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EXPRESS REGULAR ARTICLE

Enhanced Shot Peening Effect for Steels by Using Fe-based Glassy Alloy Shots

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The use of Fe-Co-Ni-Mo-B-Si glassy alloy balls as peening shots was found to cause a significantly enhanced shot peening effect for steel sheets, *i.e.*, the increase in the thickness of the shot region, higher hardness and higher compressive residual stress in the shot region, and the generation of much distinct crater-like pattern on the shot surface in comparison with those for conventional cast steel shots and high speed steel shots. It was also found that the endurance life time of the glassy alloy shots is 8 to 10 times longer than those for the conventional crystalline alloy shots. The enhanced effect was interpreted to originate from unique mechanical properties of the Fe-based glassy alloy shots such as lower Young's modulus, larger elastic elongation limit and higher tensile strength which cannot be obtained for the conventional crystalline steel shots. The finding of the effectiveness of the Fe-based glassy alloy as peening shots is promising for future applications.

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1. Introduction

Since the first synthesis of an amorphous phase in splat quenched Au-Si alloys in 1960,[1)] a great number of amorphous alloys were developed in various alloy systems by use of rapid quenching. However, all the amorphous alloys except noble metal-metalloid systems such as Pd-Ni-P and Pt-Ni-P required high cooling rates above 10^5 K/s and hence the resulting sample thickness was usually limited to less than 0.05 mm.[2)] Although most of amorphous alloys exhibit high mechanical strength and good bending ductility, it is known that the slight increase in the sample thickness causes a catastrophic embrittlement because of the coexistence of a crystalline phase.[2)] Consequently, there had been no successful data on the practical use of amorphous alloys as high strength materials for the three decades after 1960. However, for the last one and halt decades, such an enclosed situation was broken out by the discovery of stabilization of supercooled liquid in multi-component metallic alloys of Mg-,[3)] lanthanide(Ln)-,[4)] Zr-,[5,6)] Ti-,[7)] Hf-,[8)] Ni-[9)] and Cu[10)]-based systems without any metalloid elements, resulting in the fabrication of bulk glassy alloys exhibiting high strength and good ductility even in a bulk form with thickness/diameter above several millimeters. It is well known that the metal-metal type bulk glassy alloys exhibit higher tensile strength, lower Young's modulus and larger elastic elongation limit which are significantly different from those for conventional crystalline alloys.[11–14)] Owing to their unique mechanical properties, Zr-based bulk glassy alloys in Zr-Al-Ni-Cu and Zr-Ti-Ni-Cu-Be systems have been used as high-strength materials in face materials as golf clubs, reinforced materials as shaft of golf clubs and frame materials of tennis rackets, case materials in cell phones and high wear-resistant connecting parts for optical fibers *etc.*[14,15)] Considering the unique mechanical properties of bulk glassy alloys, the application to shot peening balls is interesting only when much cheaper bulk glassy alloys are used. We have paid attention to Fe-based bulk glassy alloys with low materials costs,[13–15,17)] though their formation is limited to metal-metalloid systems and the achievement of good ductility is difficult. More recently, we have succeeded in applying Fe-Co-Ni-Mo-B-based bulk glassy alloys to a peening shot material which requires simultaneously high strength, good ductility, high endurance time against cyclic bombardment load and high corrosion resistance. This paper aims to present the enhanced shot peening effect for the carbon and tool steels caused by the use of Fe-based glassy alloy shots and to investigate the origin for the enhanced effect on the basis of the features of mechanical properties of bulk glassy alloys.

