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Mechanical properties of sinter-hardened Cr–Si–Ni–Mo based steel foam

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ABSTRACT

Highly porous sinter-hardenable Cr–Si–Ni–Mo based steel foam for automotive applications was produced by space holder method. Steel powders were mixed with binder (polyvinylalcohol) and space holder (carbamide), and compacted. Carbamide in the green compacts was removed by water leaching at room temperature. The green specimens were then sintered at temperatures between 1100 °C and 1250 °C for sintering times of 15, 30 and 45 min. In addition, the steel foams were sinter-hardened to enhance mechanical properties. Sinter-hardening combines sintering and heat treatment in one step by increasing the post-sintering cooling rate. This reduces the cost of operation and makes powder metallurgy more competitive. Effects of sinter-hardening process parameters on compressive strength, Young's modulus, hardness and energy absorption of the steel foams were investigated.

1. Introduction

Metallic foams have gained industrial importance, because of their low density, high specific strength, stiffness, and energy absorption properties. Their applications include lightweight panels, crash energy absorption, exhaust mufflers, vibration and noise control for automotive industry, filters, heat exchanger, wall panels for sound insulation and biomedical implants. The application depends on their macroscopic structure (pore size and pore morphology) as well as their mechanical properties [1–3]. Space holder-water leaching technique has been used to manufacture steel and titanium foams which having high melting temperature. In addition, pore shape and pore size can be controlled by using space holder [4–6]. Steel foams, currently under development, compete with existing traditional solid materials and aluminium foams [7–9]. Low cost steel foams are promising materials for crash protection, civil engineering, lightweight construction, packaging and shipbuilding.

Metal foams absorb significant amount of energy through its deformation. The absorbed energy is a sum of energy accumulated during elastic deformation and energy absorbed by plastic deformation. The latter is very important for crash energy absorption. Metal foams are commonly used in shock absorption applications. Their structure minimises the collision damage by energy dissipation and reduces transmitted forces. In metal foams, majority of the absorbed energy is converted into plastic deformation energy. This occurs in the broad stress plateau, which is typical of metallic foams. In the plateau, energy is absorbed by the bending and collapse of cell walls. The magnitude of the plateau is affected by yield strength. Thus, when compared to aluminium foams, steel foams can show greater energy absorption because of higher yield stress. As a result, energy-absorption properties of steel foams, which are desirable for applications in the automotive, railway and construction industries, are comparable with those of aluminium, and their lower cost makes them potential competitors [1–3].

The use of wrought metals containing Cr and Si is widespread because of improvements in hardening and mechanical properties at a modest cost. In addition, both of these elements have been used in a range of commercially available powder metallurgy (PM) materials. Because Cr and Si tend to form stable oxides, powder metallurgy alloys containing either of these elements have been sintered above 1205 °C to avoid the adverse effects of oxygen on mechanical properties. It is advantageous to develop alloys that utilise the benefits of Si and Cr in one system and have the ability to be sintered at conventional temperatures. One of the difference between wrought and PM steels is the use of Mo as a dominant alloying element. Mo has been used widely as a prealloyed element because of its large effect on hardening capacity. In addition, Mo has a synergistic effect with Ni. In the presence of Ni levels above 0.75%, Mo contributes to an increase in approximately 25% more hardenability [10–12]. Recently commercialised sinter-hardenable Cr–Si–Ni–Mo based PM steel, Ancorsteel 4300, was engineered to simulate wrought steel compositions and counteract the oxygen-related problems that are associated with Cr and Si. The trade name for this PM steel was derived from AISI 4340, a common wrought steel, which is familiar to many part designers in the automotive industry. It can be sintered at relatively low temperatures. Other advantages of this alloy include good compressibility, high hardening capacity, and dimensional stability. Combining Cr

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and Si within one system provides attractive strength and hardenability without the need for secondary quench treatments [10,11].

Sinter-hardening is a one step process and refers to the ability to produce martensitic as-sintered compacts. By controlling the post-sintering cooling rate, the microstructure can be manipulated to form martensite, which provides desired mechanical properties. Sinter-hardening combines sintering and heat treatment (austenitizing and quenching) in one step by increasing the post-sintering cooling rate. This reduces the cost of operation and makes powder metallurgy route more competitive. High hardness and high strength values are obtained while minimising the number of processing steps. The type and amount of alloying elements, sintering temperature and sintering time, and the post-sintering cooling rate all affect the amount of martensite in the microstructure. Increasing the cooling rate causes more austenite to transform to martensite. The addition of alloying elements such as Mo, Cu, Ni, and Cr improve hardening capacity. Sinter-hardening PM steel compositions allow the PM industry to eliminate the time and expense of austenitizing and oil quenching parts. In general, sinter-hardening process consists of compaction, sintering, rapid cooling and tempering steps [13–16].

