Effect of shot particle conditions on the transfer of copper induced by fine particle peening

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Abstract

Fine particle peening (FPP) is a promising technology to improve fatigue life of mechanical components. In addition, transfer of shot particle elements from the particle to the treated surface occurs during the FPP process. This phenomenon is effective to modify the surface characteristics by concentrating the transferred elements onto the treated surface. In this paper, the authors carried out FPP to enrich the aluminum and steel substrate with copper, which has lots of attractive properties such as high electric conductivity, high thermal conductivity, antibacterial properties, and so on. Two types of hybridized particles which comprised the steel particle and overlying copper layer were developed to accelerate the transfer. The one was "agitated particles" prepared by mechanical mixing using the mortar, and the other was "coated particles" prepared by electroless copper deposition. FPP-treated surface with the hybridized particles and the commercial copper particles were prepared and characterized to discuss the effect of shot particle conditions on the transfer phenomena. Results indicated that the amount of copper transferred by FPP using the hybridized particles, especially the "coated particles", was greater than that by using copper particles. The hybridized particles enhanced the transfer of copper since the impact of hard steel particles effectively expose the virgin metallic surface, accelerating the bonding between the substrate and particles. Ability of the hybridized particles to induce transfer was correlated with the hardness ratio between the substrate and the particles. It was revealed that the hybridized particles were beneficial for FPP to induce transfer of low hardness material.

Keywords Fine particle peening, material transfer, hybridized particles, copper, hardness, surface characterization

Introduction

Fine particle peening (FPP), in which shot particles with a diameter of up to 200μm are bombarded to material surface, is widely applied to improve the fatigue life of mechanical components. In addition, FPP concentrates shot particle elements on the treated surface. One of the authors has investigated the detailed mechanism of the concentration [1]. According to the report, the fragments of shot particles are transferred onto the surface followed by mixing into the subsurface materials during FPP process. The driving force of FPP transfer is the micro ploughing phenomena by particles, which expose virgin metallic surface of the treated materials.It is assumed that concentrating shot particle elements on the material surface possibly improves various characteristics of the material. For example, adhesion of diamond-like carbon (DLC) films to the steel substrate can be increased by creating the chromium-rich surface by FPP using chromium particles [2]. Chromium has good compatibility to the DLC film so that the film adhesion is enhanced by enriching the surface with chromium. Copper is also a potential element to be concentrated by FPP because of its attractive characteristics such as high electric conductivity, high thermal conductivity, antibacterial properties, etc. In general, copper can be deposited by electro or electroless plating methods. However, plating methods are not suitable for the aluminum substrate because the stable passive film which covers the surface prevents the bonding between the plating and substrate. Contrastingly, FPP likely transfers copper on the aluminum surface since the passive film should be removed when particles collide with the surface. Thus, transferring by FPP has practical advantages comparing the conventional techniques.

The goal of the present study is to accelerate the transfer of copper induced by FPP. As mentioned above, transfer during FPP process are attributed with the micro ploughing phenomena accompanying plastic deformation. It is reasonable to assume that little transfer occurs if the particles of low-hardness materials, such as copper, are employed for FPP. To enhance the transfer of copper, the authors proposed hybridized particles which comprise hard steel particles and overlying copper. The effect of the preparation condition of the hybridized particles on the transfer phenomena was compared and investigated. In addition, FPP was performed to aluminum, iron and steel substrates with a ranging hardness value to investigate the influence of the hardness relationship between the particles and treated materials on the transfer phenomena.

Experimental Methods

Development of the hybridized particles

Carbon steel particles with an approximate diameter of 70 μm and an approximate Vickers hardness of 800 were employed as cores of the hybridized particles. Fig. 1 (a) shows typical feature of the steel particles. The hybridized particles were developed by creating copper layer on the steel surface. Two types of the hybridized particles were prepared by different methods; one was "agitated particles" and the other was "coated particles".

The "agitated particles" were prepared by agitating the steel particles and copper particles in mechanical mortar for 6 h. Mass ratio of steel particles and copper ones was 3:1. Copper particles employed as a starting material of the "agitated particles" is randomly-shaped and approximate diameter was 50 μm, as shown in Fig.1 (b). Mechanical agitation likely forms overlying copper layer on the steel particles.

