Formation of Fe-Al Intermetallic Compound Film on Hot Work Tool Steel by Shot Lining and Heat Treatment

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Abstract
The formation of an Fe-Al intermetallic compound film on tool steel by shot lining and heat treatment was investigated. In the experiment, a centrifugal-type peening machine with an electrical heater was employed. The shot medium was high-carbon cast steel. The substrate was a commercial tool steel, and the sheet was commercially available pure aluminum. The shot lining process of tool steel with an aluminum sheet was carried out at 573 K in air using a peening machine. Heat treatment was performed at diffusion temperatures from 873 to 1373 K in vacuum. The lined substrates exhibited a harder layer of aluminum-rich intermetallics in the diffusion temperature range of 973 to 1123 K. When the temperature of the lined substrates was more than 1173 K, the surface was covered with thicker and highly anticorrosive layers of iron-rich intermetallics. It was confirmed that the present method could be used for the formation of functional films on tool steel.

Keywords Bonding, plastic deformation, hardness, intermetallic compound.

Introduction
Surface treatments are used to improve the surface properties, such as wear and corrosion resistance. There are many processes such as plating and coating. The nanocomposite coating was investigated to produce a coating having good corrosion and wear resistance [1]. Surface fatigue and wear of PVD coated punches in fine blanking operation were studied [2]. The bonding and joining processes are also utilized in many of metal forming. The process optimization in explosive cladding of titanium–stainless steel plates was attempted to establish the influencing parameters [3]. In the case of ferrous metals, the technology to modify the surface of steel via heat treatment on the dissimilar metal-coated surfaces has been very actively utilized. Aluminum hot dipping is one of the coating technologies using heat treatment for steel materials [4, 5]. Dipping material into a molten aluminum salt bath can generate a corrosion- and heat-resistant Fe-Al alloy phase. The characterization of intermetallic layer formation in the duplex coating on mild steel was investigated [6]. A combined hot dip aluminizing and laser alloying treatment was examined to produce iron-rich aluminides on alloy steel [7]. The characterization of aluminum coatings formed on the porous ferritic stainless steel by the pack cementation process was investigated [8]. On the other hand, the authors have proposed a lining process of metals with thin foils using shot peening [9]. In the shot peening process, the surface is hit repeatedly with a large number of steel balls, making overlapping indentations on the surface. Therefore, the foil can be bonded to the workpiece surface bringing about large plastic deformation. The pressure generated by the hit of many shots is utilized for the bonding. A lining of light metals with hard powders using shot peening was examined to improve the surface properties [10]. The lining process using shot peening is very suitable for the bonding of thin and dissimilar foils. In the present study, our attempt was forming Fe-Al intermetallic compound film, which is receiving particular attention as a functional film, by compound treatment combining shot lining method and heat treatment. The effect of heating temperature on intermetallic formation of aluminum and base material bonded by the lining method was studied.

Experimental Methods

Shot peening was performed with a centrifugal-type machine using cast steel ball. The shots used were made of high-carbon cast steel, a hardness of Vickers HV445, with an average diameter of 1.0 mm. The apparatus with a heating furnace was fabricated to line the foil on the surface. The workpiece was set on the holder with the heater. The shot velocity and the coverage were controlled in the experiment. The shot velocity and the project amount were 60 m/s and 10 kg/min, respectively. The peening time was about 30 s, and it was equivalent to the coverage of 300 %. In the present study, coverage was defined as ratio of the dimpled surface to the total surface after shot peening. The coverage of 100 % was attained when the surface was just covered with the indentation. In shot peening, a metal workpiece undergoes plastic deformation near the surface due to the hit of many shots at a high speed. When the dissimilar foil is set on the workpiece and then shot-peened, it can be bonded to the surface of the workpiece. The pressure and plastic deformation break up the oxide film and contaminates at the interface between the dissimilar materials, and new and clean surfaces suitable for joining are generated. The shot lining technique is useful in joining dissimilar metals because of the utilization of plastic deformation. The foils was the commercial pure aluminum, and the workpiece was the commercial hot work tool steel SKD61, a hardness of Vickers HV254. The dimensions of the workpieces were 25 mm in diameter, 10 mm in height. The aluminum foil was 0.020 mm thick. Two foils were used in this study. Namely, the total thickness of the foil was 0.040 mm. The surface of the workpieces was cleaned with emery papers prior to shot lining, to remove oxide layer from the surface. The foil and the workpiece were heated by heater, to make the joining easy. The lining experiment was performed at 573K in air. The lined workpieces were heat treated in the range of 873 to 1373 K in a vacuum. The Vickers hardness test was performed with a microhardness tester. The conditions used for the shot peening experiment are summarized in Table 1.

