Fatigue Properties of Diffusion-bonded Molybdenum Steel Powders for High Strength Applications

Dipl.-Ing. Guido Olschewski, Dipl.-Ing. Gregor Nitsch

QMP Metal Powders GmbH
Ohlerkirchweg 66
D-41069 Moenchengladbach
Germany

Abstract: Previous studies have shown that materials manufactured from a Fe1.5Mo-4.00Ni-2.00Cu diffusion-bonded steel powder exhibit very good static properties. Further investigation has been undertaken to optimise the alloying system. A diffusionp-bonded steel powder has been developed with a lower content of alloying elements (Fe1.5Mo-2.00Ni-1.00Cu). The high-alloyed and low-alloyed materials have been compared. Very similar static properties after sintering and rapid cooling have been found. The objective of this study was to compare the influence of different sintering conditions, cooling rates and heat treatment conditions on fatigue properties on the two different alloying systems. These materials are characterised by their excellent fatigue properties which are more than 30% higher than those achieved using the more conventional diffusion-bonded Fe-0.5Mo-1.5Cu-4.0Ni grade. These improved fatigue properties allow the manufacturing of PM parts that are exposed to high dynamic loads.

Introduction

The demand for high strength sintered components with high dimensional stability has grown strongly. This has resulted in the development of hybrid materials, which allows the manufacturing of high strength applications by using sinter hardening. Sinter hardening enables the manufacturing of both high strength and high apparent hardness components at a lower cost than conventionally sintered and heat-treated parts. The sinter hardening process requires a base powder with enough hardenability to generate a high amount of martensite when the parts are cooled from the sintering temperature. A suitable material for such applications is ATOMET DB49. This material is based on a 1.50% pre-alloyed molybdenum steel powder to which copper and nickel have been diffusion-bonded. The benefit of this system is the combination of high strength and hardenability of pre-alloyed sinter hardening grades with the good compressibility of diffusion-bonded materials. The pre-alloyed Mo-steel powder has been selected as base material in order to distribute the molybdenum homogeneously in the iron matrix – this cannot be obtained by admixing of diffusion-bonding molybdenum in standard sintering conditions. [1].

The static properties of ATOMET DB49 were evaluated in a previous study [2]. Components can be produced in this material with a tensile strength of more than 850 MPa by using normal sintering conditions in belt furnaces equipped with a rapid cooling zone without additional process steps like double pressing and double sintering.

Further investigation has been done to optimise the alloying system. A diffusion-bonded steel powder was developed with a lower content of alloying elements (Fe1.5Mo-2.00Ni-1.00Cu). This material is called ATOMET DB49L. The high-alloyed and low-alloyed materials showed very similar static properties after sintering and rapid cooling.

The objective of the study presented in this paper was the comparison of the influence of different sintering conditions, cooling rates and heat treatment conditions on fatigue properties of the two different alloying systems.

Experimental procedure

Two mixes were prepared with the nominal compositions shown in Table 1. Ni and Cu were diffusion-bonded to the pre-alloyed Mo-steel powder. Graphite and wax were admixed.

Mix	Mo, %	Cu, %	Ni, %	Graphite, %	Wax, %
A	1,50	2,00	4,00	0,50	0,75
B	1,50	1,00	2,00	0,50	0,75

Table 1: Nominal material composition

The mixes were compacted into MPA test bars (dog bones) and test bars for the evaluation of the fatigue strength at a green density of 7,00 gcm³. The test specimen were sintered at different sintering conditions (Table 2). Tempering treatments were carried out at 200°C for 60 minutes in air. Apparent hardness and tensile properties were determined according to ISO and MPIF standards. Microstructural characterisation was performed by optical microscopy.