2. Experimental Procedure

Commercial steels (JIS-G4801 and SKD11) with approximate composition of Fe-0.83%C-0.25%Si-0.5%Mn (mass%) and Fe-1.5%C-12%Cr-1.0%Mo-0.35%V,[18)] respectively, were used as the test specimens for shot peening. The former carbon steel was in an annealed state and had Young's modulus (E) of 200 GPa, tensile strength (σ_f) of 1000 MPa and Vickers hardness (H_v) of 450. The latter tool steel was in quenched and tempered state and the E, σ_f and H_v were 210 GPa, 2000 MPa and 740, respectively. Their specimens were in a sheet form of 0.8 mm in thickness and $19 \times 76\,mm^2$ in area. Shot peening treatment was performed by using an air-type shot peening machine (Sintobrator Ltd., Eco-Bluster AB-ML069) with a nozzle diameter of 4 mm.[19)] The initial ejection pressure of air was 0.35 MPa and the mixing weight ratio of air to shot balls was 2.0. The estimated bombardment velocity was 70 m/s and the peening time was 40 s. The peening shots were made of an $Fe_{44}Co_5Ni_{24}Mo_2B_{17}Si_8$ (at%) alloy with glassy structure and their diameter was in the range from 74 to 88 μm. The alloy composition represents nominal atomic percentages. Figure 1 shows the outer shape and surface morphology of commercialized $Fe_{44}Co_5Ni_{24}Mo_2B_{17}Si_8$ glassy alloy shots with a diameter of about 80 μm.[20)] The glassy alloy balls were produced by water atomization, followed by sieving to the powder size distribution. The alloy balls have a nearly spherical shape with smooth outer surface and neither distinct concave nor ruggedness is observed. In addition, no appreciable contrast due to the precipitation of a crystalline phase is observed over the whole cross section.

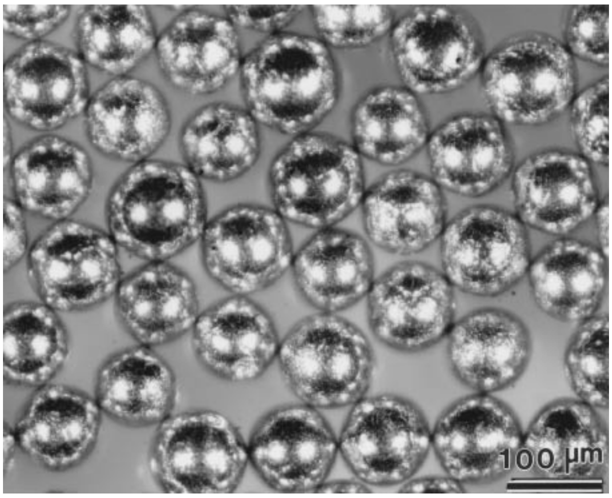

Fig. 1 Outer shape and surface morphology of commercialized $Fe_{44}Co_5Ni_{24}Mo_2B_{17}Si_8$ glassy alloy shots with a diameter of about 80 μm.

The shot peening balls of 74 to 88 μm in size made of the Fe-based glassy alloy used in the present study had the same features in outer shape, surface morphology and internal structure. The glass transition temperature (T_g) and crystallization temperature (T_x) at a heating rate of 0.67 K/s were 786 K and 823 K, respectively. The E, σ_f, H_v and specific weight (ρ) were 80 GPa, 3200 MPa, 930 and 7.4 Mg/m^3, respectively. For comparison, the same shot peening treatment was also performed by using two kinds of conventional crystalline alloy shots made of high speed steel (JIS-SKH55) and cast steel (JIS-Z0311) with approximate composition of Fe-1.15%C-4%Cr-5%Mo-2.5%V-6.5W-8%Co and Fe-1%C-0.9%Si-0.7%Mn (mass%),[21] respectively. The E, σ_f, H_v and ρ were 215 GPa, 2100 MPa, 815 and 7.70 Mg/m^3, respectively, for the SKH55 steel and 210 GPa, 1100 MPa, 810 and 7.55 Mg/m^3, respectively, for the Z0311 steel. The structure of the shot alloy sheets was examined by X-ray diffraction, optical microscopy (OM) and scanning electron microscopy (SEM). The roughness on the surface of the shot steel sheet was also examined by SEM. Hardness and residual stress as a function of distance from shot surface were measured by a Vickers hardness tester with a load of 100 g and X-ray diffraction method.

