Solid Free-Form Fabrication of Dense Metallic Parts

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Abstract

Manufacturing of metallic parts has been performed by a novel variant of the three-dimensional printing technique. Green parts have been processed on a customized ink-jet printer by selective deposition of a solvent on powder-polymer granulate beds. Appropriated debinding and sintering treatments allowed to obtain 430L, 316L and 17-4PH stainless steel parts with good shape retention, and properties close to those of metal injection molding parts. In addition, the potential of this cost-effective technique for processing other engineering materials is shown. For instance, NiTi shape memory alloys and FeNi alloys have been successfully processed from pre-alloyed powders.

Introduction

Three-dimensional printing is a solid free-form fabrication technique, which consists in growing a part by consolidating layers of powders by binder deposition. The technique was developed at MIT [1] and some companies have licensed the technology for particular fields of use. Among the commercial non-metallic 3D-Printing materials one can mention plaster, starch, cellulose, and plaster-ceramic mixtures [2]. Parts made of these materials usually need a further polymer infiltration step for consolidation. 3D-Printing of metals with commercial machines is almost limited to stainless steel-bronze mixtures. In this case, as-printed green bodies are sintered to obtain 60% dense steel, which is infiltrated with bronze in an additional step to achieve full density [3]. Recently, manufacturing of dense steel parts has been reported [4]. Current 3D-Printing techniques use the deposition of proprietary binders on a powder bed for layer consolidation. Green strength, surface roughness and shape retention are common issues. In this paper, a novel process is described, which allows a greater flexibility in the choice of base-materials.

Experimental

A 3D-printer has been designed and built for rapid manufacturing of metal parts. A commercial ink-jet printer head is used to selectively drop solvent on powder-polymer granulate beds. The manufacturing process consists in growing a green body by spreading a granulate bed on a working table, selective printing solvent on a 2D area, moving down the working table, and repeating the process until consolidation of the final layer. The size of the printed solvent droplets is about 10 pL. The granulate layer thickness can be set between 50 µm and 200 µm. After removing loose powder, the green body is extracted and subjected to conventional debinding and sintering steps.

Raw materials are gas atomized powders eg pre-alloyed 17-4PH and 316L stainless steel powders (85% -16 µm, Carpenter Powder Products), 430L stainless steel (90% -16 µm, Osprey Powders), Fe50.0%wt.Ni powder and Ni50.5%at.Ti (D_{50} ~ 50 µm, Special Metals) prealloyed powders. Polymer-metal powder granulates were prepared by conventional methods and sieved to –100 µm. Green bodies were debinded and sintered in an ECM Lilliput furnace.

Particle size distribution was measured with a Malvern Mastersizer IP apparatus. The particle size distribution of 17-4PH steel powder is shown in Figure 1. Density measurements were performed by the Archimedes method. The microstructure was investigated by scanning electron microscopy with a LEO 1525 microscope. Hardness and tensile tests were performed on an Instron Wolpert Testor 930/250 durometer and a Zwick 1475 tensile test machine respectively.

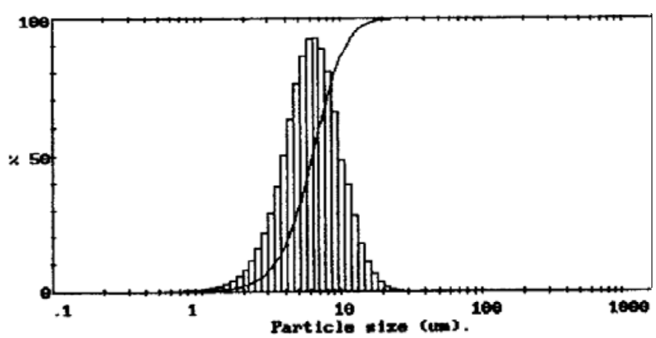

Figure 1: Size distribution of 17-4PH steel powder

Results and discussion

Figure 2a shows the layered microstructure of a 3-D printed 17-4PH steel green body. Figure 2b shows the spherical steel powder grains bonded by polymer, after reaction between the granulate and the printed solvent. The green strength is high enough to allow easy handling and eventual secondary operations (as selective polishing) previous to the debinding and sintering steps. Green parts were debinded at temperatures between 450°C and 650°C under hydrogen, and sintered at 1330°C for 3h under argon protective atmosphere. The measured density was about 95% of the theoretical density. Figure 3 shows reduced porosity in a section of a sintered part.