Experimental Results and Discussion

The coating process of the dissimilar foil to the substrate steel by shot peening is important. To examine the joinability, the lining of the workpiece with the pure aluminium foil was performed. The appearances of the surface of the workpiece lined by shot peening are given in Figure 1. The surface is uniformly hit with many shots. No cracks were visible on the surface. The cross section of the lined workpiece was observed by optical microscope. The crack and void were not observed at the interface.

Table 1. Working conditions of shot lining

Equipment	Centrifugal type machine
Shot material	High carbon cast steel Diameter: 1.0 mm, Hardness: HV445
Shot velocity	60 m/s
Peening time	30 s (project amount: 10 kgf/min)
Base metal (substrate) 0.40C, 0.84Si, 0.36Mn, 5.01Cr, 1.24Mo, 0.82V (mass%)	Hot work tool steel (SKD61) Diameter: 25 mm, Height: 10 mm Hardness: HV254
Foil	Pure aluminum Thickness: 0.040 mm , Hardness: HV 30
Lining temperature	573 K
Atmosphere of lining	Air
Heating temperature	873 - 1373 K
Heating time (holding time)	3.6 ks
Atmosphere of heating	Vacuum

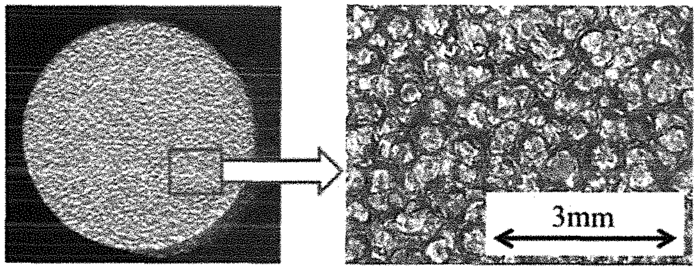

Figure 1. Appearances of lined workpiece after shot peening.

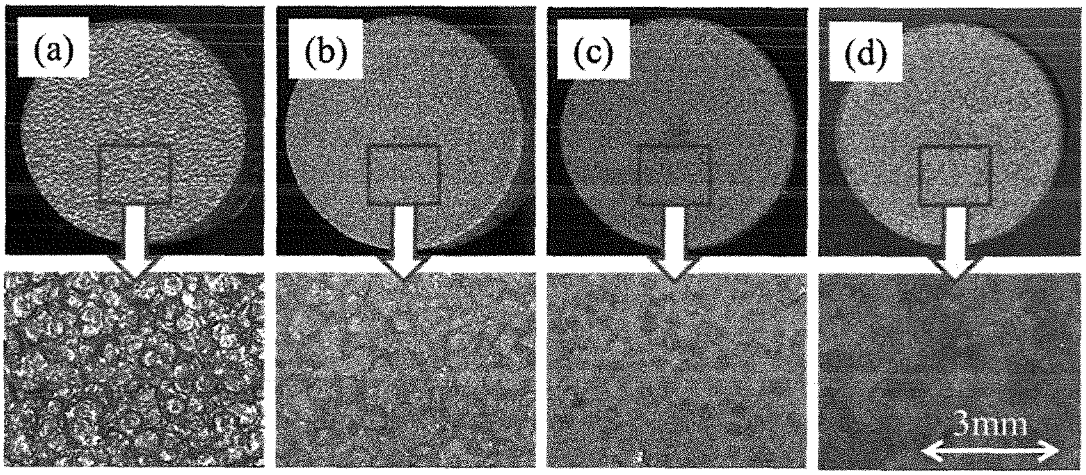

Figure 2. Appearances of lined workpieces after heat treatment at 873 K(a), 973 K(b), 1173 K(c), 1373 K(d).