No.	Furnace type	Temperature	Atmosphere	Cooling rate
1	muffle furnace	1120°C	H_2/gettered	low
2	mesh belt furnace	1120°C	endothermal gas	high
3	mesh belt furnace	1120°C	90% N_2 / 10% H_2	high
4	walking beam furnace	1190°C	90% N_2 / 10% H_2	high

Table 2: Sintering conditions

Bending fatigue properties with a load factor R = -1 have been determined by means of a resonance flat bending tester. Tests were done utilizing the staircase method. Each testing point represents the results of eight (8) up to fifteen (15) tested specimen. The step size was set to 10 MPa. Specimen which reached $2*10^6$ cycles were considered as run out. Test frequency was around 80 Hz. Calculation of σ_{10}, σ_{50} und σ_{90} was done according to MPIF 56.

Results and discussion

Specimen made from mix A as well as from mix B and sintered in industrial furnaces obtained hardness levels of up to 400 HB2.5/187.5 – independent of the gas atmosphere or the furnace type. In particular the level of alloying had no significant influence on the apparent hardness. Specimen sintered in QMP GmbH's muffle furnace showed lower hardness values due to low cooling rate.

Furthermore values of material B (215 HB2.5/187.5) were lower than those obtained with material A (254 HB2.5/187.5). Tempering reduced the hardness of all specimen. The decrease was approx. 50 HB 2.5/187.5 for material A and 35 HB 2.5/187.5 for material B. Hardness of muffle furnace specimen was decreased by 20 HB 2.5/187.5 for material A and respectively 5 HB 2.5/187.5 for material B.