The "coated particles" were developed by creating copper films on the steel particles with electroless deposition. Table 1 shows the composition of electroless deposition bath for the "coated particles". Prior to the deposition, the steel particles were degreased followed by acid pickling. Deposition was performed by immersing the steel particles into the bath for 5 min. After deposition, particles were rinsed in distilled water, filtrated, and then sieved with a 45 μm mesh.

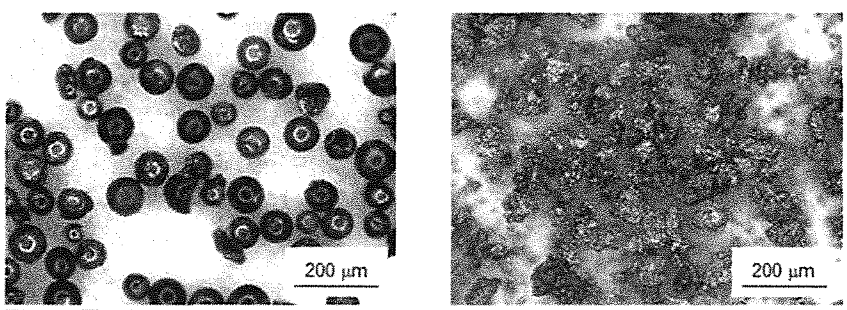

Fig. 1 Typical feature of carbon steel particles and copper particles employed to develop the hybridized particles

Table 1 Composition of electroless copper deposition bath

$CuSO_4 \cdot 5H_2O$	23.3 g/L
H_2SO_4	7.0 mL/L

Preparation and characterization of FPP-treated specimens

Aluminum, iron and steel substrates listed in table 2 were used as substrate materials for FPP. In order to investigate the effect of the ratio of particle hardness against substrate one on the transfer phenomena, hardness of the substrate was ranged from 30 to 150 HV for aluminum and from 100 to 800 HV for iron and steel. Each substrate was polished with emery paper prior to performing FPP.

FPP was performed with suction-type peening apparatus with a nozzle diameter of 6 mm. The "agitated particles", the "coated particles" and as-received copper particles were used for FPP. Detailed condition of FPP was as follows: peening pressure: 0.5 MPa, peening time: 30 s, peening angle: 90 °, and distance between nozzle and specimen: 50 mm.
FPP-treated specimens were characterized with electron prove micro analyzer (EPMA) to clarify the transfer phenomena of copper. The intensity of Cu Kα line, which is corresponding to the Cu concentration, obtained by EPMA analysis was compared for the quantitative investigation on the transfer amount of Cu. The effect of shot particles condition on the transfer phenomena was investigated by comparing the transfer phenomena induced by different shot particles.

Table 2 Substrate materials for FPP

Material	Vickers hardness
AA1070	30
AA2017 (annealed)	60
AA6061-T6	100
AA2017-T4	130~150
Commercial pure iron	100
AISI304 stainless steel	250
AISI1045 structural carbon steel (as quenched)	800

Experimental Results and Discussion

Observation of the hybridized particles

To confirm whether the hybridized particles were successfully developed or not, two types of the hybridized particles, the "agitated particles" and the "coated particles", were characterized with EPMA.
Fig. 2 shows back scattered electron image and elemental maps of Cu and Fe of the "agitated particles" analyzed by EPMA. Because copper particles are relatively softer than steel ones, they are deformed and ground during agitation process, forming fine copper fragments. Some of the fragments adhere onto the steel particles surface. Thus, steel particles are very partially hybridized with copper although the overlying copper incompletely covers the particles surface. Copper particles as well as steel particles not hybridized each other are also observed.
Fig. 3 compares typical scanning electron microscopic images of as-received steel particles and the "coated particles". The "coated particles" are almost uniformly covered with deposit while the deposit partially detaches from the surface. Cross sectional EPMA analyses of the "coated particles" (Fig. 4) proves that the deposit is composed of copper. The thickness of copper layer can be estimated to be 2~3 μm.

