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Consolidation of Fe-Cu PM alloy for recycling of scrap iron

H. Kakisawa, K. Minagawa, S. Takamomi, Y. Osawa and K. Halada
Ecomaterials Research Center, National Institute for Materials Science
1-2-1 Sengen, Tsukuba City, Ibaraki 305-0047, JAPAN
Fax: 81-29-859-2601 e-mail: KAKISAWA.Hideki@nims.go.jp

For the purpose of utilizing copper-rich scrap iron as have been dumped or used for die casting, a new powder metallurgical technique was investigated. Rapidly solidified iron-copper powder was produced by high-pressure atomization and consolidated at a low temperature of 873K. The consolidation succeeded without pores in all the range of copper content, 0.5-5mass%. The microstructure of the powder and the consolidated samples were observed; they had the microstructure where copper was dispersed on the order of nanometers in ferrite matrix.

Mechanical properties of the consolidated samples were examined and correlated with the microstructure. They showed a good ultimate tensile strength of over 700MPa and an elongation over 10%. The good performance of the samples was attributed to the microstructure of the consolidated samples ascribable to the copper-dispersed microstructure of the powder.

It was shown that the copper rich scrap iron could be reproduced into a material with higher performance than before recycling by the newly proposed processing, when we utilize the impurity properly and control the microstructure.

Keywords: Fe-Cu alloy, rapidly solidified powder, tensile behavior, strengthening mechanism

1. INTRODUCTION

Copper, a major impurity in scrap iron from such as vehicles and electrical appliances, is one of the most troublesome elements. It is very difficult to remove from iron by a conventional refining process when it is mixed during the shredding process. The iron scrap with significant copper impurity has been recycled in casting at best, or dumped without recycling. A huge amount of scrap iron is being produced, and the copper content in iron scrap has continued to increase over the years [1].

On the other hand, iron-copper systems have been applied often in powder metallurgy to obtain high-performance consolidated products. Liquid phase sintering is often used for the consolidation of iron powder. Melted copper surrounding iron powder fills up opening spaces and helps densification [2-4]. In advanced researches, mechanically alloyed Fe-Cu powders where copper is supersaturated are consolidated in various methods at relatively low temperatures of ~873K [5-8]. The immiscibility of these metals produces an ultrafine microstructure, and the maintained powder microstructure due to the low consolidating temperature results in nanostructured materials with good mechanical properties.

Our intention is to utilize copper impurity as reinforcement in powder metallurgy because it was reported that the nano-precipitated copper in ferrite matrix gave rise to remarkable precipitation hardening [9-15]. For this purpose, a high-pressure water atomization is applied to obtain a powder where copper is minutely precipitated by rapid solidification. To consolidate the powder with the copper-dispersed microstructure maintained, a rolling technique is used because it gives the consolidation at a relatively low temperature.

In this paper, the appropriate consolidation condition is examined, and the mechanical properties of the consolidated samples are investigated.

2. EXPERIMENTAL PROCEDURE

Fe-Cu alloy powder (Nippon Atomized Metal Powders Corporation, Tokyo, Japan) was prepared by high-pressure water atomization. The mean grain size of the powders was 5 μm in diameter, and the copper content was 0.5 mass%, 2mass% and 5 mass%. X-ray diffraction (XRD) analysis of the powder was done using CuKα radiation, and the transverse section was observed by scanning electron microscopy (SEM).

The powder was kept in a vacuum at 753 K for 54 ks in order to remove surface contaminants of

Table I Rolling path and cross-section reduction rate.

