**Temperature History
and Metallographic Structure
of 0.45%C Steel
Processed by Frictional Stir Burnishing***

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Abstract

Significant enhancement of hardness characteristics was achieved through the Frictional Stir Burnishing (FSB) process. The enhanced region was generated by the FSB process where the thickness and hardness were approximately 200 μm and 900 HV, respectively, under the conditions of spindle speed of 10000 min^{-1} , a feed rate of 200 mm/min and a processing load of 750 N. The processing temperature was approximately 600~750 $^{\circ}\text{C}$ under compressive stress condition. Although this temperature is lower than A_3 transform point (normally 780 $^{\circ}\text{C}$), it is known that A_3 transform point decreases under the compressive stress condition. And after the tool passed, the temperature dropped rapidly. This process can be assumed to be the same as a quenching process. However, the obtained hardness value is harder than that of the regular quenched material. When the processing load was 500 N, extremely hard regions over 1000 HV were obtained. In this case, it is thought that the material was not transformed into martensite. It can be concluded that the severe stirring process of FSB caused the grain refinement.

Key words: Friction, Stir, Burnishing, Martensite, Surface Enhancement, Severe Plastic Deformation

1. Introduction

There are various methods of surface enhancement to improve the strength, fatigue strength, surface hardness or corrosion resistance of mechanical parts. For example, induction hardening, carburized quenching and shot peening are very popular. Induction-hardened or carburized-quenched parts are given strength and abrasion resistance because their surfaces are hardened while the inner areas maintain their toughness. These methods are used for auto parts and various other mechanical parts. By the way, cutting is the general machining method used to achieve high accuracy. However, the tensile residual stress induced the surface after machining causes the fatigue strength to weaken. Therefore, shot peening is often applied after cutting in order to induce the compressing residual stress within the surface layers.

However, most surface enhancement methods require special or additional devices after machining. Moreover, the manufacturing process becomes complicated, especially for parts with complex shapes or deep valleys where the shot dose is unable to reach the desired location.

Segawa et al.⁽¹⁾ have proposed a cutting-burnishing combined process tool to generate compressive residual stress in a single operation without using any special devices. This tool consists of a cutting tool edge and a burnishing pin. It has been shown that this process can generate compressive residual stress and improve the fatigue strength of the machined parts. The Frictional Stir Burnishing (FSB) technique has been proposed by Sasahara et al.⁽²⁻⁴⁾; in this technique, the FSB tool does not have a cutting edge. The tool rotates at a high speed and rubs on the surface. Sasahara et al. reported that the FSB process can generate an extremely hard layer. However, the mechanism by which the hard layer is generated is not clear. Therefore, the objective of the present study is to clarify the mechanical and metallurgical properties and enhancing mechanism of the proposed FSB process.

2. Experiment on the Frictional Stir Burnishing process

The workpiece material used was 0.45%C steel (composition: 0.42 to 0.48%C, 0.15 to 0.35%Si, 0.06 to 0.90%Mn, less than 0.030%P, less than 0.035%S). The FSB tool assembly (Fig. 1) consists of a burnishing pin made from cemented carbide. It is hemispheric in shape and is attached at the end of the tool top. A spring is inserted into the tool shank, and the spring preload can be controlled. The FSB tool is then mounted in the spindle, and it rotates and moves on the workpiece surface as in the ball-end milling process with cross-feed, as shown in Fig. 2.

The FSB trials were undertaken on a vertical machining center (Mazak NEXUS 410-A). The experimental setup and conditions are shown in Fig. 2 and Table 1, respectively. The number of times the tool traversed the workpiece surface with cross feed was set to 10 for each condition. Processing length of each path is 42 mm. Two types of temperature measurement, namely a tool-work thermocouple and an embedded thermocouple, were used to measure the temperature generation during the process as shown in Fig. 3. The tool-work thermocouple was used to measure the temperature across each path (Fig. 4). The electrical connection between the burnishing pin and a recorder was achieved by setting a brush made of the same material as the pin to avoid the thermo electromotive force. Meanwhile, the embedded thermocouple (Fig. 5) measured the temperature at the designated location. An alumel wire was embedded into the 1st path and the 10th path.