3. Results

Figures 2(a) and (b) show the surface structure of the carbon steels subjected to bombardment for 40 s with the glassy alloy shots and the cast alloy shots, respectively. It is seen that the steel sheet bombarded with the glassy alloy shots has a much homogeneous crater-like surface pattern as compared with that for the cast steel shots. In addition, the average size of the crater-like pattern was measured as about 20 μm for the glassy alloy shots and about 7 μm for the cast steel shots. The distinct difference in the crater-like pattern indicates that the bombarded area generated by one bombardment is much larger for the glassy alloy shots. The average height of the crater edges was measured as 15 μm for the glassy alloy shots and 5 μm for the cast steel shots, being much larger for the former shots. The larger height is thought to result from the larger bombarded area. The significant difference in the surface structure seems to result from the much smaller Young's modulus and higher strength for the glassy alloy, as discussed later in section 4. Figures 3(a) and (b) show the cross sectional structure of the steel sheets subjected to bombardment for 40 s with the glassy alloy shots and the high speed steel shots, respectively. The etched microstructure enables us to distinguish clearly the shot-peening effected region and the non-effected region. The depth of the effected region from the sheet surface is measured to be about 100 μm for the glassy alloy shots and about 45 μm for the cast steel shots. It is thus noticed that the use of the glassy alloy shots can produce a much thicker effected region in spite of the same shot peening condition. The X-ray diffraction patterns of the shot regions in the steel sheets subjected to bombardment for 40 s with the glassy alloy and cast steel shots are shown in Fig. 4, together with the data of the enlarged $(111)_\alpha$-Fe diffraction peaks and the angles of their half width. The intensity of the diffraction peaks is weaker and their half width is wider for the steel sheet bombarded with the glassy alloy shots. The difference indicates that a much higher degree of strain has been accumulated in the use of the glassy alloy shots, being consistent with the thicker effected region in the use of the glassy alloy shots.

Figure 5 shows Vickers hardness of the shot steel sheet as a function of distance from the sheet surface. The hardness is about 440 for the non-shot matrix and increases to a

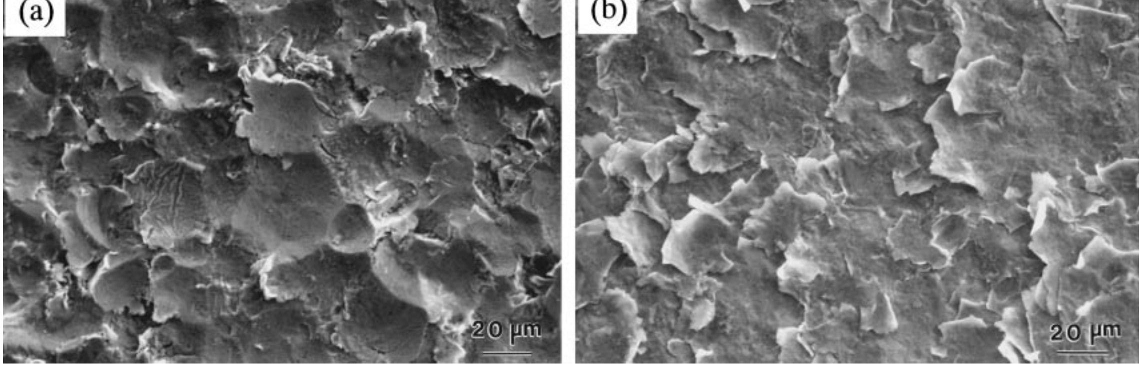

Fig. 2 Surface structure of the carbon steel (JIS-G4801) sheets subjected to bombardment for 40 s with the Fe-based glassy alloy and cast steel (JIS-Z0311) shots of 80 μm in diameter. (a) glassy alloy shots, (b) cast steel shots.

