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Fracture behaviour of additively manufactured MS1-H13 hybrid hard steels

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ABSTRACT

This study investigated the tensile and fracture behaviour of additively manufactured MS1-H13 hybrid hard steel. Samples were prepared using Direct Metal Laser Sintering (DMLS) technique to additively deposit MS1 powder on as received H13 tool steel round bars. Four different heat-treatments were subsequently applied to the samples and uniaxial tensile tests to fracture were completed. Results found peak hardness/strength could be achieved with a single heat-treatment cycle and fracture in peak hardened samples occurred in MS1 adjacent to the print interface, as verified by Energy Dispersive X-ray (EDX) analysis. As-printed samples fractured in the H13 material away from the interface.

1. Introduction

The advent of additive manufacturing through 3D printing technologies can provide an economical alternative to replacing damaged tools, whereby a damaged surface can be printed to repair the tool back to working condition with desired properties. This could have a profound impact on tooling industry by reducing lead time and equipment capital while increasing tooling design flexibility. However, printing materials tend to differ in composition and performance from conventionally produced tool steels. In addition, the interface between the parent tool material and the additively produced repair material maybe inadequate to suit the demands of the tooling.

High-Speed Tool Steel (H13) is a well-known chromium-molybdenum steel that has been widely used in tooling applications mainly for hot working [1]. Its application arises from excellent thermal fatigue cracking resistance (or heat checking), which occurs as a result of cyclic heating and cooling cycles in hot work tooling applications [1,2]. The DMLS Maraging steel (MS1) has comparable heat-treatability and mechanical properties with H13, boasting an achievable hardness of >50 HRC approaching 60 HRC upon mild work hardening [3,4]. MS1 has a chemical composition corresponding to US classification 18% Ni Maraging 300 [5]. In addition to good mechanical properties, MS1 can also be easily machined, spark-eroded, welded, micro-shot peened, polished and coated in both as-built and age-hardened states [6,7]. Chemical composition of H13 and MS1 steels are presented in Table 1.

Previous studies have shown characterization and effect of heat-treatment on tensile and fracture properties of bi-metallic 3D printed steel and aluminum with copper [8–10]. However, the tensile strength of the interface directly is not presented. Thus, this study investigates the combined mechanical and fracture properties of 3D printed MS1 onto H13 tool steel and the effect of heat-treatments. This is accomplished from five hybrid samples processed through various heat-treatments and pulled in uniaxial tension to fracture. Stress-strain response, hardness, and SEM fractography are presented for all five samples.

2. Materials and methods

As-received and annealed round bars of H13 steel were mounted to the printing bed of an EOS M290 DMLS metal 3D printer, while the bed temperature was kept at 40 °C. The MS1 powder, provided by EOS of North America (produced by gas atomization method, particle size 15–45 μm), was subsequently printed vertically on to the H13 bars with a layer thickness of 40 μm (courtesy of Additive Metal Manufacturing (AMM) company in Concord, ON, Canada). All the hybrid samples were produced with 285 W laser

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Table 1
Chemical composition (wt%).

H13 tool steel					
C	Cr	Mo	Si	V	Fe
0.40	5.25	1.35	1.00	1.00	Balance

MS1 maraging steel									
Ni	Co	Mo	Ti	Al	Cr, Cu	C	Mn, Si	P, S	Fe
17–19	8.5–9.5	4.5–5.2	0.6–0.8	0.05–0.15	≤0.5	≤0.03	≤0.1	≤0.01	Balance

power at 960 mm/s scan speed with 0.11 mm hatch distance using stripes hatch strategy. One set of baseline samples was kept in the as-printed state, while four succeeding sets were heat-treated in a furnace to four different heat-treatment profiles. The first profile (P1) is the recommended heat-treatment for age-hardening MS1, which is simply aged at 914 °F (490 °C) for 6 h and then air cooled [6]. The second profile (P2) is the age-hardening profile for H13, which is preheating to 1500 °F (815 °C); then heat rapidly from the preheat in furnace to 1800 °F (982 °C) and hold at temperature for 1 h, and finally air quench. The five heat-treatment conditions tested were as follows: as-printed (sample 1), P1 (sample 2), P2 (sample 3), P1 then P2 (sample 4), P2 then P1 (sample 5).