In order to examine the effect of the heating temperature on the surface of the lined workpiece, the processing material was heated in vacuum at a given temperature. The appearances of the lined workpieces after heat treatment at 873 K(a), 973 K(b), 1173 K(c), 1373 K(d) are shown in Figure 2. In case of workpiece(a), metallic luster remains on the surface and the indentation from steel ball collision is observed in the same way as on a bare lining surface (see Figure 1 for as-lined workpiece). Meanwhile, in case of workpiece(b), metallic luster vanishes and a dark grey color is exhibited on the surface. In case of workpiece(c), there is no longer a concavo-convex shape on the surface. In cases when the lined workpieces were heated at temperatures of the order of 1073 K and above, similar results were obtained.

The cross section of the lined workpiece was observed to examine the effect of the heating on the surface layer. The scanning electron microscope pictures are useful for examining the fine structure of alloy layer. Figure 3 is a cross sectional view of the lined workpiece. As can be seen, several layers are present in the film, according to the cross section SEM. In case of workpiece(a), no crack is observed at the interface, and thickness of the film is uneven which resembles the condition at cross section of workpiece of bare lining. However, in case of workpiece(b), and thickness of the film is even in some degree. As a result, it is understood that alloying proceeds from the change of this film layer. At temperatures of the order of 1073 K and above, the film was successfully joined to base material, and no voids were observed. The thickness of the film has been increased. This is considered a result of progressed diffusion by heating and accelerated alloying.

The distributions of Vickers hardness on the lined workpieces after heat treatment are given in Figure 4. Hardness of top surface indicates the maximum value for each heating temperature, and decreases as heating temperature increases. Also, hardness distribution shows two major divisions depending on heating temperature. First, hardness of films ranged from 973 to 1123 K measured from HV1100 to HV1200, and this is considerably high compared with that of pure aluminum or base material. It is supposed that an intermetallic compound is formed between aluminum and iron. Next, hardness of films ranged from 1173 to 1373 K measured from HV400 to HV450. According to past references [11, 12], different types of intermetallic compounds were more likely to be formed.

In order to compare the results obtained from other researchers [11, 12], hardness in two kinds of intermetallic compounds was examined. In comparison of the results obtained from this study, it is discovered that hardness of film processed with temperature ranged from 973 to 1123 K is equivalent to an Al-rich phase, and hardness of film processed with temperature ranged from 1173 to 1373 K is equivalent to Fe-rich phase.

These layers have characteristics in that Al-rich phase and Fe-rich phase were identified by X-ray diffraction using a Cu-Kα ray. Figure 5 shows the X-ray diffraction pattern at different depth from surface. XRD pattern of crystalline materials shows sharp peaks. Fe_2Al_5 phase was observed at entire area of film heated at 973 K(a) which was the equivalent temperature where Al-rich phase was created. At 1373 K(b) which was equivalent temperature where Fe-rich phase was created, FeAl phase was observed.

