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ADVANCED POROUS STRUCTURES MADE FROM INTERMETALLIC AND SUPERALLOY FIBERS

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In the past years, a new approach towards highly porous metal components has been under development at the Dresden based Department of Powder Metallurgy and Composite Materials of the Fraunhofer Institute for Manufacturing and Advanced Materials (IFAM). The components are made from melt extracted metal fibers, where the consolidation of the porous structure is achieved by sintering.

Interest in such open-porous structures arises mostly from functional high-temperature applications. Accordingly, components with porosities of 50 to 95 % were manufactured from intermetallics and superalloys like Ni_3Al and FeCrAl, respectively. Depending on the type of application, they were made in different shapes such as flat plates for heat shielding or tube-shaped filter candles for hot gas filtration.

In this paper, an overview of testing results relevant to potential applications is given. Measured material properties include heat conductivity, RT and HT strength, and oxidation resistance. In addition, the thermal cycling / thermoshock behavior of the porous structures was examined.

Keywords: *Cellular Metals, Superalloys, Intermetallics, Metal Fibers, Oxidation Resistance*

1. Introduction

Using the crucible melt extraction process (Fig. 1), it is possible to make short fibres from almost any fusible material **[**1**]**. A rotating wheel with a notched surface is placed over a melt pool. The rotating extraction device is water cooled and thus generates a high solidification rate. As a result, homogenous distribution of the alloying elements, small grain sizes, reduced segregation and extended solubility, as well as the formation of metastable phases is achieved. The melt extracted fibres typically show a sickle or kidney shaped cross-section.

FhG IFAM Dresden has improved the crucible melt extraction process to produce fibres of a mean equivalent diameter from 50 to 150 µm in batch sizes of one to several kilograms. The fibre length can be set from 3 to 25 mm with a deviation of approximately ± 15 %.

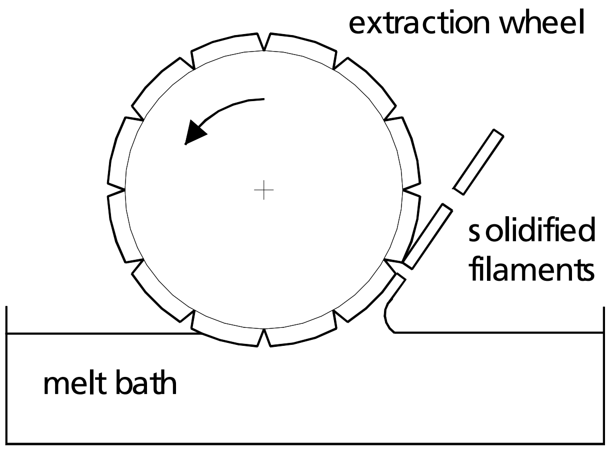


Fig. 1: Schematic drawing of the crucible melt extraction process

Plates, rings, and cylinders can be manufactured from the fibers by depositing them on a suitable sintering substrate, followed by sintering and machining to the desired dimensions (Fig. 2). The porosity of these structures can be anywhere between 70 and 95 % and is completely interconnected, allowing for free through-flow of fluids. The pore size is ususally between 10 and 250 µm, depending on the porosity and the fiber diameter.

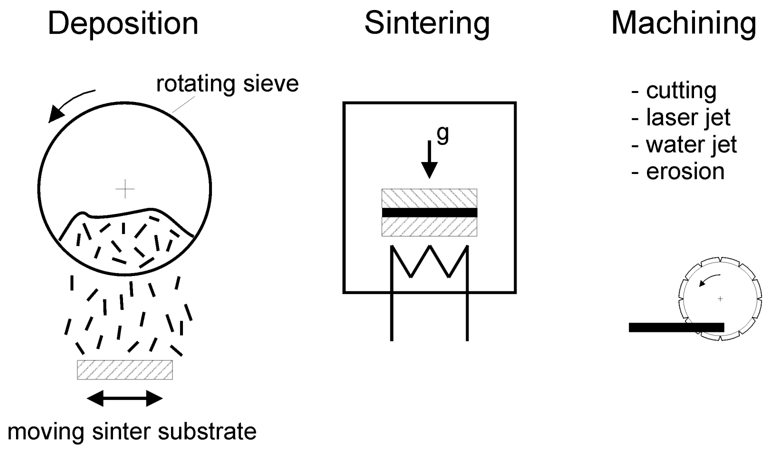


Fig. 2: Manufacturing of fiber structures

Alternatively, cold isostatic pressing can be applied in order to manufacture filter cartridges. The porosity of these structures is comparably low and amounts to only 50 % [2].