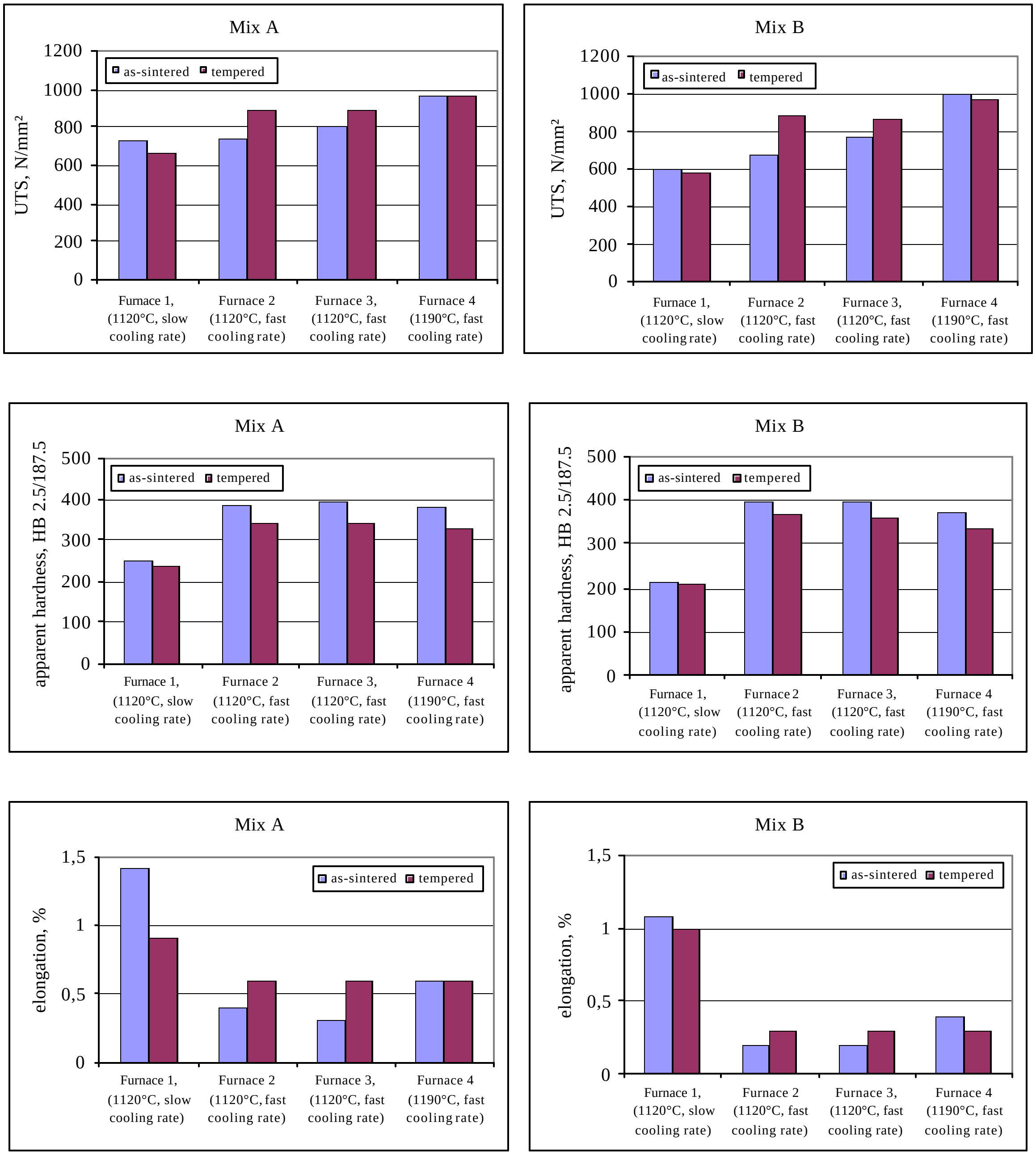


Figure 1: Effect of sintering conditions on tensile strength, apparent hardness and elongation of as-sintered and tempered (200°C/60 min/air) specimen

Tensile strength values of specimen sintered in mesh belt furnaces were between 870 MPa and 900 MPa after tempering. The results were comparable for specimen made from material A and material B. In the as-sintered condition, however, significant differences were observed. Material A sintered in N_2/H_2 –atmosphere showed the best value (801MPa) while material B sintered in endothermal gas showed the lowest strength level (675 MPa).

For both materials tempering slightly increased the elongation, which however remained on a low level of max. A=0.5%.

Specimen sintered in the walking beam furnace at 1190°C reached a tensile strength of 970 MPa for material A and more than 1000MPa for the lower alloyed material B. Tempering did not increase strength or elongation. Sintering in the lab muffle furnace resulted in lower strength levels (735 MPa for material A and 602 MPa for material B) compared to the other sintering conditions. Furthermore, tempering decreased the strength of those specimen. Elongation of slow cooled specimen was in the area of 1%.