Workpiece cross-sections were mounted, ground using SiC paper and polished with diamond compound. After being polished, they were etched using nital solution (5% nitric acid in ethanol). Subsurface microstructural analysis was conducted using an optical microscope and scanning electron microscopy (SEM). Vickers microhardness measurements using a load of 25 gf for 20 seconds were taken at 100 μm intervals.

Table 1 Processing conditions

Spindle speed	S	min^{-1}	10000
Feed rate	F	mm/min	200
Cross feed	CF	mm	0.3
Processing force	P	N	750, 500
Workpiece material			0.45%C steel
Tool tip radius	R	mm	3
Tool tip material			Cemented carbide (Sumitomo H1)

(a) External view

(b) Components

Figure 1 Tool for frictional stir burnishing

Figure 2 Experimental set-up

Figure 3 Temperature measuring points

Figure 4 Setup for measuring temperature

Figure 5 Workpiece where alumel wire was embedded

3. Thermal influence on the surface due to FSB

In this experiment, spindle speed $S=10000 \text{ min}^{-1}$, feed rate $F=200 \text{ mm/min}$, cross-feed $CF=0.3 \text{ mm}$, processing force $P=750 \text{ N}$, and tool tip radius $R=3 \text{ mm}$ were used. The results of the processed surface are shown in Fig. 6. It can be seen that the color of the surface changed to bluish brown. This indicated that an oxide film covered the surface. In addition, regular striations like circular arcs were produced on the surface. This is mainly due to the stirred surface layer and plastic flow induced on the processed surface. Moreover, a burr-like pleat was formed on the surface on the right side of the feed direction of the tool. This is probably due to the softening of the material by friction and heat generation during the process. As a result, the rotated tool pushes the material out to form a burr.

Figure 7 shows a photomicrograph of the etched micro structure on a cross-section of the processed surface layer and the micro-hardness distribution. It can be seen that the appearance of the processed layer is significantly different than that of the base material. The thickness of this layer is approximately $200 \text{ }\mu\text{m}$. Most of the enhanced regions observed appear black in color. However, the enhanced region on the last path was white in color due to its unetched condition. The hardness value at this region reached 900 HV . However, the hardness value of the black enhanced region was lower than that of the white enhanced region. In addition, the hardness of the black enhanced region varied considerably.

Figure 8 shows the processing temperature as measured by two kinds of thermocouples. The temperature of the processing point ranges between $600 \text{ }^{\circ}\text{C}$ and $750 \text{ }^{\circ}\text{C}$ roughly. Although processing temperature partly exceeds A_1 transform point (normally $723 \text{ }^{\circ}\text{C}$), it does not exceed A_3 transform point (normally $780 \text{ }^{\circ}\text{C}$). Therefore, it is thought that only perlite was transformed into austenite by this process at least. Figure 9 shows the temperature of two fixed measurement points as measured by embedded thermocouples. The distance between the two measuring points in the cross-feed direction was 3 mm . The temperatures of each path were plotted in one graph with an expanded time axis. The number of tool passes traversing the workpiece surface was 10. Fixed measurement points 1 and 2 represent the temperature measured during the 1st path and 10th path, respectively. These temperature distributions show that the temperature tended to decrease soon after tool passed. This can be explained by the fact that the processing area at the tool tip is very small, and the heat can rapidly diffuse into the workpiece. The elapsed time during the cooling from maximum temperature to the M_s point ($388 \text{ }^{\circ}\text{C}$) was less than 0.5 seconds. This cooling rate is high enough to transform into martensite from austenite. Normally, a carbon steel shows mixed structure that consist of austenite and ferrite when it is heated up to the temperature between A_1 transform point and A_3 transform point. When this structure is cooled faster than the critical cooling rate, it becomes a mixed structure that consist of martensite and ferrite, which means only the austenite transforms into martensite. However, it can be recognized that white enhanced region is uniform structure from Fig.7. It can be assumed that the measured temperature is not exactly at the junction point but in the junction area of each point. Therefore, if the temperature in the junction area was not uniform, there is a possibility that the true maximum temperature was higher than the measured temperature, and exceeded A_3 transformation point. Moreover, it is known that A_3 transformation point decreases under the compressive stress condition ⁽⁵⁾. From these situations, it is thought that the white enhanced region is martensite.