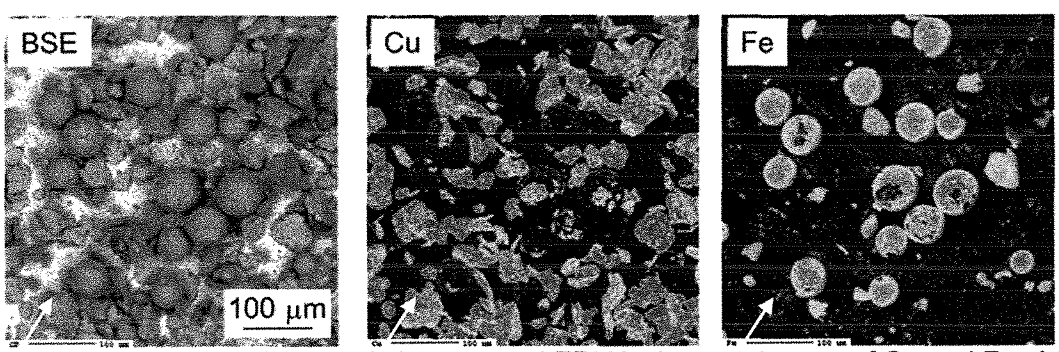

Fig. 2 Scanning electron microscopic images and EPMA elemental maps of Cu and Fe obtained from the "agitated particles".
Allow marks shows copper fragments attached to the steel particles.

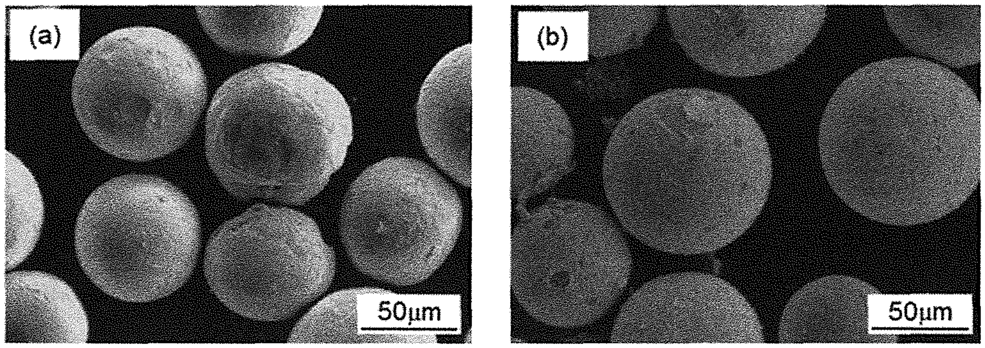

Fig. 3 Typical features of (a) as-received steel particles and (b) the "coated particles".

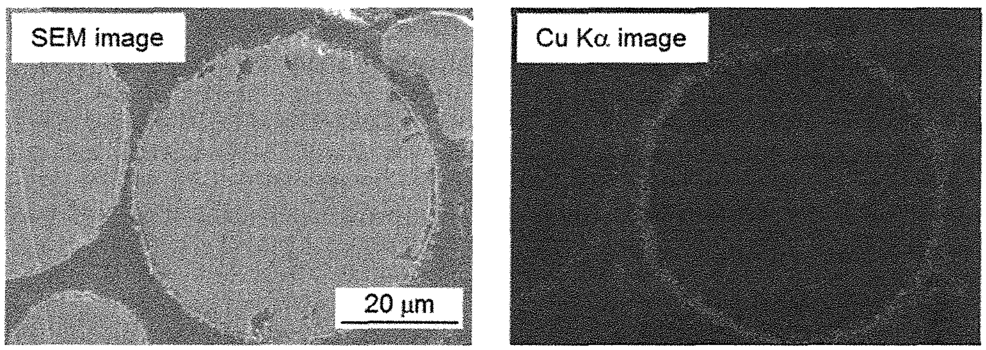

Fig. 4 Cross sectional observation of the "coated particles".

As we described above, both the mechanical agitation and electroless deposition can create the hybridized particles where copper is attached onto the steel particles. However, the feature of the hybridized particles is different depending on the preparation methods; the "coated particles" prepared by electroless deposition is more uniform comparing to the "agitated particles".