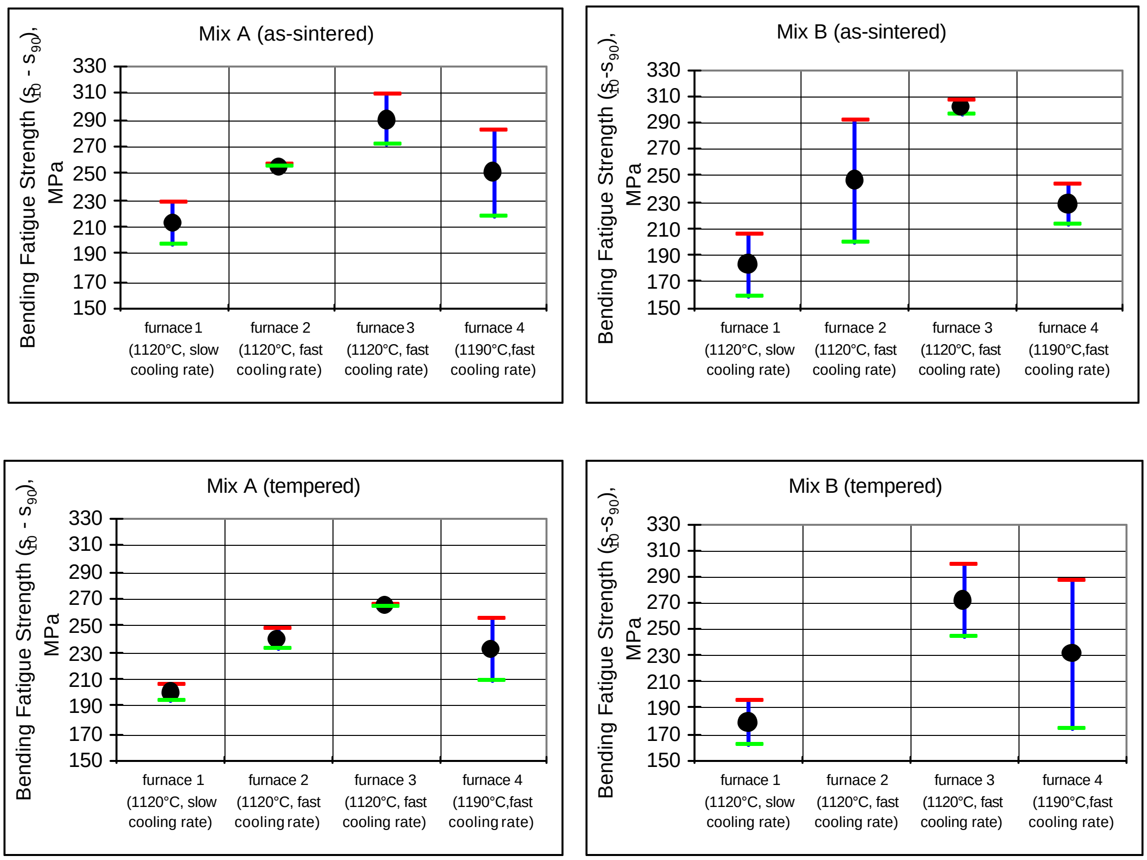
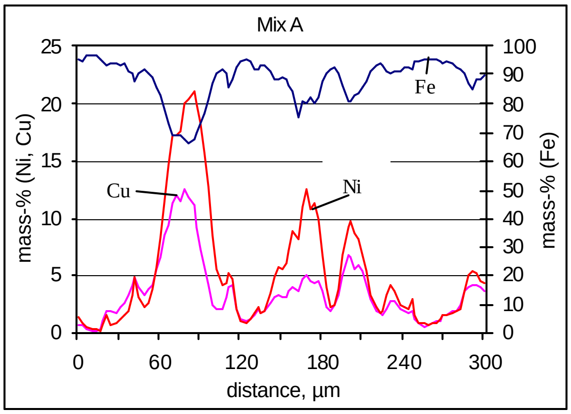


Figure 2: Bending fatigue strength of material A and material B

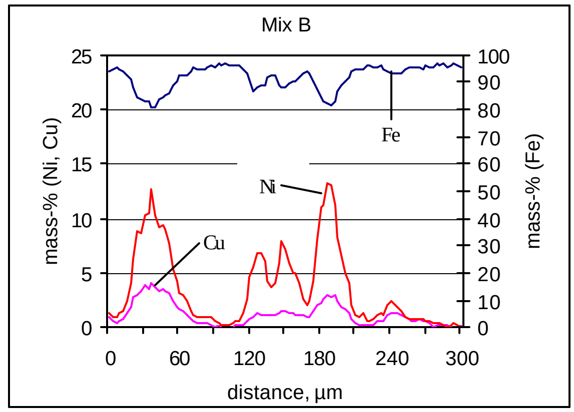
Specimen sintered in mesh belt furnaces showed comparable σa_{50} for both - material A and material B. However, specimen sintered in Endogas had significantly lower σa_{50} (approx. 250MPa) than those sintered in N_2/H_2 (approx. 290 MPa).

Specimen made from material A and sintered in a walking beam furnace showed comparable fatigue strength to those sintered in Endogas (σa_{50}=250MPa). Specimen made from material B were in the range of σa_{50} = 230 MPa. After 1120°C sintering there is no difference between σa_{50} for material A and material B.

Tempering decreased bending fatigue strength by approx. 20MPa for all specimen (material A & B, furnace 1 - 4) except for those made from material B sintered at 1190°C. Specimen sintered in the lab muffle furnace showed by far lower σa_{50} than the rapid cooled specimen.
Although there could be limitations on the accuracy of the σa_{10} and σa_{90} calculation using only 8 to 15 specimen, it can be seen as a trend that specimen made from material A had a more narrow range $T(\sigma a_{10} / \sigma a_{90})$ than those made from material B. This trend should be confirmed by a more extensive test with a larger number of specimen in the future.