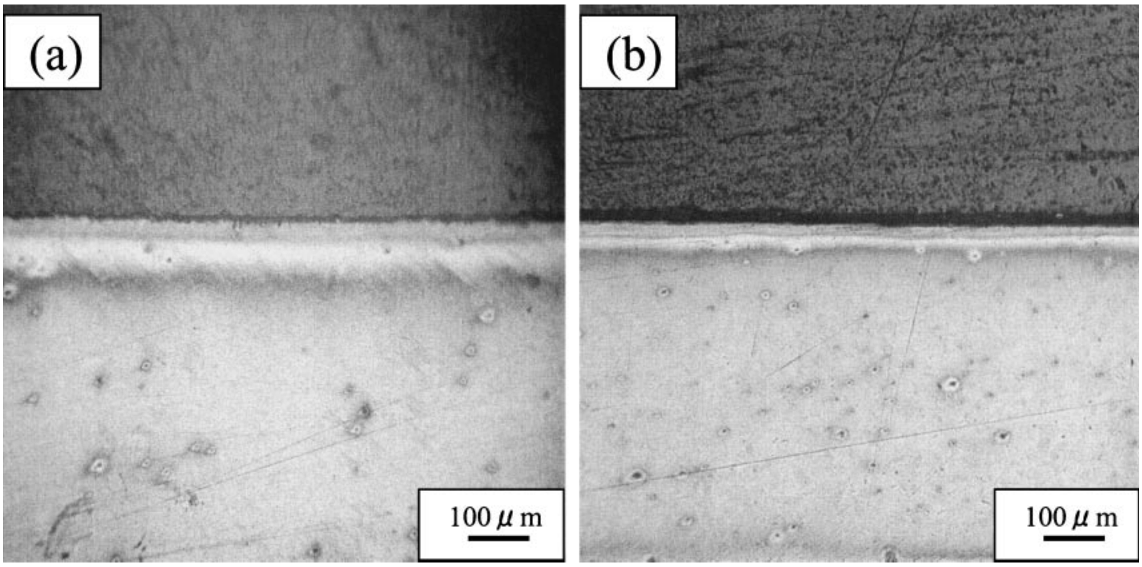

Fig. 3 Cross sectional structure of the carbon steel (JIS-G4801) sheets subjected to bombardment for 40 s with the Fe-based glassy alloy and cast steel (JIS-Z0311) shots of 80 μm in diameter. (a) glassy alloy shots, (b) cast steel shots.

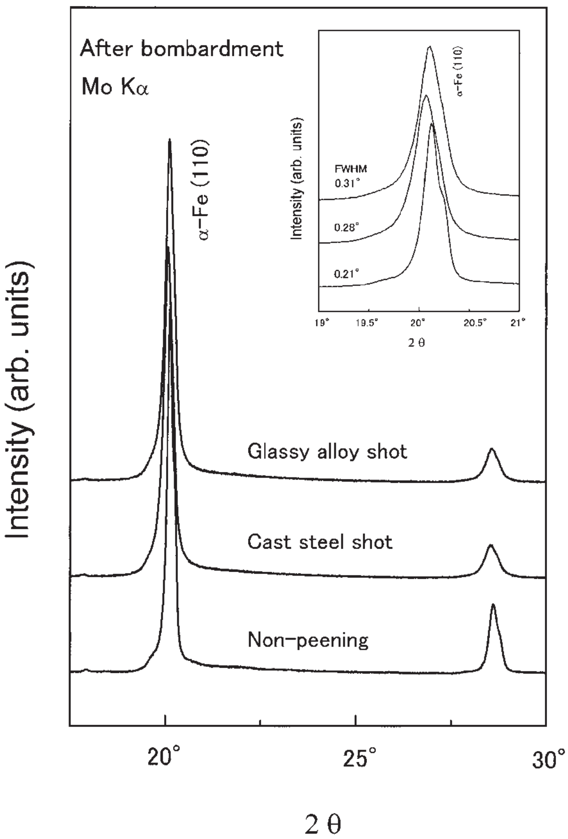

Fig. 4 X-ray diffraction patterns of the shot surface of the carbon steel (JIS-G4801) sheet subjected to bombardment for 40 s with the Fe-based glassy alloy and cast steel (JIS-Z0311) shots of 80 μm in diameter.