Rolling Path	0	1	2	3	4	5	6	7	8	9	10
Bar Diameter (mm)	40.0	35.0	31.7	28.7	25.9	23.5	21.3	19.3	17.5	15.8	14.3
Cross-Section Reduction Rate	0.0	23.4	37.2	48.5	58.1	65.4	71.6	76.7	80.8	84.4	87.2

the powders such as hydroxides and then the powder was canned in a low carbon steel sheath with an outer diameter of 40mm. The capacity of the sheath was about 84.8cm^3 and 330g of the powder were put into the sheath; the powder packing density in the sheath was about 50%. The sheath was rolled into a bar just after being heated at 873 K for 3600 s. The powder in the sheath was consolidated through the rolling. The rolling paths are listed in Table I. During the rolling, the sheath was re-heated at 873K for 300 s every three steps to avoid temperature drop. The time for the 3-step rolling was less than 60 s. The cross-section reduction rate, R, defined by

$$R = \frac{S_0 - S}{S_0} \times 100 \quad (1)$$

where S_0 is the initial cross-section of the bar and S is the cross-section after rolled, was varied; the bars with R = 65.4, 71.6, 76.7, 80.8, and 87.2 were obtained.

Microstructure of the rolled samples was observed by SEM and transmission electron microscopy (TEM). Energy dispersive X-ray spectroscopy (EDS) was done in TEM observation. Round tensile test specimens of which the parallel span was 24.5 mm and the diameter was 3.5 mm were prepared from the obtained samples, and tensile testing was done in air at room temperature with a constant crosshead speed of 8.3×10^{-3} mm/s.

3. RESULTS AND DISCUSSION

3.1 Powder characterization

Figure 1 shows the X-ray diffraction pattern of the as-atomized powders. The peak of ferrite and fcc copper were detected. The peak of copper became remarkable with the increase of copper content, indicating the copper state in the powder is the precipitates within ferrite matrix rather than super-saturation.

The transverse section of the as-atomized powder (Cu: 0.5mass%) is shown in Fig. 2. There were no coarse copper precipitates either in the powder or on the powder surface. Precipitates (gray dots in the photograph) of several tens nanometers were observed. At the powder surface, an oxide layer formed during water atomization was observed.

3.2 Microstructure of the consolidated samples

Figure 3 shows the relation between pore volume fraction and cross-section reduction rate for the copper content of 2mass%. With the progress of the rolling, the consolidation proceeded. In the sample rolled at R = 87.2,

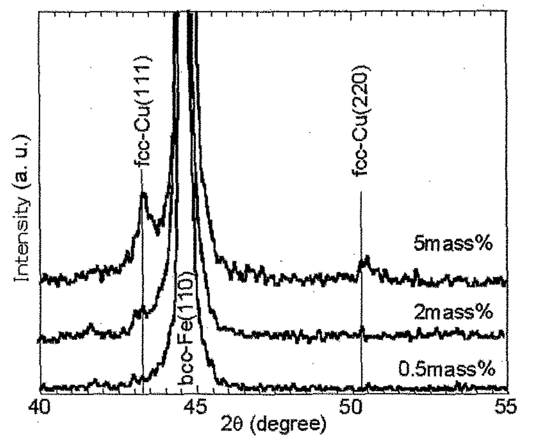

Fig.1 X-ray diffraction pattern of the powder.

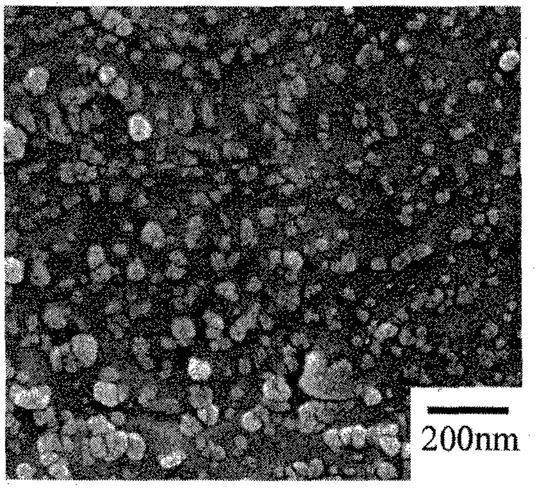

Fig.2 Microstructure of the powder (Cu: 0.5mass%).

