The effect of boriding on wear resistance of cold work tool steel

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Abstract. Recently, boriding has attracted extensive attention as surface stiffening processing of plain steel. In this research, the influence of processing time on the formation layer of cold work tool steel (KD11MAX) by Al added fused salt bath was examined. In addition, in order to improve the abrasion resistance of KD11MAX, the effect of the treatment of boronization on the formation layer has been investigated. Boriding were performed in molten borax which contained about 10 mass% Al at processing time of 1.8 ~ 7.2 ks (processing temperature of 1303 K). As a result of the examination, the hardness of the boriding layer becomes about 1900 HV when the processing time of 3.6 ks. Also the abrasion resistance has improved remarkably. Furthermore, it was revealed that the formation layer was boronized iron from the Vickers hardness and analysis of the X-ray diffraction measurement.

1. Introduction
In recent years, machine parts manufactured by forging have been increasing. The reason is that it because processing speed of forging is extremely faster than that of cutting. Among them, the workpiece manufactured by cold forging has good dimensional accuracy and surface finish to perform a compression molding of metallic materials at room temperature with die. However, a die for cold forging have a short life because the molding pressure and the load to a die is high. Thus, to elongate the lifetime of a die, it is necessary to improve the surface hardness and wear resistance by surface reforming.

As for the cold working tool steel used for cold forging, the surface hardness and wear resistance are generally improved by quenching or nitriding [1-3]. Nevertheless, the hardness of the hardening layer to be formed by each hardening method is less than 1200 HV. On the other hand, a boron compound is an example of a compound which had high wear resistance and hardness [4, 5]. As a boriding method, the molten salt immersion method is known as the method that special equipment are unnecessary, and is the simplest. However, there is very little report about boriding than nitriding and carburizing of cold working tool steels.

In this study, for the purpose of mechanical property improvement of the cold working tool steel, boriding was carried out with quenching by performing heat treatment at the time of the quenching in Al added fused salt bath. The mechanical property of the processed layer was evaluated by the surface and sectional hardness measurement and abrasion test. The identification of the processed layer was analysed by using an X-ray diffractometer (XRD).
2. Experimental details
As shown in Figure 1, the specimen used in this study comprised a 50 × 30 × 5 mm³ plate cut from cold work tool steel (Nihon Koshuha Co., Ltd., Japan, KD11MAX) ingot. The surface to be treated of the steel was finished by grinding with emery paper (grade 1200). The Al added fused salt bath was made by dissolving a mixture in crucible made by SUS304 stainless steel after mixing 10% Al with sodium tetraborate. Boriding were performed by immersing a specimen in Al added fused salt bath while turning a specimen at rotary speed of 20 rpm with shaft. The boriding temperature was fixed at 1303 K, although the boriding time was changed ranging from 1.8 ks to 7.2 ks. After boriding, the specimen was air-cooled after taken out from a bath. Subsequently, the specimen was boiled in water for 1.8 ks to remove surface contamination. The surface and the sectional hardness was measured by using Vickers hardness tester. To determine the compound formed on the surface after the boriding, the treated surfaces were investigated using an X-ray diffractometer (XRD) with CuKα radiation working at the optimum voltage of 32 kV and anodic current of 20 mA. Furthermore, a specimen showing the vertical cross section of the boriding surface was also prepared and observed by SEM and EDX analysis at an acceleration voltage of 15 kV. This specimen was prepared by first polishing it using emery paper (grade 1200), followed by ion milling system. The abrasion test was carried out at room temperature under a load of 4.9 N (sliding distance of 5760 m) by the ball-on-disk-type abrasion testing equipment. In addition, the ball is made by ZrO₂ of a radius of 3/32 inch. The depth profile of the sliding portion after the abrasion test was measured by a laser microscope.

3. Results and discussion
3.1 Surface hardness and X-ray structure analysis
To identify influence of the processing time on the surface hardness, the surface hardness was measured by Vickers hardness tester. The measuring load is changed to investigate a crack resistance. As shown in Figure 2, surface hardness decreased with increase of the processing time without depending on measuring load. Regardless of processing time, surface hardness decreased with increase in measuring load.