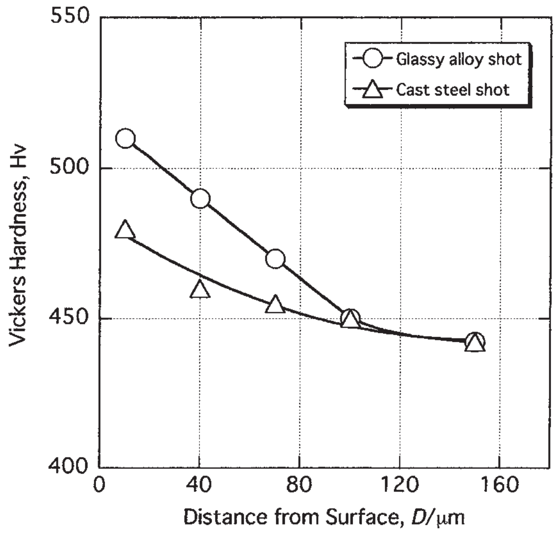

Fig. 5 Vickers hardness as a function of distance from the shot surface for the carbon steel (JIS-G4801) sheet subjected to bombardment for 40 s with the Fe-based glassy alloy and cast steel (JIS-Z0311) shots of 80 μm in diameter.

maximum value of 510 for the sheet bombarded with the glassy alloy shots and 480 for the sheet bombarded with the cast alloy shots. It is further noticed that the thickness of the shot region with higher hardness is much larger for the glassy alloy shots. Figure 6 shows the change in the compressive residual stress in the shot tool (SKD11) steel as a function of distance from the sheet surface. The shot surface region has very high compressive residual stress and its maximum stress is 1600 MPa for the sheet bombarded with glassy alloy shots and 1470 MPa for the sheet bombarded with high speed steel shots. In addition, the thickness of the shot peening effected region with compressive residual stress above 500 MPa is measured to be 27 μm in the use of the glassy alloy shots and 18 μm in the use of the high speed steel shots. It is thus concluded that the magnitude of compressive residual stress and the thickness under compressive residual stress are considerably larger for the sheet bombarded with the glassy alloy shots. Finally, it is important to point out the significant difference in the endurance time for the three kinds of peening shots. As shown in Fig. 7, the endurance time required up to final rupture of the peening shots at the present fixed bombardment condition was measured to be about 101 ks for the glassy alloy shots, 12 ks for the high speed steel

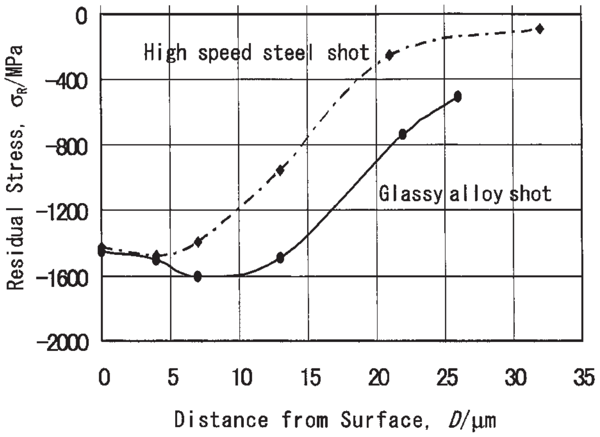

Fig. 6 Residual stress as a function of distance from the shot surface for the tool steel (SKD11) sheet subjected to bombardment for 40 s with the Fe-based glassy alloy and high speed steel (JIS-SKH55) shots of 80 μm in diameter.