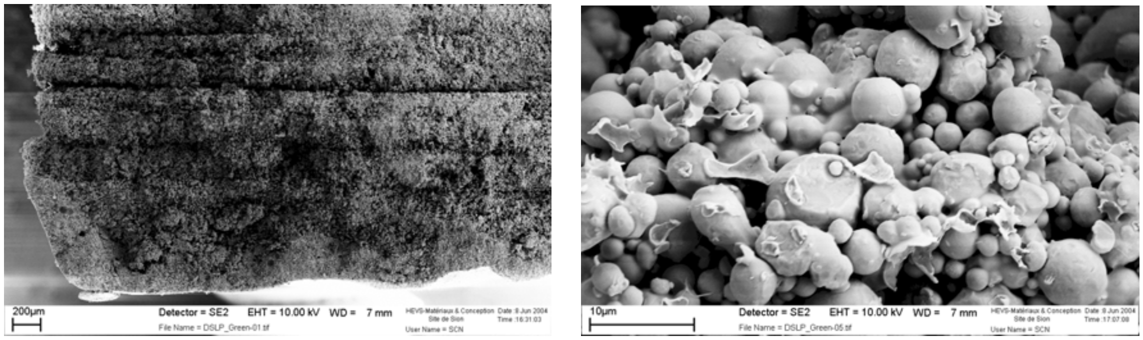

Figure 2: Microstructure of a 17-4PH stainless steel printed green body

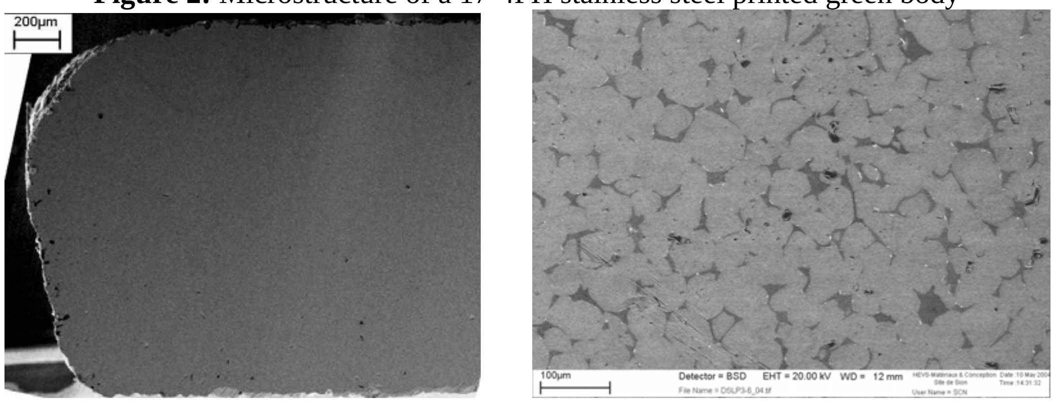

Figure 3: Microstructure of a 17-4PH steel finished part, after debinding and sintering.

Sintered parts were subjected to a solution treatment at 1035°C for 1h under cracked ammonia, followed by air quenching and precipitation hardening at 480°C for 4h. The tensile behaviour of both, as sintered and heat treated net shape specimens is shown in Figure 4. Yield strength, tensile strength and hardness values are similar to those of parts processed by metal injection molding (Table 1).