By the way, there can be observed two kinds of enhanced regions. Enhanced region excluding white region, processed by last path, is black in color. The processed region was reheated to over $400 \text{ }^{\circ}\text{C}$ at 0.6 to 0.9 mm (2 to 3 pathes) away from the processing point. It appears likely that white enhanced region was transformed into black enhanced region by reheating as tempering.

It was noted that white enhanced layer was harder than usual hardened $0.45\%\text{C}$ steel. When martensite content rate of $0.45\%\text{C}$ steel is 99.9% , its hardness is about 660 HV . It is believed that the material was hardened by the combination of martensite transformation and work hardening. Moreover, there is a possibility that the material was processed via hot working. During hot working, dynamic recovery occurs with work hardening. If the dislocation density is increased by work hardening more than it is decreased by dynamic recovery, dynamic recrystallization will take place ⁽⁶⁾. Dynamic recrystallization produces grain refinement and thus makes the material harder ⁽⁷⁾.

Figure 6 Processed surfaces ($P=750$ N)

Figure 7 Etched microstructures on a cross-section with hardness distributions ($P=750$ N)

Figure 8 Processing temperature measured by two kinds of thermocouples ($P=750$ N)

(a) Fixed measuring point 1

(b) Fixed measuring point 2

Figure 9 Processing temperature at fixed measuring points ($P=750$ N)

4. Influence of severe plastic deformation by FSB

A lower processing force of 500 N was used in this investigation in combination with other conditions. The experimental conditions were as follows: spindle speed $S=10000$ min^{-1} , feed rate $F=200$ mm/min, cross feed $CF=0.3$ mm, processing force $P=500$ N, and tool tip radius $R=3$ mm. Figure 10 shows the color of the processed surface, which is partially brown. However, most of the processed surface has a metallic luster. This suggests that the oxide film that covered the processed surface was very thin or not present at all in parts. Regular striations like circular arcs can be seen on the surface at the last path. A burr-like pleat was formed on the surface intermittently. However, when $P=750$ N was employed, this circular arc and burr were more pronounced.

Figure 11 shows a photomicrograph of the etched microstructure on a cross-section of the processed surface layer with the hardness distribution. It can be seen that a layer that was obviously different from the base material was generated. The thickness of this layer was approximately 100 to 150 μm . It was thinner than the layer processed with $P=750$ N. The color of the etched enhanced region is similar across the layer. An extremely hard region (more than 1000 HV) was found at a point 1.4 to 2.0 mm to the right of the measurement origin, and 0.025 mm in depth.

Figure 12 shows the processing temperature measured by two kinds of thermocouples. It was found that the processing temperature measured by a tool-work thermocouple was about 500 $^{\circ}\text{C}$. Figure 13 shows the temperature of the fixed measurement points measured by an embedded thermocouple. From this figure, the maximum processing temperature of 550 $^{\circ}\text{C}$ was recorded at point 2. The measured processing temperatures did not exceed the A_1 transformation point, which is 723 $^{\circ}\text{C}$. It can be assumed that the measured temperature is not exactly at the junction point but in the junction area of each point. Therefore, if the temperature in the junction area is not uniform, there is a possibility that the true temperature is higher than the measured temperature. If the true temperature exceeds the A_1 point, the structure may transform into martensite.

Kahles ⁽⁸⁾ reported that a white layer generated when drilling 0.4%C steel

(composition: 0.35 to 0.45%C, 0.05 to 0.35%Si, 0.06 to 0.10%Mn) under severe processing conditions was martensite. However, the temperature measured near the hole was about 500 °C. He suggested that the temperature at which the structure transforms into austenite was reduced by pressure during drilling. Also, it cannot be assumed that the structure transformed into martensite once the processing temperature exceeded the A_1 transformation point. Umemoto ⁽⁹⁾ reported that, when drilling 0.56%C steel, the white layer contained 20% nanocrystalline ferrite, and the remaining 80% was martensite. Nanocrystalline structure consists of fine grains and has a clear boundary between the base material and nanocrystalline, is extremely hard and does not grow by tempering ⁽⁹⁻¹⁰⁾. It is known that nanocrystalline can be obtained by severe plastic deformation and consequently can cause dynamic continuous recrystallization and reduce the grain size.