1120°C/30 min/fast cooling rate



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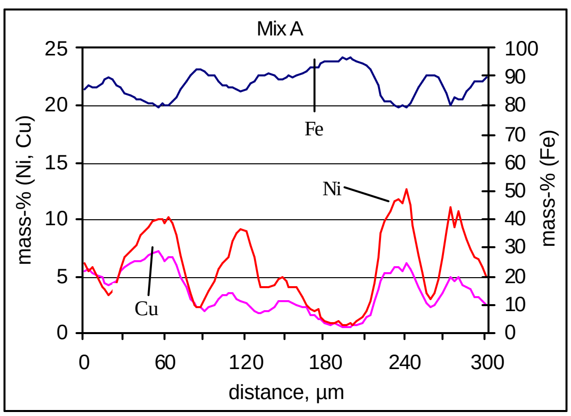
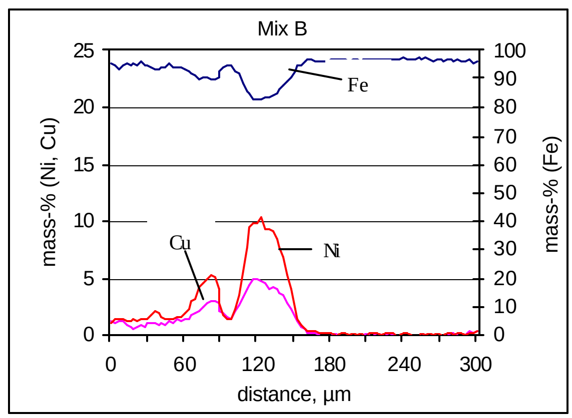


1190°C/30 min/fast cooling rate



1190°C/30 min/fast cooling rate

Figure 3: line scans of material A and B after sintering and tempering (200°C/60 min/air)

The above mentioned results show that the hardening mechanism differs between the muffle furnace and the production furnaces used in this study. This is particularly related to the low cooling rate of the muffle furnace. The cooling rate was not fast enough to form a martensitic microstructure. The specimen sintered in the muffle furnace showed the highest differences between material A and material B in apparent hardness, tensile strength and elongation. Tempering of these specimen did not significantly decrease the apparent hardness values. This confirms that microstructure is composed of only a few martensitic areas and mainly consists of bainite, pearlite and nickel-rich austenite as shown in Figure 4 This also explains the highest elongation values obtained.

Increasing the sintering temperature leads to higher tensile strength. It was confirmed by line scans (Figure 3) that the Ni-distribution is more even after sintering at 1190°C. As a matter of fact low alloyed Ni-material (material B) has also a lower fatigue bending strength after sintering at higher temperatures. One can assume that the percentage of nickel-rich austenite has become too low to act as an effective crack stopper. This was also observed in a previous study [3].

Apparent hardness of specimen made from material A dropped by 50 HB 2.5/187.5 after tempering while those made of material B was reduced by about 35 HB2.5/187.5. This proves that the amount of martensite is lower in material B. However, the apparent hardness of both materials A and B in the as-sintered condition is similar since the percentage of the relative soft austenite in material B is lower, thus compensating the lower percentage of martensitic structure.

Conclusion

The newly developed ATOMET DB49L (Fe1.5Mo-1.00Cu-2.00Ni) is a cost effective alternative for sinter hardening applications. The bending fatigue limit of ATOMET DB49L exceeds the one of the well-established diffusion-bonded material Fe0.5Mo-1.50Cu-4.00Ni by up to 30% [4, 5].

Very similar static and fatigue properties can be achieved with this material compared to those provided by the higher alloyed sinter-hardening grade ATOMET DB49 in case of adequate cooling rates.

The cooling rate is a key parameter dictating not only the static properties but also the fatigue properties of sinter hardenable PM materials.

