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High temperature mechanical properties of low alloy steel foams produced by powder metallurgy

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ABSTRACT

Cu–Ni–Mo and Mo based steel foams having different porosity levels for high temperature applications were produced by the space holder-water leaching technique in powder metallurgy. Steel powders were mixed with binder (polyvinylalcohol) and spacer (carbamide), and compacted. Spacer in the green compacts was removed by water leaching at room temperature and porous green compacts were sintered at 1200 °C for 60 min in hydrogen atmosphere. The successful application of foams at higher temperatures requires a good understanding of their high temperature mechanical properties. Compression tests were carried out on steel foams with different porosities at temperatures varying from room temperature to 600 °C in argon atmosphere. Effect of high temperature on compressive properties of the steel foams was investigated. It was found that the compressive strength of steel foams was greater at elevated temperatures than that at room temperature. This occurs across a range of temperatures up to 400 °C. Beyond this point the compressive strength decreased as the temperature increased. The reason for the enhancement of the compressive strength of Cu–Ni–Mo and Mo based steel foams is expected to be due to the effect of the dynamic age-hardening.

1. Introduction

Metal foams possess lightweight structure and good physical, chemical and mechanical properties, which make them suitable for a wide range of industrial applications [1,2]. The excellent combination of good mechanical properties and low weight is the prime advantage for such class of materials and in particular for steel foams [3–5]. Steel foams can be used as lightweight and high-functional materials in applications such as transport vehicles, machines and structural parts due to their low cost, low thermal conductivity, high working temperature, high specific mechanical properties, high impact energy absorption, high heat resistance and good weldability [6]. In recent years space holder-water leaching technique in powder metallurgy has been used to manufacture steel foams [7–12]. This technique is rather cost effective, flexible and leads to desired foam properties such as size, shape and volume fraction of the pores using an appropriate space holder material [13,14].

Metallic foams have a potential for use in applications where high temperatures are involved, e.g. the transpiration cooled rocket nozzles, a cooling system in the burning chamber of gas and steam turbines and as heat shielding for aircraft exhaust. In the case of metallic foams, there is a number of existing and prospective applications in which elevated temperatures are involved, e.g. open-cell foams are used as a key component in heat exchangers or as catalyst carriers in chemical reactors. Closed-cell foams are used as core materials in light-weight sandwich components, for example in automotive and aerospace constructions, where high temperatures exist frequently next to combustion or propellant engines [15,16]. Steel foams are promising materials for these applications because of their suitable properties.

To date, research on the mechanical properties of steel foams has mainly been focused on the room temperature mechanical behavior [7–12]. This is due to that steel foams are mostly used at room temperatures. However, in order to expand their applicability in the near future at high temperatures, information is required regarding their high temperature mechanical properties. Aly et al. [16] used the slip reaction foam sintering (SRFS) method to produce Cu–Ni–Mo and Mo based foams with densities between 1.3 g cm^{-3} and 2.0 g cm^{-3}. The foams' compression tests were carried out at different temperatures, ranging from room temperature to 600 °C in argon atmosphere. The compressive strength of steel foams increased with increasing the temperature up to 450 °C, beyond which the strength decreased with increasing the temperature. The reason for the enhancement of the compressive strength of foams is expected to be due to dynamic age-hardening. The foams' compressive strengths were less than 18 MPa at 450 °C temperature. Banhart [17] pointed out that the SRFS method may yield low-

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er strength values resulting from crack formation in the foamed material. Thus, space holder-sintering method could be used for processing steel foams having better mechanical properties.

It is well-known from the physical metallurgy of metals and alloys that the strength is reduced at high temperatures, and materials become softer and more ductile as temperature increases. However, the rate and direction of property changes can vary widely for the yield strength of various alloys as a function of temperature. These changes are due to various metallurgical factors. For example, aging, precipitation and resolutioning can occur in two phase alloys, both during heating prior to testing and during testing itself. The hardness and strength increases remarkably during high temperature testing due to dynamic ageing, especially in low carbon steel. Under certain combinations of strain rate and temperature, interstitial atoms can be dragged along with dislocations, or dislocations can alternately break away and be repined. The increase in strength at elevated temperature is attributed to the acceleration of precipitation in the grain boundaries [18]. It is important to understand mechanical behavior and microstructural changes during high temperature testing to achieve desired mechanical properties. High temperature mechanical behaviors of high density steels have been studied in several research works [19–22]. Kaçar et al. [23] investigated the high temperature mechanical properties of 2205 duplex stainless steel. It was found that the strength and hardness of the specimens increased until 500 °C. The reason for this increase was explained with the free interstitial atoms that obstruct the dislocation motion. A decrease in the mechanical properties was observed at 500 °C as a result of over aging. Lee and Zuidema [24] reported that sizes of the precipitations formed in the structure increase with an excessive increase in temperature. Therefore these precipitations cannot prevent the dislocation motion sufficiently. This situation is the main cause of the decrease in the mechanical properties.