Potential applications are mainly utilizing the functional properties of the sintered fiber structures. Examples include high temperature filtration, flame stop elements, catalyzer substrates, heat shielding, radiant burner surfaces, or heat regenerators. Fig. 3 shows a prototype heat regenerator for a Stirling machine.

Fig. 3: Heat regenerator prototype for a Stirling machine made from sintered stainless steel fibers (porosity: 85 %)

2. High temperature oxidation resistance of fibers

In the course of an European project (POMFICO, Brite EuRam Project BE-5059) the elevated temperature performance of the fibres was a key issue, with special regard to the oxidation resistance in different environments. Because of the remarkable effect of higher Al-contents above 5 wt.% with regard to longer service life time of HT metallic materials, intermetallics based on NiAl were investigated as well as FeCrAl with an aluminium content of up to 15 wt.%.

Several test campaigns with Ni_3Al- and FeCrAl-based fibres were carried out. Fibres were manufactured by melt extraction techniques under inert gas conditions in a diameter range of 50 to 80 µm. The oxidation investigations were done at 1100 °C in air up to 1000 h holding time. The results have shown that the Ni_3Al-fibres doped with 0.5 % Hf and 0.2 % Zr reveal the lowest oxidation rate. Additions of Cr, Mo and Ta increase the oxidation due to internal oxidation. Higher contents of Silicon and Boron (1-2 %) exhibit a strong increase of the weight gain. This is a consequence of the formation of mixed oxides (Al_2O_3, SiO_2 and B_2O_3) with a porous and inhomogeneous scale morphology. In comparison to the unmodified Ni_3Al- as well as FeCrAl-fibres, the modified Ni_3Al-fibres have shown a 3 times lower oxidation rate in terms of weight gain, whereas the FeCrAl-fibres reveal a 2 times lower weight gain.

Further oxidation experiments showed that for FeCrAl small additions of Si lead to marked improvements. This way, oxide build-up could be further reduced by a factor of 3. The results were confirmed by optical micrographs. It was speculated that this effect may be the result of SiC formation instead of CrC. With these results, FeCrAl oxidation resistance becomes comparable to that of the best Ni_3Al based compositions. It seems thus to be reasonable to use the optimized fiber compositions in oxidizing environments up to 1200 °C with satisfactory service times.

3. Mechanical strength of sintered fiber structures

The mechanical behavior of sintered fiber structures can be approximated by the scaling laws for open-cell foams. Accordingly, the moduli decrease with the relative density squared, and strength decreases with the relative density to the power of 3/2 [3]. This means that high porosities (or, in other terms, low relative densities) naturally bring about a dramatic decrease in the mechanical properties. I.e. at a porosity of 90 % (corresponding to a relative density of 0.1) the modulus drops down to 1 % and the strength drops down to 3 % of the original value. This should be kept in mind when discussing the mechanical properties of highly porous materials.

The bending strength of sintered fiber structures was measured at room temperature and at 1000 °C. The size of the samples was 80 x 10 x 5 mm^3, with the distance of the supports being 60 mm and the support diameter being 10 mm. Taking the maximum value of the bending force, a bending strength was calculated. However, it should be noted that the failure mechanism of the fiber structures is different from that of bulk materials since rupture of single fibers may occur already before the maxium force is obtained. Tab. I gives an overview of the experimental results.

Table I: Bending strength of porous structures at different temperatures

Material		**FeCrAl 23.15**[1)]	**FeCrAl 23.15**	**Ni_3Al**	**Ni_3Al**
Porosity	(%)	70	90	70	90
Density	(g/cm3)	1.94	0.65	2.25	0.75
Bending strength at RT	(N/mm2)	83.4	9.8	119.6	19.6
Bending strength at 1000 °C	(N/mm2)	12.8	-	32.2	-

[1)] FeCrAl 23.15 consists of 23 % Cr, 15 % Al, bal. Fe

At 1000 °C, the bending strength drops down to 15 to 25 % of the RT value. The magnitude of this decrease is in good accordance with the reduction of the mechanical properties of bulk high temperature alloys at the same testing temperature.

5. Heat conductivity of sintered structures

The thermal conductivity was measured between 100 - 800 °C, using a comparison method.

For samples of comparably low porosity (70 % or less), the comparative method can be replaced by faster measurements via the Laser Flash Method. The thermal conductivity of 70 % porosity samples was therefore also measured via laser flash at temperatures ranging from 100 to 1200 °C. The results were in good agreement with former measurements obtained via the comparation method.