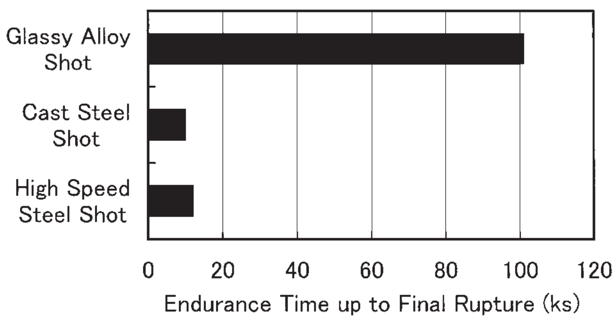

Fig. 7 Endurance times required up to final rupture for the Fe-based glassy alloy, cast steel (JIS-Z0311) and high speed steel (JIS-SKH55) shots of 80 μm in diameter which were used for the bombardment to the carbon steel (JIS-G4801) sheet.

shots and 10 ks for the cast steel shots. It is noticed that the life time for the glassy alloy shots is 8 to 10 times longer than those for the conventional crystalline steel shots.

4. Discussion

It was shown in section 3 that the use of the Fe-Co-Ni-Mo-B-Si glassy alloy shots yielded the much thicker peening effected region with higher compressive residual stress level as well as the much longer endurance time up to final rupture, in comparison with the high speed steel and cast steel shots. Here, we discuss the reason why the Fe-based glassy alloy shots can have much better characteristics in the application to peening shots. The Young's modulus, tensile strength and elastic strain limit are 80 GPa, 2900 MPa and 0.02, respectively, for the glassy alloy,[18] 215 GPa, 2100 MPa and 0.005, respectively, for the high speed steel[20] and 210 GPa, 1100 MPa and 0.006, respectively, for the cast steel.[20] It is said that the glassy alloy has much lower Young's modulus, much higher strength and much larger elastic elongation limit. The specific weights of their materials are nearly the same and hence it is reasonable to assume that the bombardment energy is nearly the same among the three kinds of peening shots. However, the much lower Young's modulus of the glassy alloy shot causes a significant increase in the shot area of the steel sheet, resulting in the endowment of much higher deformation energy to the shot steel sheet. This is also supported from the much larger diameter of the crater-like pattern on the surface of the steel plate subjected to the bombardment with the glassy alloy shots, as shown in Fig. 2. On the other hand, the much higher strength and the much larger elastic strain limit cause a decrease in the damage for the glassy alloy shots suffered by cyclic bombardment, as compared with those for the conventional steel shots with much lower strength and much smaller elastic strain limit. It is thus concluded that the much better performance of the glassy alloy shots originates from the unique mechanical properties of the Fe-based glassy alloy with high glass-forming ability leading to the formation of glassy alloy balls with diameters up to about 0.2 mm by conventional water atomization.

5. Summary

We examined the effectiveness of using Fe-Co-Ni-Mo-B-Si glassy alloy as peening shots in comparison with conventional high speed steel (JIS-SKH55) and cast steel (JIS-Z0311) shots. The results obtained are summarized as follows.

(1) The surface of the shot steel sheet produced by bombardment with the glassy alloy shots had a more distinct crater-like pattern with larger diameter of about 20 μm and larger edge height of about 15 μm as compared with the cast steel shots.

(2) The thickness of the shot area produced by bombardment with the glassy alloy shots is about two times larger than those for the two kinds of steel shots. In addition, the use of the glassy alloy shots caused an increase in the maximum values of compressive residual stress and Vickers hardness in the shot region as well as an extension of the shot region with compressive residual stress.

(3) The endurance life time of the glassy alloy shots was 8 to 10 times longer than those for the conventional steel shots in the same shot peening condition.

(4) These enhanced effects in the use of the Fe-based glassy alloy as peening shots were interpreted to be due to the unique mechanical properties of the glassy alloy, *i.e.*, lower Young's modulus, higher strength and larger elastic strain limit, which had not been obtained for any kinds of crystalline alloys. The significant enhancement effects in the application to peening shot material are encouraging for the mass uses of the Fe-based bulk glassy alloy.

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