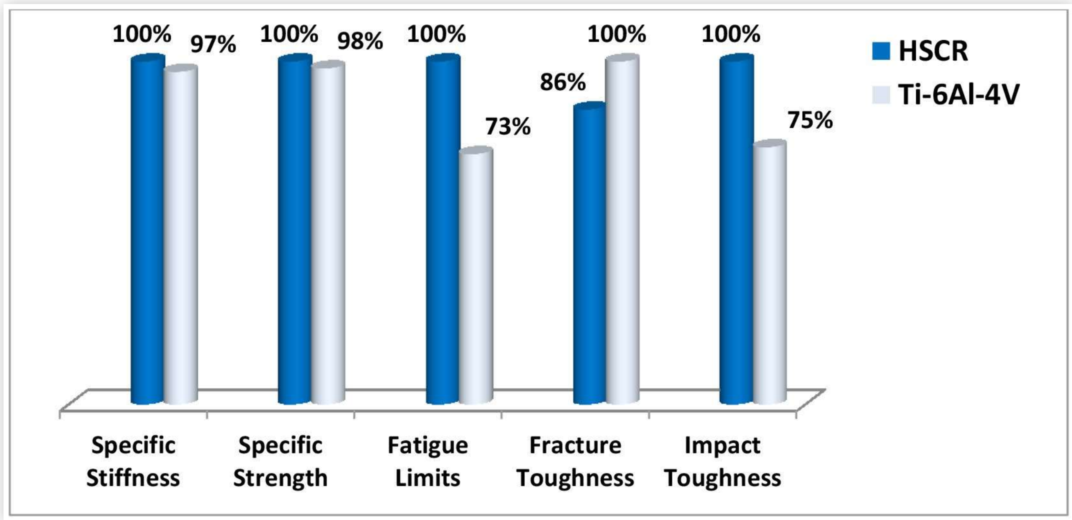
Also, HSCR steel has higher elevated temperature strength, better workability and machinability, and better wear resistance; however, corrosion resistance of Ti-6-4 alloy is higher than HSCR steel.

The projected manufacturing costs of the VIM-VAR melted and forged bars of HSCR steel is ~6.0 USD/lb while the cost of Ti-6Al-4V alloy is 12-18 USD/lb.

Additionally, HSCR steel reduces the titanium dependency of the aircraft manufacturers from the monopoly of titanium suppliers on the world market.

Industrial production of HSCR steel is underway at Deutsche Edelstahlwerke Specialty Steel GmbH & Co KG (DEW) that is a producer of specialty steel (stainless, engineering and tool steel) and produces regularly 300M/1.6928 for aviation applications. The production facilities includes electric arc furnaces, ingot and continuous casting machines,

FIGURE 3



re-melting (ESR, VAR) shops, forging and rolling plants and heat treatment furnaces. The company is certified according ISO 9001, IATF 16949, AS9100, ISO 17025, ISO 50001 and ISO 14001.

Summary

Cobalt-free, quenched and tempered HSCR steel is applicable for the aircraft landing gears and structural components. The steel has the same strength, ductility, and toughness as 300M steel while it possesses corrosion resistance in the ASTM standard salt spray test.

HSCR steel and the components made it can be manufactured by the following four processes: vacuum melting of ingots, hot working of them followed by machining and hardening; powder metallurgical-based, hot isostatic pressing to the near net shapes, followed by finish machining and hardening; additive manufacturing followed by surface finishing and heat treatment; and vacuum casting and hot isostatic pressing followed by surface finishing and hardening.

The projected manufacturing cost of the VIM-VAR melted and forged bars of HSCR steel is ~6.0 USD/lb while the manufacturing cost of 300M steel is ~3.5 USD/lb.

HSCR steel possesses slightly higher specific strength and specific stiffness, slightly lower fracture toughness, and higher impact toughness compared to Ti-6Al-4V alloy; however corrosion resistance of Ti-6Al-4V alloy is higher than HSCR steel. These facts allow substituting the components made from Ti-6Al-4V alloy by the same weight components made from the HSCR steel without sacrificing their durability and life-time.

The HSCR steel reduces the aircraft manufacturers' titanium dependency of the aircraft manufacturers from the monopoly of titanium suppliers of titanium on the world market.

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