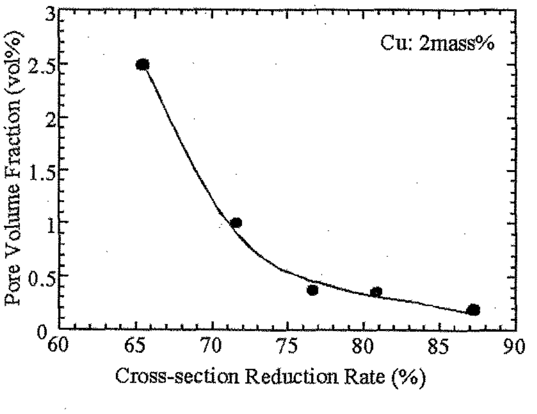

Fig. 3 Relation between pore volume fraction and cross-section resduction rate.

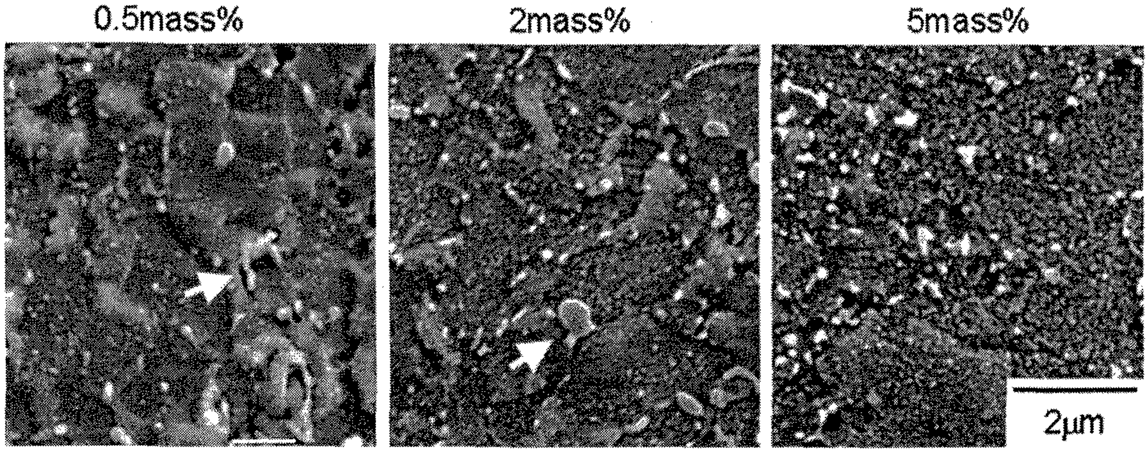

Fig. 4 Microstructure of the consolidated samples.

nearly the full density of the 99.8% was obtained. Since the powder packing density of 99.8% was obtained. Since the powder packing density in the sheath before consolidation was about 50%, the data indicate that good consolidation was achieved though the rolling procedure used in this study.

Figure 4 shows the microstructure of the transverse section of the consolidated samples. In any of samples, the primary powder boundaries remained. Copper was precipitated both at the boundaries and within the boundaries. The size of the precipitates at the boundaries ranged from 40 to 200nm, while the precipitates within the boundaries was too minute to measure the size with SEM. The precipitation became more remarkable with the increase of copper content. The oxide inclusions (indicated by arrows) which had been originally at the powder surface were observed.

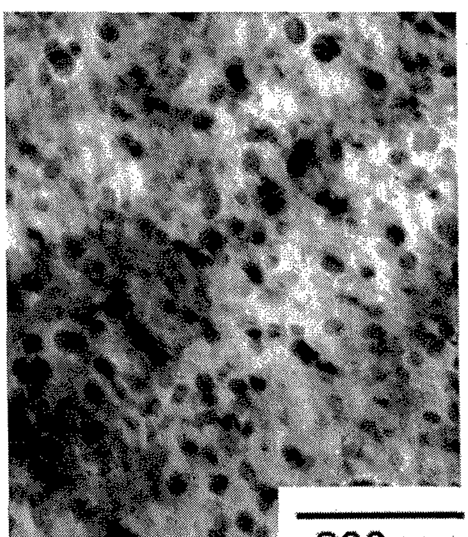

Fig. 5 Precipitates in the consolidated sample.

Figure 5 shows the result of more precise observation by TEM for the sample with 5mass% copper. Round precipitates of approximately 20nm in diameter were distributed in the sample. The number of precipitates increased with the increase of copper content. From the result of EDS from one of the precipitates, as shown in Fig. 6, the precipitates were found to be copper rich phase.

