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The characterization of HG10MNN and an evaluation of suitability for use in naval applications

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HIGHLIGHTS

- HG10MNN alloy showed good strength, hardness and ductility compared to NAB.
- In air, four point bending fatigue tests suggest an endurance limit between 8 and 10 ksi.
- As compared to NAB, HG10MNN has excellent casting and corrosion behavior.

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ABSTRACT

An initial mechanical evaluation and standard material characterization were conducted for the stainless steel alloy HG10MNN in order to evaluate its use in naval and marine applications. HG10MNN is a newly developed stainless steel designed for improved resistance to mechanical and thermal fatigue. This material could eventually replace the Nickel–Aluminum–Bronze (NAB) currently used in many naval propulsion systems, however, additional testing is required to validate the alloy's performance characteristics. Although stainless steels are commonly used in marine applications, there is insufficient HG10MNN documentation to permit its use in naval ship design. This investigation also involved an evaluation of castability and machinability to determine whether the material could be formed into the complex shapes required in a modern naval construction. Initial results showed that the alloy exhibits a fully austenitic microstructure in the as-cast condition, while maintaining acceptable mechanical properties and superior castability as compared to NAB.

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1. Background and objectives

The general properties required in a marine material include high corrosion fatigue resistance (in sea water), high resistance to cavitation erosion, good resistance to general corrosion, high resistance to impingement attack and crevice corrosion, high strength to weight ratio, good repair characteristics (including weldability), and favorable casting characteristics (Carlton, 2007). A main advantage of austenitic stainless steel is toughness which, along with other attendant benefits, enables the material to withstand impact damage. Many stainless steels, however, have reduced corrosion fatigue strength when compared to NAB, which retains approximately 27% of its fatigue strength (Meigh, 2009). In a typical propeller, to retain a comparable amount of fatigue strength in a stainless steel blade would require an increase in the blade section thickness by approximately 17% (Carlton, 2007; Meigh, 2009; Tuthill, 1987; Davis, 2001; Roberts et al., 1998; Rabensteiner et al., 2012).

HG10MNN was selected for this investigation as a propeller blade replacement material, due to superior mechanical properties as compared to other stainless steels. As compared to NAB, HG10MNN exhibits an increased elastic modulus, which may serve to limit or reduce the structural response of the propeller. Although HG10MNN exhibits a lower tensile yield compared to NAB, shown in Table 1, the overall performance of the propeller and platform may be improved (ASM, 2008; Carlton, 2007; Meigh, 2009; Merz et al., 2009; ASTM, 2013, 2014a,b).

1.1. HG10MNN

In May 2007, CF8C-Plus was submitted to ASTM for approval of a new heat-resistant cast alloy grade – HG10MNN. The alloy was originally developed by Oak Ridge National Laboratory and the

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Table 1
Properties of HG10MNN (per ASTM A743) and NAB (per ASTM B505) (ASM, 2008; Meigh, 2009; ASTM, 2014a, 2013).

	Tensile strength (ksi)	Yield strength (ksi)	Elongation to 2 in. (%)
HG10MNN	76	33	20
NAB	95	42	10

Table 2
Chemical composition of HG10MNN (per ASTM A297) given in maximum percent by weight (ASTM, 2014a).

C	Mn	Si	P	S	Cr
0.07–0.11	3.0–5.0	0.70	0.04	0.03	18.5–20.5

Ni	Mo	Cu	Nb	N
11.5–13.5	0.25–0.45	0.50	8.0–10.0	0.2–0.3

Caterpillar Technical Center for use in diesel engine exhaust manifolds. It is heat and corrosion resistant in its fully-austenitic cast condition (Maziasz et al., 2008a,b, 2009; Evans et al., 2010; Maziasz, 2008; ASM, 2008). Table 2 shows the chemical requirements of HG10MNN grade steel (ASM, 2008; ASTM, 2014a).