After heat-treating, hardness across the sample interface was measured. The samples were then machined to ASTM E8 standard 6 mm round tension test specimens. After machining, the samples were pulled to fracture at 1.3 mm/min. In total, 10 specimens were tested, two as-printed and two for each heat-treatment condition. The fracture surface of the samples was then prepared for SEM/EDX analysis.

3. Results and discussion

3.1. Hardness

Hardness tests were performed on the samples before machining across the interface and results are presented in Fig. 1. All samples showed relatively constant hardness properties at distances greater than 1 mm from the boundary. The printed MS1 steel in samples 1 (40 HRC) and 2 (55 HRC) was significantly harder than the annealed as-received state of the H13 steel. In samples 3 and 4, hardness was marginally higher in H13 steel (55 HRC) than MS1 (51–53) and nearly equal hardness (54–55 HRC) for both steels in sample 5. In the as-printed state, the H13 steel's hardness is merely 5–6 HRC, and after the P1 treatment in sample 2 only increases to 10–11 HRC. The significantly lower temperature and shorter aging time of the MS1 designated heat-treatment profile (P1) is not observably effective in artificially aging the H13 steel. Conversely, the high temperature and hold times of the H13 desig-

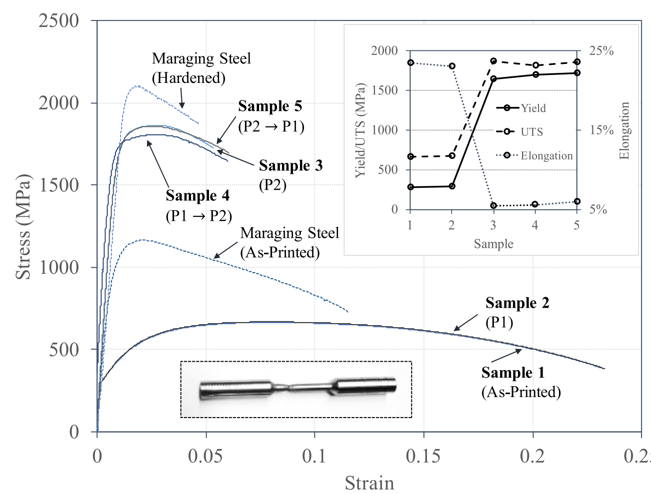

Fig. 2. Engineering stress-strain curves for hybrid test samples as-printed and heat-treated. Printed and heat-treated/hardened pure Maraging steel stress-strain curves are also shown as the dotted lines for comparison. The top inset summarizes the yield and ultimate stresses and elongation to failure of the five samples.

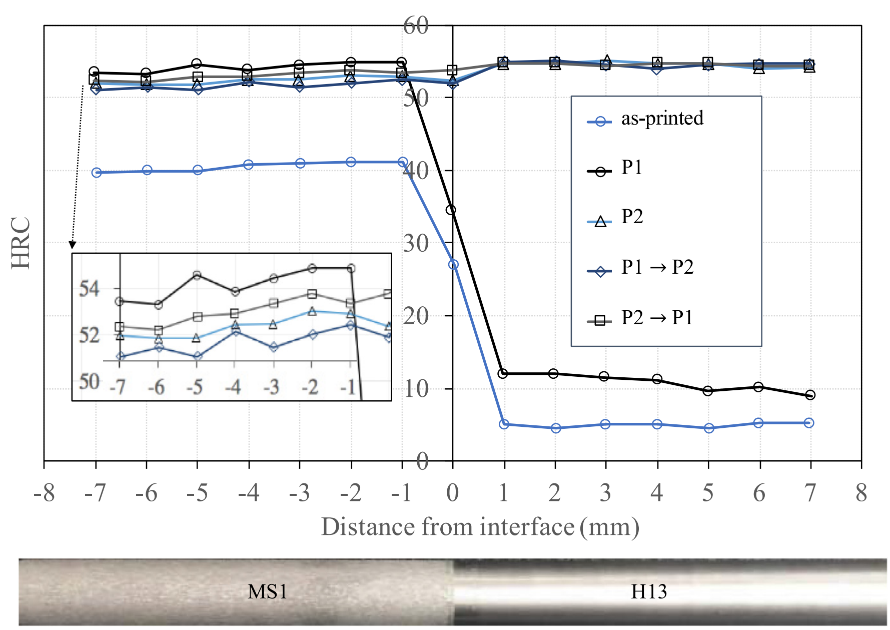

Fig. 1. Hardness of hybrid steel samples across the hybrid steel samples. All printed samples measured 99.8% density.