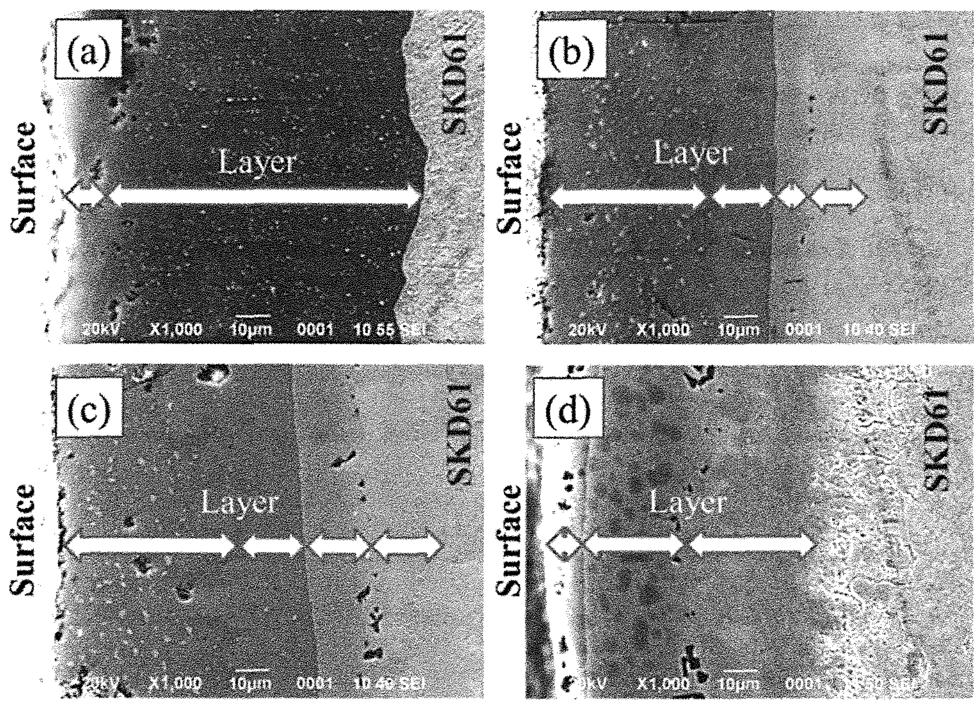

Figure 3. Cross section SEM photographs of workpieces heat-treated at 973K(a), 1173K(b), 1273K(c), 1373K(d).

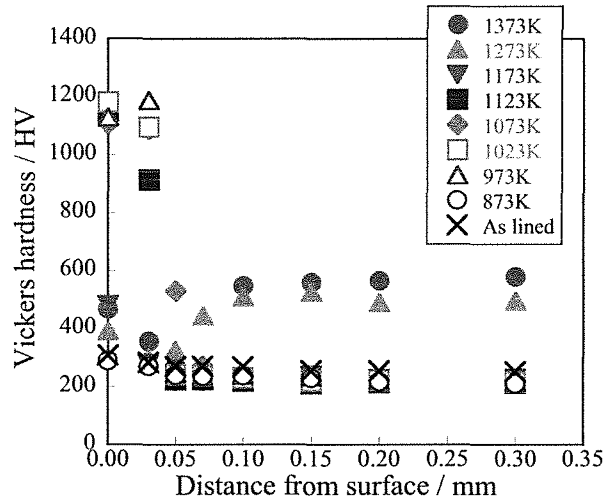

Figure 4. Distributions of Vickers hardness on lined workpieces after heat treatment.

From a result of the X-ray diffraction, the distribution of the Fe-Al phase in the surface layer is shown in Figure 6. In the case of workpiece heated at 973 K(a), the surface and lower layers were $FeAl_3$ and Fe_2Al_5, respectively. In the case of layers heated at 1173 K(b), around the boundary between layer and base material, a mix of $FeAl_2$ phase and FeAl phase was observed. On the other hand, at 1273 K(c) which was equivalent temperature where Fe-rich phase was created, FeAl phase was observed for the area at a depth of approximately 0.070 mm from the top surface. $FeAl_2$ phase was observed for the area at a depth of approximately 0.030 to 0.070 mm. The alpha-Fe phase was observed around the boundary between layer and base material. From above studies, for both Al-rich and Fe-rich layers, the area close to the surface is an intermetallic layer, and the area near the boundary between layer and base material is a mixed layer of intermetallic and alpha-Fe phase.