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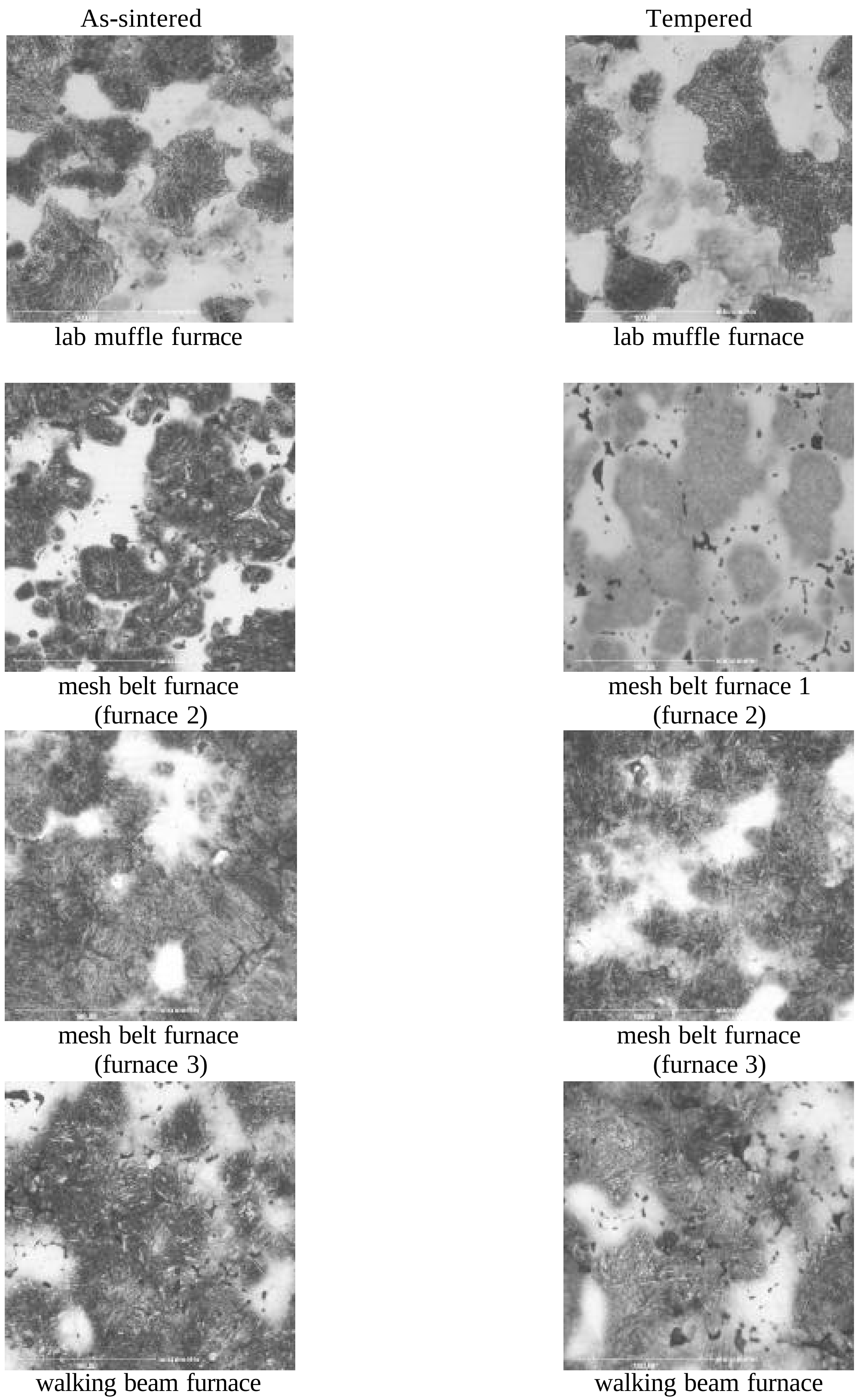

Figure 4: Micrographs of test bars made from material A, sinter conditions see Table 2 (ATOMET DB49 + 0,50% graphite + 0,75% wax)