3.3 Tensile properties

In all the tensile testing of the samples, the stress increased linearly and then continuously yielded. After the yielding, the stress increased up to a maximum. Then the stress started to decrease, and the samples fractured.

The ultimate tensile strength and elongation of the samples consolidated in the optimum condition are plotted against the copper content in Fig. 7. The strength increased with the increase of copper content in the samples, clearly indicating the contribution of copper to strengthening. The elongation decreased as the copper content increased. The sample with 5masss% had a significantly high strength of 867MPa compared with ones consolidated by conventional sintering with an equivalent copper

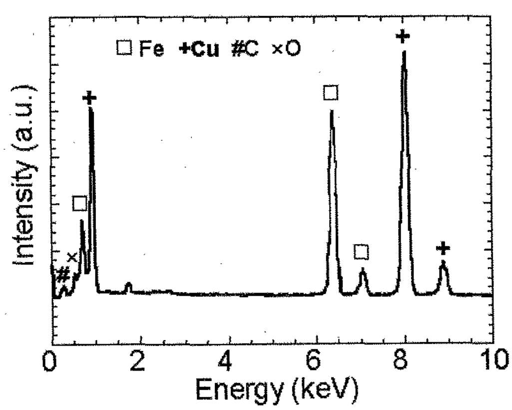

Fig. 6 EDS from a precipitate observed by TEM.

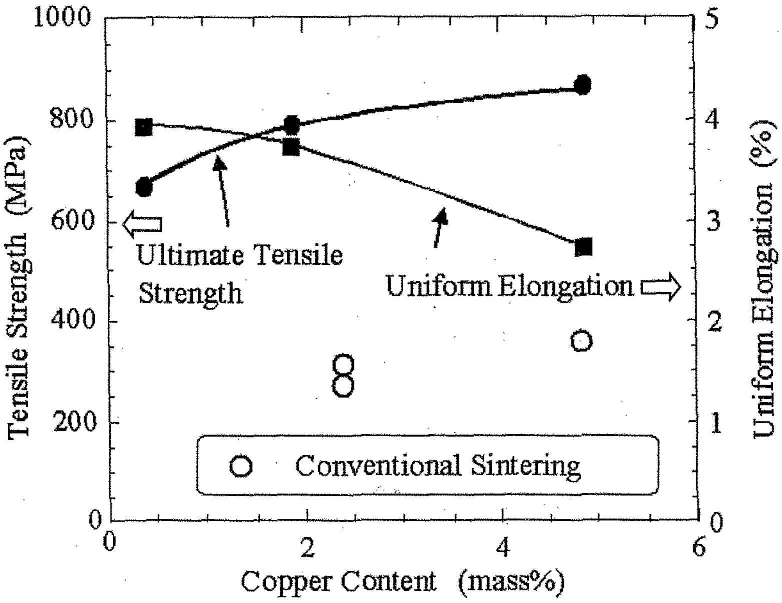

Fig. 7 Plots of ultimate tensile strength and uniform elongation of the consolidated samples against copper content.

content. Moreover, the samples had considerable elongation in all the range of copper content, exhibiting a good strength/elongation balance: 11.7% total elongation 3.9% uniform elongation at 0.5mass% copper; 6.9% total elongation and 2.7% uniform elongation even at 5mass% copper. A high strength powder-consolidated product utilizing copper has been achieved by the combination of rapidly solidified powder and rolling consolidation technique, and the process is applicable up to the copper content of 5mass%, which is the extremely high amount as a tramp element. This indicates that the great possibilities of supplying a new use of scrap iron including significant copper, as has been applied only to casting.

4. CONCLUSION

Rapidly solidified Fe-Cu powder was successfully consolidated by rolling procedure at a low temperature of 873K. This resulted in maintaining the fine powder microstructure where copper was nano-dispersed. The Consolidated samples showed significantly higher tensile strength than that of sintered materials. It was attributable to the fine microstructure of the samples. The potential of utilizing copper by the proposed powder metallurgical technique was shown.

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