Fig. 4 and 5 show measured values of the heat conductivity of different materials in dependence of the density and the temperature. The heat conductivity of the bulk materials at 100 °C is approx. 8 W/(m K) for the FeCrAl 23.15 and 20 W/(m K) for the Ni_3Al. In the porous materials, the heat conductivity drops down to values significantly lower than those of the bulk material. Thermal conductivity was lowest in samples with 90 % porosity at low temperatures (approx. 0.5 W/(m K)). The highest thermal conductivity measured in the porous materials was found for Ni_3Al with 70 % porosity (2.25 W/(m K) at 800 °C). Thermal conductivity increases approximately linearly with temperature, however, between 100 °C and 800 °C, it almost doubles! This effect is slightly stronger in the porous materials due to the onset of convection in the pores.

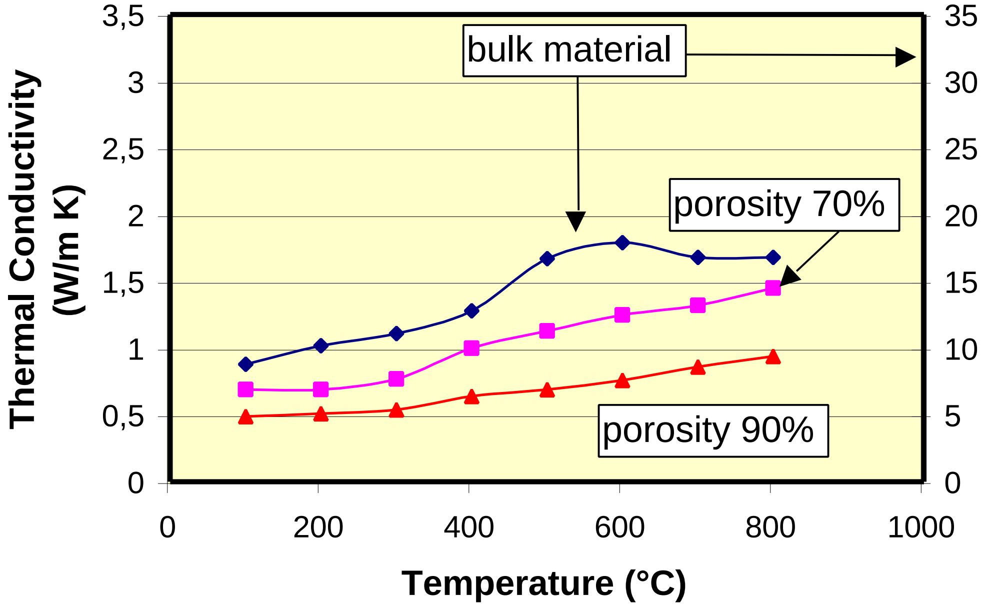


Fig. 4: Thermal conductivity of FeCrAl 23.15 in depence of the density and the temperature