Transfer induced by FPP using the hybridized particles

In order to investigate the effect of particle conditions on the FPP transfer phenomena, surface analyses were carried out on the FPP-treated 1070 aluminum specimens with the "agitated particles", the "coated ones" and as-received copper ones. Fig. 5 compares typical results of EPMA mapping analyses on the specimen surface. Cu elements are present on the each FPP-treated surface. This result implies that each FPP treatment induces transfer of copper from shot particles to the aluminum substrate despite the difference in conditions of shot particle employed for FPP. Fig. 6 compares Cu Kα intensity obtained from FPP-treated surfaces with different shot particles. FPP-treated surface with the "coated particles" shows the highest intensity among the three specimens. This result means that transfer of copper is more significantly induced by FPP using the "coated particles" than using as-received copper particles. According to the previous study by the author [1], driving force of the FPP transfer phenomena is the micro ploughing by the colliding particles, which exposes virgin metallic surface. Because the hardness of interior steel particle is much higher than that of aluminum, the "coated particles" possibly induce the micro ploughing more effectively than as-received copper ones. Since shot particle surface possibly bonds to the exposed virgin metallic surface, the transfer from the overlying copper layer of the "coated particles" onto the aluminum surface is successfully accelerated.
On the other hands, the Cu Kα intensity is only slightly larger in the FPP-treated surface with the "agitated particles" than that with the as-received ones. For the "agitated particles", collision of

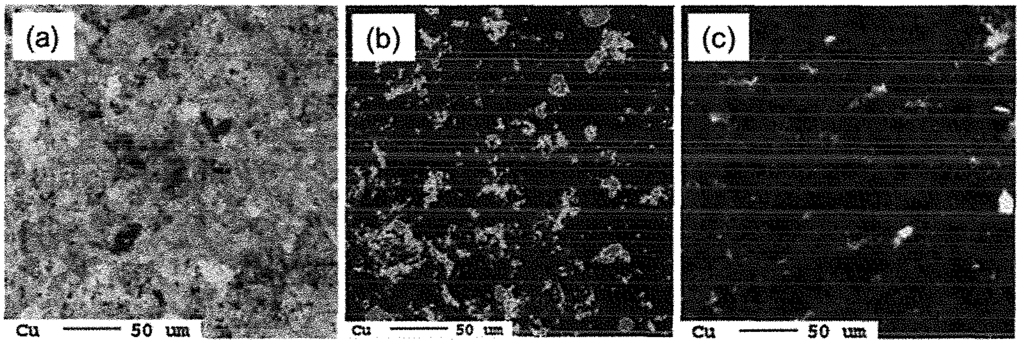

Fig. 5 Elemental map of Cu analyzed by EPMA concerning to FPP-treated 1070 aluminum with (a) "coated particles2, (b) "agitated particles" and (c) as-received particles.

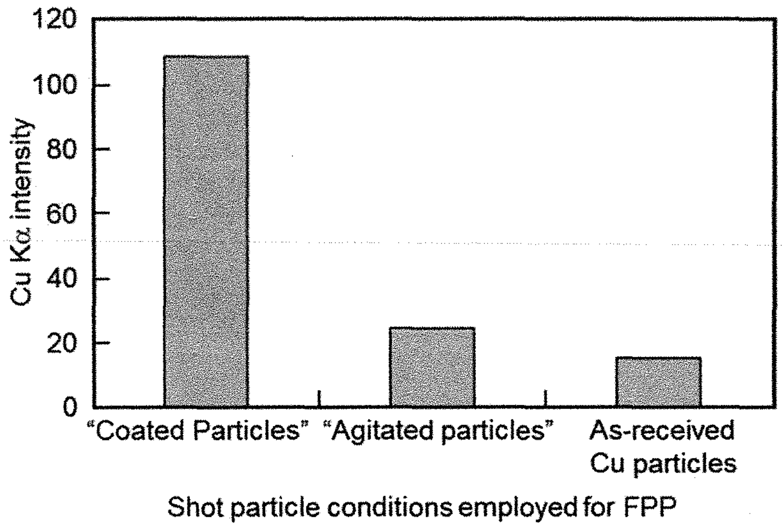

Fig. 6 Comparison of Cu Kα intensity of the FPP-treated surface

hard steel particles might induce the micro ploughing and resulting activation of the aluminum surface. This is a considerable reason for the slight increase in transfer amount from the "agitated particles" comparing to from the as-received particles. However, because of little presence of overlying copper layer on the "agitated particles", amount of transfer from them is quite smaller than that from "coated particles".