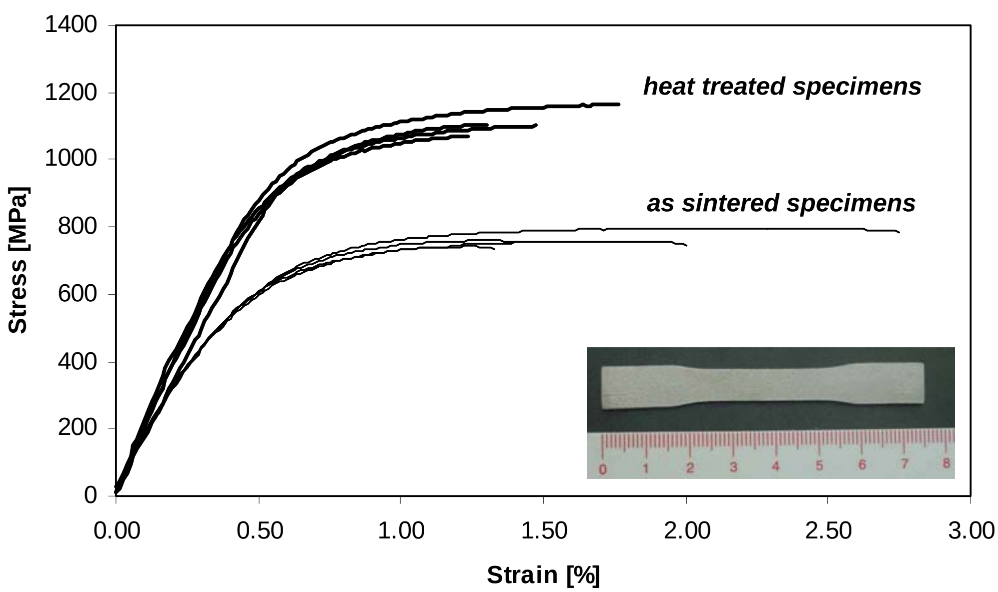

Figure 4: Tensile behaviour of 17-4PH stainless steel printed specimens

material	YS [MPa]	UTS [MPa]	HV Hardness
as sintered	696	765	205
heat treated	1006	1110	345
MIM (heat treated)	1090	1185	350

Table 1: Mechanical properties of 17-4PH steel (mean values on 4 specimens) processed by 3D "solvent on granulate" printing. MIM typical values are given for comparison [5]

The novel variant of the 3D-Printing process we present in this paper offers a great potential for obtaining dense parts of a wide diversity of materials, with good shape retention, density and mechanical properties. Some examples of complex net shape parts manufactured from different pre-alloyed powders are shown in Figure 5.

Figure 5: Finished parts on 17-4PH stainless steel (a, b, c, e), 316L stainless steel (d) and FeNi alloy (f)

Finally, new perspectives appear for materials, which are difficult to form by conventional methods. For instance, NiTi shape memory plates have been successfully processed up to 95 % of theoretical density. Differential scanning calorimetry and specific tests showed a sound shape memory behavior. These results will be published in a further work [6]. Experiments on manufacturing of ceramic and metal-ceramic composite parts are in progress.

Concluding remarks

A novel variant of the 3D-Printing process has been developed, which consists in selective deposition of a solvent on a granulate bed. The granulates are composed of metal powders and binder, which are mixed and sieved by conventional methods. The printed parts exhibit a sound green strength. Experiments conducted on 17-4PH stainless steel show that after debinding and sintering the density, tensile strength, yield strength and hardness are similar to the values obtained for MIM parts. Good density, shape retention and mechanical properties obtained for different materials show the flexibility and great potential of this 3D "solvent on granulate" printing technique.

Acknowledgements

The authors wish to thank A. Moreillon and J.-E. Bidaux for fruitful discussions. The technical support of N. Schmidt and D. Zufferey is gratefully acknowledged. This work has been supported by the University of Applied Sciences of Western Switzerland under HES-SO RS Grant.

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