The selection and use of pre-alloyed powders have many advantages over mechanical properties of sintered materials. Distaloy AB is a partially pre-alloyed iron powder containing copper, nickel and molybdenum. With additions of graphite, high strength is obtained after sintering. Distaloy AB consists of very pure iron powder which includes finely distributed diffusion bonded alloying elements. In this way the extremely high compressibility of the iron powder can be maintained where the risk of segregation is minimized. Distaloy AB has a good green strength. The alloying composition and the low oxygen content make Distaloy AB extremely dimensionally stable. Astaloy Mo is a water-atomized steel powder which is pre-alloyed with 1.5% molybdenum. This grade exhibits high compressibility and a homogenous microstructure after sintering. This, in combination with its optimal hardenability, makes this powder an excellent choice for components requiring surface hardening. The result is high surface hardness and good core toughness [25]. The alloying elements such as Ni, Mo and Cu have influence on the solubility of carbon in the austenite slowing down the rate of cooling at which martensite formed. Mo and Ni are used to increment the hardenability of steels. The alloying elements which tend to form carbides such as molybdenum decrease the %C that can be dissolved in the austenite, thereby increasing the amount of retained austenite. In addition, molybdenum increases the steel's strength and heat resistance [26,27]. Bekoz and Oktay [11,12] produced Distaloy AB and Astaloy Mo steel foams having different porosities by the space holder-water leaching technique in powder metallurgy. In the previous years, many researchers produced high density similar steel specimens by the powder metallurgy technique [27–29]. In all mentioned studies, mechanical properties at the room temperature of the produced specimens were investigated. Although a wide range of these steels have recently become available, investigations about the effect of high temperature on their compression behavior are still lacking.

The behavior of the mechanical properties at high temperatures should be further examined in order to use steel foams in a large scale. In this study, Cu–Ni–Mo and Mo based low alloy steel foams having different porosities were produced by the space holder-water leaching technique in powder metallurgy. Compression tests were carried out on the steel foams with different porosities at temperatures varying from room temperature to 600 °C in argon atmosphere. The influence of elevated temperature on the mechanical properties of the steel foams was investigated. The deformation behavior of steel foams was also characterized at different test temperatures.

2. Experimental procedure

Low alloy steel foams were produced using steel powders commercially known as Distaloy AB and Astaloy Mo, which is a registered trademark of Höganäs Company, Sweden. Distaloy AB is diffusion alloyed. The chemical composition of the powder was 1.5 wt.% Cu, 1.75 wt.% Ni, 0.5 wt.% Mo, and balance-Fe. Astaloy Mo is pre-alloyed, water atomized steel powder and contains 1.5 wt.% Mo. Both the powder premixes consisted of 0.8 wt.% zinc stearate as lubricant, and 0.2 wt.% carbon was added as fine graphite (UF4). Distaloy AB and Astaloy Mo steel powders had a size distribution between 45 μm and 150 μm with an average particle size of 112 and 109 μm, respectively and a rounded but irregular shape. The binder for green strength was polyvinylalcohol (PVA), supplied by Merck, Germany. Carbamide particles were used as space holder for its advantage of ease of removal in water. Spherical carbamide particles, supplied by Merck, Germany, had a density of 1.34 g cm^{-3}, melting temperature of 133 °C, and solubility in water at 20 °C of more than 1000 g L^{-1}. Spherical carbamide particles were crushed and sieved to obtain the fraction of 710–1000 μm with irregular shape. PVA solution, which consists of 2.5 wt.% PVA and water, was manually added to the steel powder. The weight ratios of the steel powder to the amount of carbamide were calculated to obtain defined porosities in the range of 50–80 vol.%. The spacer was moistened with distilled water to form a sticky surface and then the steel powder was added. Steel and spacer particles mixing were performed in a Turbula mixer for 60 min. The weight of steel-carbamide mixture was constant and equal to 50 g in all experiments. A small amount of water (about 1% in weight) was added in the mixture in order to avoid segregation of dissimilar powder and particles. Fig. 1 shows scanning electron microscope (SEM), Jeol JSM 5600, image of the steel powers. Typical morphologies of the carbamide particles, and coated carbamide particles with the steel powder are shown in Fig. 2. A homogeneous coating of carbamide particles with the steel powder was obtained.

Initially, 2.5 wt.% PVA solution was added to the steel powder as a binder. Mixing of the steel powder, PVA and carbamide particles was performed in a Turbula type mixer. The coated carbamide particles were then compacted uniaxially at 200 MPa into cylindrical shapes with a 12 mm diameter and height of about 18 mm. The green specimens were immersed in distilled water at room temperature to leach the carbamide. The green specimens' densities were determined from measurements of the specimens' weights and dimensions. More than 90% of the carbamide could be removed for theoretical porosities of 70 and 80 vol.%. About 15–25% carbamide remained in the green specimens for theoretical porosities of 50 and 60 vol.%. Thermal debinding temperature of the PVA was determined to be 450 °C by using thermo-gravimetric analysis (TA, SDT Q600) at a constant heating rate of 5 °C under argon atmosphere. The PVA in the green specimens was thermally removed as part of sintering cycle, which consisted of heating at a ramp rate of 5 °C min^{-1} to 450 °C with a dwell time of 30 min, followed by heating at a rate of 10 °C min^{-1} to sintering tempera-