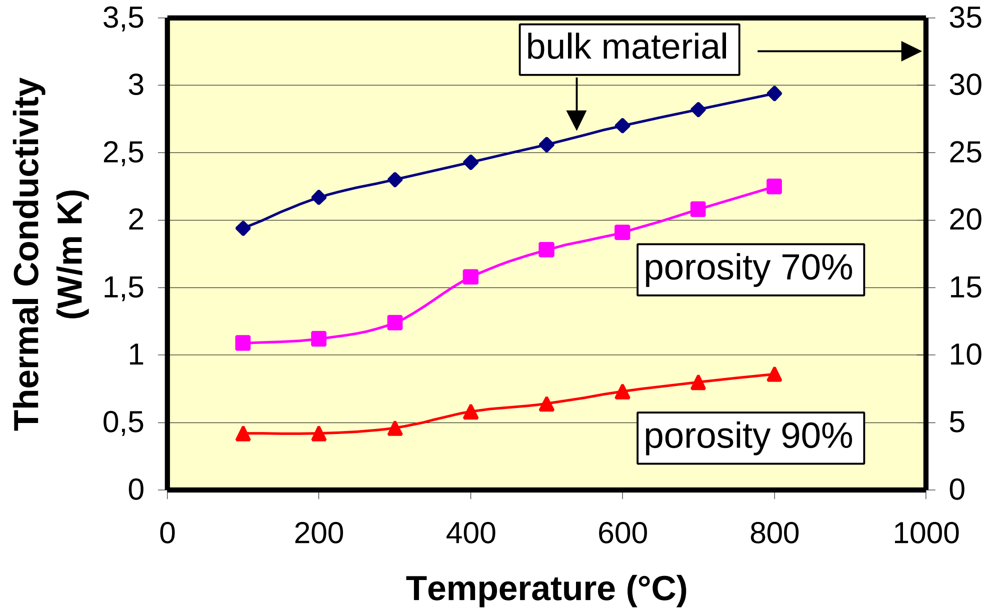
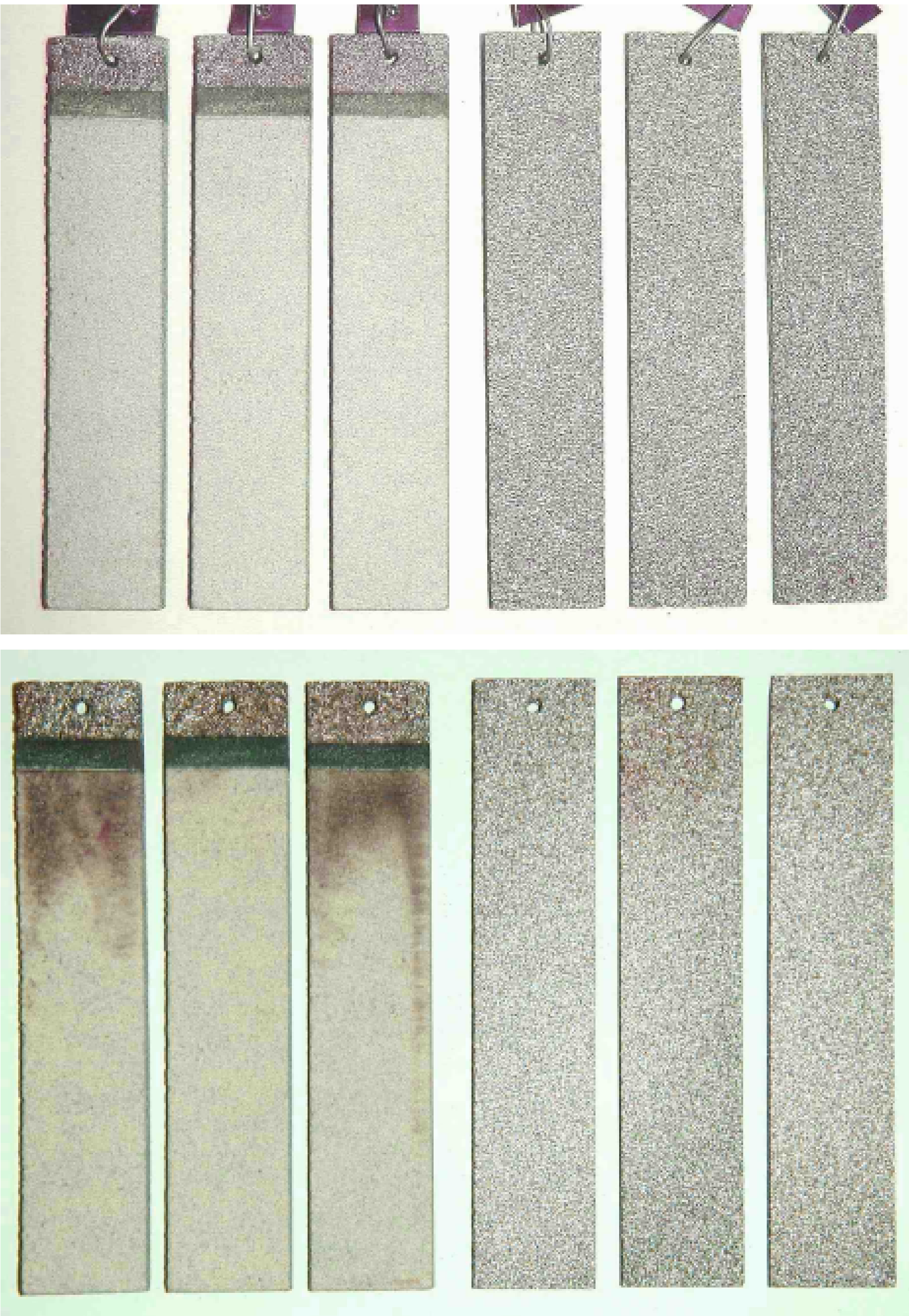


Fig. 5: Thermal conductivity of Ni_3Al in depence of the density and the temperature

6. Thermal cycling of sintered fiber structures with a thermal barrier coating

Due to their low thermal conductivity, highly porous metal fiber structures lend themselves as thermal shock resistant heat shields. For this purpose, sintered fiber structures were coated on one side with a thermal barrier coating (TBC) consisting of yttria stabilized zirconia. The coated specimens were tested for thermal shock response at temperatures between –50 and 400 °C under atmospheric conditions. No major changes in the samples were observed, the coating remained intact after 100 cycles (Fig. 6).



Sintered fiber strips before thermal cycling

left: coated side
right: uncoated side

Sintered fiber strips after thermal cycling

left: coated side
right: uncoated side

Fig. 6: Sintered FeCrAl 23.15 fiber structures before and after thermal cycling

7. Acknowledgements

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