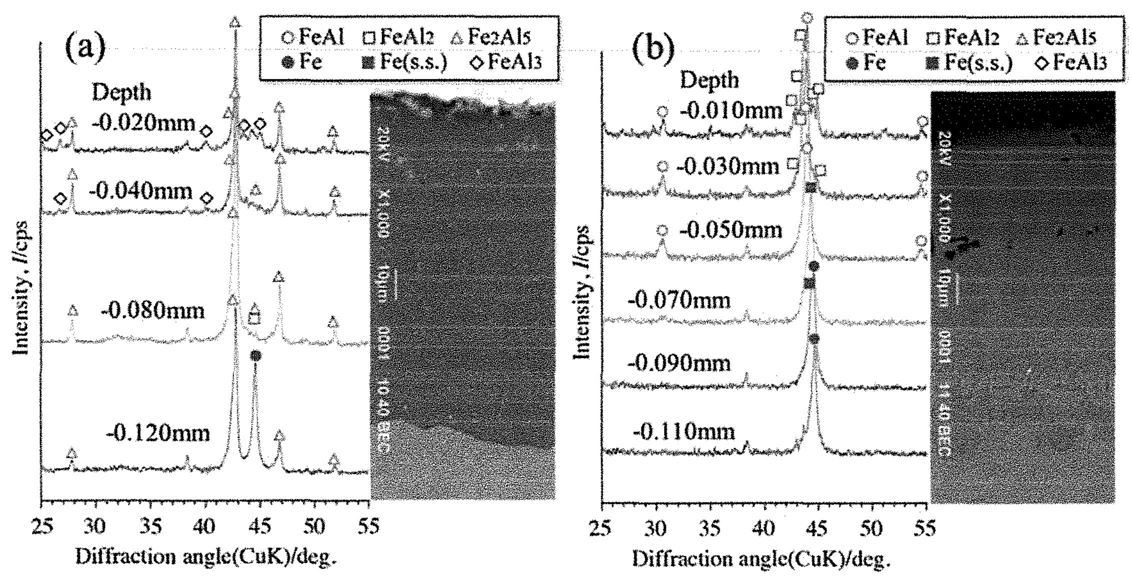

Figure 5. X-ray diffraction patterns at different depth from surface:
(a) 973 K; (b) 1373K.

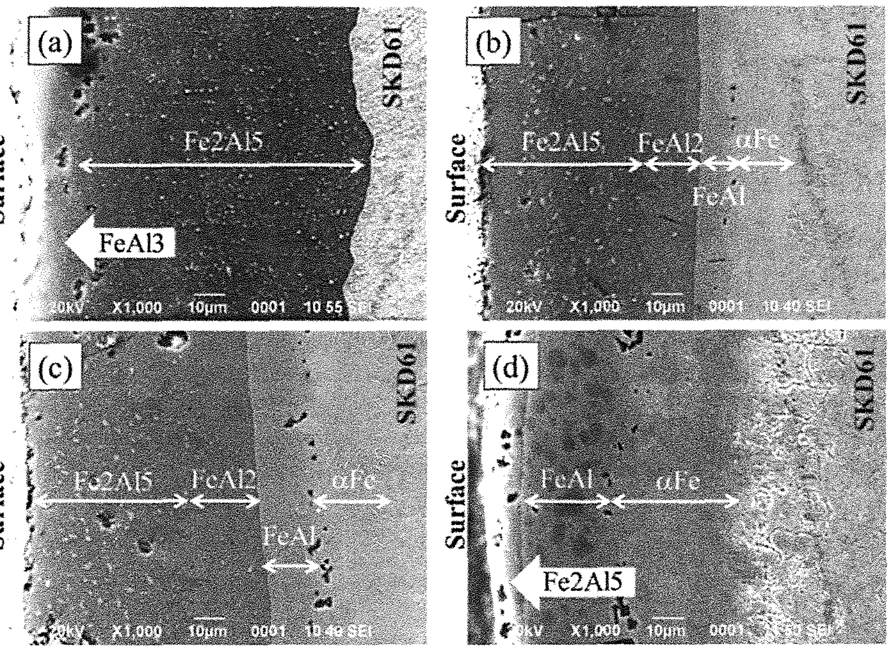

Figure 6. Cross section SEM photographs of workpieces heat-treated at 973K(a), 1173K(b), 1273K(c), 1373K(d), indicating the distribution of the intermetallic compounds.

Conclusions

The formation of an Fe-Al intermetallic compound film on hot work tool steel by shot lining and heat treatment was investigated. The shot lining process of hot work tool steel with an aluminum sheet was carried out at 573 K in air using a peening machine. The results obtained are as follows.
The lined substrates exhibited a harder layer of Al-rich intermetallics, such as Fe_2Al_5 and $FeAl_2$, in the diffusion temperature range of 973 to 1123 K. The hardness values of the Al-rich layers were from HV900 to HV1200.
When the temperature of the lined substrates was more than 1173 K, the surface was covered with highly anticorrosive layers of Fe-rich intermetallic FeAl. The hardness values of the Fe-rich layers were from HV400 to HV500.
It was confirmed that the present method could be used for the formation of functional films on hot work tool steel.

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