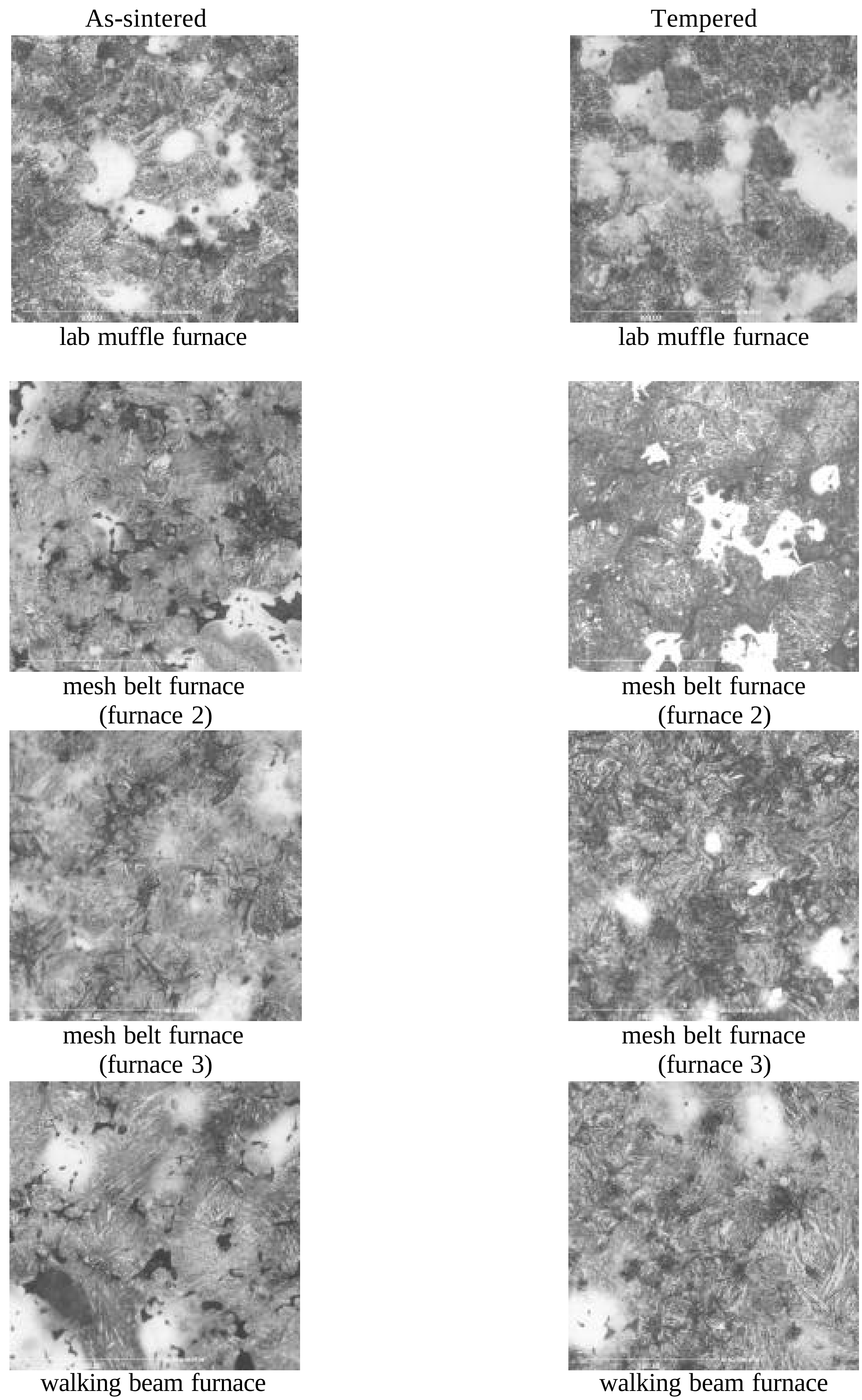

Figure 5: Micrographs of test bars made from material B, sinter conditions see Table 2 (ATOMET DB49L + 0,50% graphite + 0,75% wax)