FSB produces not only frictional heat but also extremely large strain. Figure 11 shows a clear boundary between the enhanced region and the base material, and a maximum hardness of approximately 1000 HV was recorded. In addition, the hardest point was not located in the margin. It can be suggested that the tool that passed repeatedly caused a great deal of strain in this location. Moreover, it can be seen that the processed area was reheated to 300 to 400 °C by heat transmission in the following pathes. The processed area was changed by the reheating when it was processed with $P=750$ N. However, Fig. 11 shows that the color of the etched enhanced region was not changed and the hardness was not softened by reheating. These results suggest that the enhanced region was made by grain refinement.

Figure 10 Processed surfaces ($P=500$ N)

Figure 11 Etched microstructures on a cross-section with hardness distributions ($P=500$ N)

Figure 12 Processing temperature measured by two kinds of thermocouples ($P=500$ N)

(a) Fixed measuring point 1

(b) Fixed measuring point 2

Figure 13 Processing temperature at fixed measuring points ($P=500$ N)

5. Observation of the enhanced region by SEM

For further investigation, the enhanced region samples were observed under SEM. Figures 7 and 11 show the microstructure of the enhanced region obtained by the FSB process. Meanwhile, Figs. 14 and 15 show cross-sectional SEM views of the enhanced layer, which was processed with $P=750$ N and $P=500$ N.

Figure 14 (a) shows that the boundaries between the base material, white enhanced region and black enhanced region are clear. Fine dents in the SEM image of the white enhanced region can be recognized in Fig. 14 (c). However, the grains cannot be observed. On the other hand, a rough face and spheroidal particles can be seen on the SEM image of the black enhanced region as shown in Fig. 14 (d). If the black enhanced region is tempered martensite, it is possible that the spheroidal particles are precipitated cementite.

It was also easy to identify the boundary between the base material and the enhanced region as shown in Fig. 15 (a). The fine structure that can be recognized by its appearance seems like the black enhanced structure processed with $P=750$ N as shown in Fig. 15 (c). Troostite and sorbite, which are obtained by tempering martensite, are fine perlite. It can be suggested that the structure of the enhanced region is ferrite and perlite because the processing temperature did not exceed the A_1 transformation point when processed with $P=500$ N. This is the main reason that the structure consists of ferrite and perlite.

(a) The boundary between the base material, white enhanced region and black enhanced region

(b) Base material

(c) White enhanced region

(d) Black enhanced region

Figure 14 SEM image on a cross-section ($P=750$ N)

(a) The boundary between the base material, white enhanced region and black enhanced region

(b) Base material

(c) Enhanced region

Figure 15 SEM image on a cross-section ($P=500$ N)

6. Conclusions

In this paper, FSB with a high-speed rotating tool was conducted. The following conclusions can be drawn:

- (1) The white enhanced region, where the hardness reaches 900 HV and thickness is 200 μm , was obtained under the conditions of $S=10000 \text{ min}^{-1}$, $F=200 \text{ mm/min}$, $P=750 \text{ N}$, and $R=3 \text{ mm}$. During the FSB process of a steel, processing temperature elevates up to transform to austenite phase, then the temperature rapidly decreases after tool passes. In addition, severe plastic strain is induced at the processing point. It should be noted that the white enhanced region is harder than the commonly quenched 0.45%C steel. It can be assumed that the hard layer obtained in this experiment was generated by not only the martensite transformation but also the grain refinement during the FSB process.
- (2) When the white enhanced region was reheated for tempering, the black enhanced region was obtained. The level of hardness of the black enhanced region is lower than that of the white enhanced region.

- (3) A region with hardness of 1000 HV was obtained under the conditions of $S=10000 \text{ min}^{-1}$, $F=200 \text{ mm/min}$, $CF=0.3 \text{ mm}$, $P=500 \text{ N}$, and $R=3 \text{ mm}$. Although it is considered that the processing temperature was not high enough to transform into austenite, severe plastic deformation was given to the material. It can be assumed that the hard layer obtained in this experiment was generated by the grain refinement caused by dynamic continuous recrystallization.

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