In this study, highly porous Cr–Si–Ni–Mo based steel alloy foams especially for automotive industry and lightweight construction applications were produced by powder metallurgy based space holder technique. Although, high-density Cr–Si–Ni–Mo steel specimens have been produced by powder metallurgy route and the corresponding mechanical properties were determined [10], there is no study on production and sinter-hardening of Cr–Si–Ni–Mo steel foam. In addition, there is no study on sinter-hardening of any highly porous steel in the literature. Steel foams exhibit high energy absorption capacity due to their wide-plateau deformation region. But, their compressive strength is low for using it as a load bearing material. Therefore, improving the compressive strength of the steel foams without reduction of their energy absorption capacity is necessary. To get this aim, strength of the steel foams should be improved by heat treatment. In this study, the steel foams were sinter-hardened to enhance the mechanical properties. Influence of sinter-hardening process parameters (sintering temperature, sintering time and post-sintering cooling rate) on compressive yield strength, Young's modulus, hardness and energy absorption capacity were investigated. The most common metal which was selected for energy absorption applications is aluminium and its alloys due to their light weight [17–19]. The sinter-hardenable Cr–Si–Ni–Mo based steel alloy foams with low densities have better mechanical properties than Al alloys. In addition, Cr–Si–Ni–Mo alloy has lower raw material cost than Al alloys and powder metallurgy approach is also cost effective than liquid phase foaming process, which is used for Al based foam production. Other advantages of steel foams over Al foams are higher melting temperature, higher specific stiffness, and compatibility with steel structures.

2. Experimental details

Cr–Si–Ni–Mo based steel foams were produced by powder metallurgy based space holder method using Ancorsteel 4300 powders, which is a registered trademark of Hoeganaes Corporation, USA. The powder premix consisted of 98.65% irregular shaped Ancorsteel 4300 powder, 0.75% Acrawax (lubricant) and 0.6% graphite. The chemical composition of the powder was 1.09 w.% Ni, 0.99 w.% Cr, 0.80 w.% Mo, 0.12 w.% Mn, 0.10 w.% O, 0.64 w.% Si, and balance-Fe. Total and sintered carbon contents were 1.19 and 0.54 w.% respectively. Apparent, tap and pycnometer densities of the Ancorsteel 4300 steel powder were determined to be 3.16 g/cm^3, 4.60 g/cm^3 and 7.81 g/cm^3 respectively. Carbamide particles were used as space holder for its advantage of ease of removal in water. Spherical carbamide particles, supplied by Merck, Germany, were crushed and sieved to obtain the fraction of 710–1000 µm with an irregular shape. The weight ratios of the steel powder to the carbamide were calculated to obtain defined porosities in the range of 40–70%. The binder for green strength was polyvinyl alcohol (PVA), supplied by Merck, Germany. Fig. 1 shows scanning electron microscope (SEM), Jeol JSM 5600, image of the Ancorsteel 4300 powder.

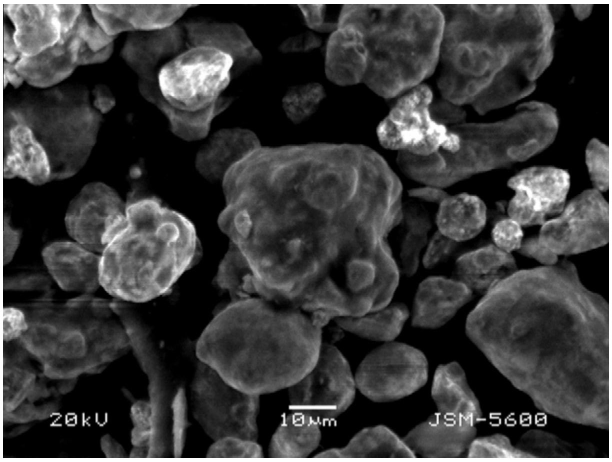

Fig. 1. SEM image of the steel powder.

Initially, 6 w.% PVA solution was added to the steel powder as a binder. Mixing of the steel, PVA and carbamide was performed in a Turbula type mixer. The mixture then compacted uniaxially at 180 MPa in a steel die using a hydraulic press into cylindrical specimens with a diameter of 12 mm and heights of 15–20 mm. The green specimens were immersed in distilled water at room temperature to leach the carbamide. About ~90% of the carbamide was leached in ~8–10 h, as confirmed by weighing the specimens before and after the space holder removal step. Thermal debinding temperature of the PVA was determined to be 410 °C by using thermo gravimetric analysis (TA, SDT Q600) at a constant heating rate of 5 °C under N$_2$ atmosphere. The PVA in the green specimens was thermally removed as part of sintering cycle.

Sintering process was consisted of heating at a ramp rate of 5 °C/min to 410 °C with a dwell time of 40 min (debinding), followed by heating at rate of 10 °C/min to sintering temperatures. The specimens were sintered at 1100, 1150, 1200 and 1250 °C temperatures for sintering times of 15, 30 and 45 min. The

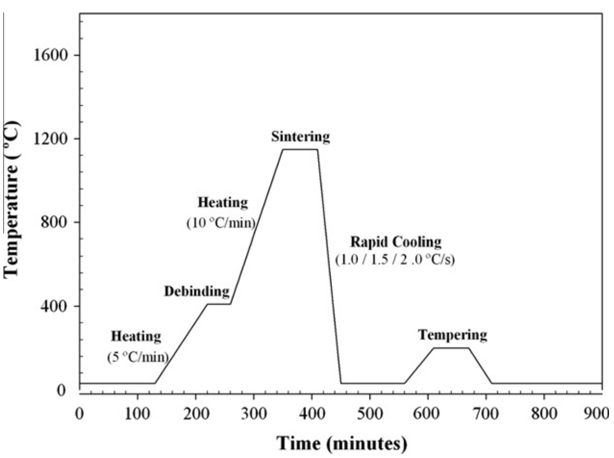

Fig. 2. Thermal cycle of the foam production and sinter-hardening process.