Consequently, hardness of the particles is one of the important factors which affect the FPP transfer phenomena. For further discussion, materials with a ranging Vickers hardness values were treated with FPP to investigate the effect of hardness relationship between the particles and the treated materials on the transfer phenomena. Fig. 7 shows the Cu K intensities concerning to FPP-treated surfaces of iron, stainless steel and hardened steel analyzed with EPMA. In this figure, the horizontal axis indicates a hardness ratio; hardness of particles $H_{particle}$ / hardness of substrate $H_{substrate}$. For the hardness ratio up to 8, transfer amount increases with a hardness ratio. This result implies that FPP transfer occurs more significantly in the materials with low hardness than that with high hardness. This fact agrees with the result shown in Fig. 6, in which slightly larger amount of transfer can be observed from the "agitated particles" than from as-received ones. Fig. 8 shows the Cu Kα intensity concerning to aluminum substrates (1070, 2017-annealed, 6061-T6, and 2017-T4) FPP-treated with the "coated particles", "agitated particles" and as-received copper particles. For hardness ratio up to 5, transfer amount increases with the hardness ratio, being consistent with the result shown in Fig.7. On the other hand, no significant increases in transfer amount are observed for the hardness ratio greater than 5. It is implies that transfer amount might be saturated if hardness of particles employed for FPP is much higher than that of treated materials. Considering the results shown in Figs. 7 and 8, it is supposed that optimum hardness ratio to accelerate FPP transfer phenomena is 5~10.

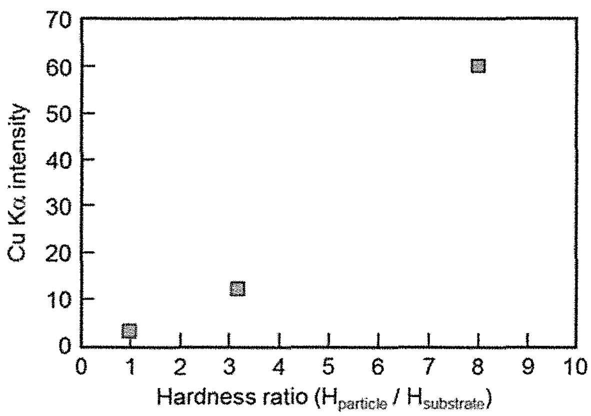

Fig. 7 Cu Kα intensity of iron or steel substrate FPP-treated with the "agitated particles" as a function of hardness ratio.

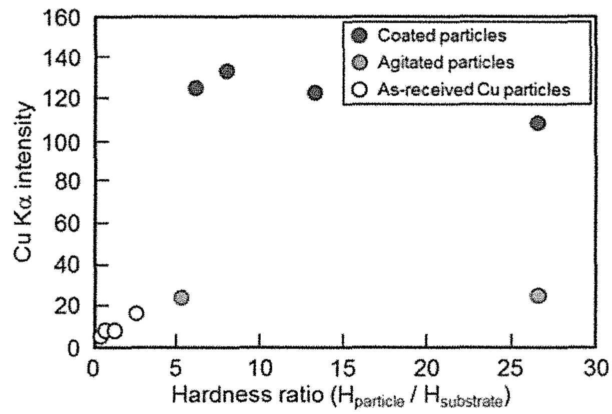

Fig. 8 Cu Kα intensity of aluminum substrate with FPP as a function of hardness ratio.

Conclusions

The effect of shot particles conditions on the transfer phenomena is investigated to accelerate transfer of shot particles elements induced by FPP. Two conditions of the hybridized particles, the "coated particles" and the "agitated particles", which comprise copper and steel are employed for FPP to induce transfer of copper and compared with the as-received copper particles. The effect of hardness relationship between the particles and the treated materials on the transfer phenomena is also investigated. The following conclusions resulted from this study:

(1) Employment of the hybridized particles for the FPP shot particles effectively accelerates the transfer phenomena during FPP process.

(2) The advantages of the hybridized particles to accelerate transfer can be attributed with two reasons; high hardness of interior particles which activate the surface of treated material and the presence of overlying layer of materials to be transferred. Uniformity of the overlying layer is also important.

(3) Hardness relationship between the particles and the treated materials is an important factor to induce FPP transfer phenomena. In terms of enhancing transfer, assumed optimum value of a hardness ratio (hardness of particles $H_{particle}$ / hardness of substrate $H_{substrate}$) is 5~10.

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