The austenitic matrix phase of this alloy has been stabilized through additions of Mn and Ni, eliminating the precipitation of intermetallics during thermal aging. Furthermore, the formation of stable nano-sized NbC and nitride constituents provides improved high temperature creep strength (Maziasz et al., 2008b; Evans et al., 2010). The alloy exhibits superior high-temperature mechanical properties; including tensile strength and ductility, creep resistance, fatigue behavior, and aging resistance relative to the standard grade CF8C cast stainless steel (Maziasz et al., 2008a,b, 2009; Evans et al., 2010; Maziasz, 2008; ASM, 2008) Also, Niobium, having higher affinity for carbon than chromium, prevents the carbon from bonding with chromium at the grain boundaries, which would result intergranular corrosion (Maziasz et al., 2009).

HG10MNN exhibits excellent castability for both thin and thick section application, and requires no post casting heat treatment for best properties. The alloy exhibits as-good or better fluidity compared to CF8C at equivalent pour temperatures due to its higher manganese content. The alloy is considered to be easily repaired due to its excellent weldability and Oak Ridge National Laboratory has reported good weldment properties at room temperature with no post-weld heat treatment (Maziasz et al., 2008a,b, 2009; Evans et al., 2010; Maziasz, 2008; ASM, 2008).

1.2. Objectives

The primary objective of this research was to investigate HG10MNN as an alternate material for use in a marine propulsion system. The microstructural and mechanical characteristics were compared to those of NAB, which is currently the primary material used in naval propeller blading.

Further objectives included demonstrating the ability of this alloy to be used in the manufacture of large scale propellers. A casting of HG10MNN was used to quantify thick section properties, as well as to evaluate coating systems and surface preparation. Furthermore, specimens from the casting were used obtain both high cycle corrosion fatigue data and qualitative corrosion data. As part of this project, castings of two test propellers were fabricated for installation on Yard Patrol (YP) craft at the United States Naval Academy (USNA).

An extended in-service evaluation on the casted YP propellers will be performed to measure high cycle corrosion fatigue and in-service performance. For this alloy, there is currently no quantitative corrosion data at low temperatures or in other corrosive environments. Due to the fact that only one propeller is being installed on the YP, there is concern for issues involving galvanic corrosion currents or minor weight imbalance. Since the propeller geometry will remain unchanged, the experimental propeller will generate the same thrust horsepower as the propellers currently in service.

Other special requirements for this alloy's application as a marine propeller were also considered: (1) the blading is required to be treated with anti-corrosive/anti-fouling paint system, (2) the propeller will be installed in concert with cathodic protection system implementing zinc sacrificial anodes, and (3) the propeller will likely operate for 6–12 months between maintenance inspections.

1.2.1. Castability

The castability of HG10MNN was evaluated at the Naval Foundry and Propeller Center (NFPC) in order to demonstrate that this alloy could be manufactured into the complex shape of modern propellers. Castability includes a qualitative evaluation of the molten fluidity, the ability to achieve the correct chemical composition, as well as a characterization of the solidified material's soundness (e.g., porosity, grain size uniformity, and the uniformity of mechanical properties) throughout the cast. As such, the castability of a 7 in. thick section was evaluated in order to demonstrate process quality and repeatability. In addition, future numerical modeling of large scale castings also requires that the thermo-physical properties of nominal HG10MNN be verified.

1.2.2. Material characterization

The objective of material characterization was to determine whether HG10MNN is a suitable material for use in a marine environment. One of the primary objectives was to obtain high cycle corrosion fatigue data in order develop fatigue curves in air and, eventually, in seawater. Secondary objectives included metallographic characterization and the evaluation of properties such as elastic modulus, tensile strength, ductility, hardness, impact strength, and corrosion resistance.

1.2.3. In-service data

The final objective of this research was to make preparations for obtaining initial in-service data via a demonstration project on a Naval Academy YP craft. This objective involved the manufacture and installation of two prototype propellers for long term evaluation over a period of approximately three years.

2. Description and discussion of work

2.1. Evaluation of casting

Casting trials were conducted at NFPC in July 2014. The purpose of these trials was to evaluate the casting characteristics for this alloy in order to establish and document a satisfactory casting procedure. Although detailed conditions of the casting procedure are