![Figure 1. Schematic illustration of to-be-processed specimen (in mm).](image1)

![Figure 2. Surface microhardness of the specimen after boriding.](image2)
In addition, the X-ray diffraction measurement was performed to examine a metallic structure formed on the boriding surface. As shown in Figure 3, from the x-ray diffraction measurement, it was revealed that FeB and Fe$_3$B were formed. Moreover, with an increase in processing time, peaks shifted to the low angle side. From the X-ray diffraction measurement result, it is inferred that the boriding surface has the compression stress. It is thought that the reason why the surface hardness decreased at the processing time of 5.4 ks or more is because a crack progressed around an indentation when the hardness testing was performed. Actually, from the circumstance of the indentation, a radial crack was observed.

### 3.2. Cross-sectional structure and hardness distribution

To determine the effect of the processing time on the cross-sectional metallic structure and hardness distribution of a boriding layer, SEM and EDX analysis was carried out. As shown in Figure 4, a lamellar structure consist of three layers was observed in the vicinity of the surface. As a result of the EDX analysis, the difference in color of each layer was shown to depend on the B content. With increase of the processing time, the tendency that thickness of the lamellar structure increased was recognized. In addition, the detected amount of Cr was decreased in the third layer from the surface. It is inferred that this is because chromium boride was precipitated and chromium-depleted zone was formed.

![Figure 3](image3.png)

**Figure 3.** X-ray diffraction patterns of the surfaces of various specimens after boriding: (a) 1.8 ks, (b) 3.6 ks, (c) 5.4 ks and (d) 7.2 ks.

![Figure 4](image4.png)

**Figure 4.** Cross-sectional SEM images and line analysis profiles of the surface layer after boriding: (a) 1.8 ks, (b) 3.6 ks, (c) 5.4 ks and (d) 7.2 ks.
As shown in Figure 5, with increase of the processing time, the width of the high hardness layer increased. The hardness decreased gradually following two stepped hardness distribution. As for the boronized iron, the hardness of FeB and Fe$_2$B is known as 1800–2000 HV and about 1600 HV, respectively. Hence, it is inferred that first layer and second layer from the top surface consisted of FeB and Fe$_2$B, respectively.

3.3. Effect of the processing time on the abrasion resistance

Figure 6 shows the relationship between processing time and the wear depth of the processed specimen. The wear depth can be calculated by the next equation (1) by supposing that an abrasion partner ball is worn.

\[
    d = \left( (2.381)^2 - \left( \frac{w}{2} \right)^2 \right)^{1/2}
\]

(1)

In the equation (1), \(d\) and \(w\) represent a calculated value of the wear depth and a measured value of wear width.

With increase of the processing time, the wear depth increased linearly although the wear width increased quickly from the processing time of 5.4 ks. As described above, at the processing time is more than 5.4 ks, boron is dissolved and supersaturated in base metal (refer to Figure 3). Because an excessive solid-dissolution of boron into base metal promoted the spalling in FeB layer, it was revealed that the wear depth increased. As shown in Table 1, at the processing time is more than 5.4 ks, a calculated value of the wear depth exceeded a measured value. It was found from these results that the abrasion of the ball surface was caused in addition to the boriding surface. It is inferred that the cause of this disagreements are changes from mechanical wear to abrasive wear.

![Figure 5](image5.png)

**Figure 5.** Microhardness profiles of the specimen after boriding (load = 0.025 kgf).

![Figure 6](image6.png)

**Figure 6.** Influence of processing time on wear depth.
Table 1. Wear width and depth of the specimens after wear testing at various processing time.

| Processing time, $t$ [ks] | Wear width, $w$ [μm] | Wear depth, $d$ [μm] |
|---------------------------|----------------------|----------------------|
|                           | measured             | calculated           |
| 30                        | 746                  | 5.39                 |
| 60                        | 651                  | 6.70                 |
| 90                        | 1778                 | 28.5                 |
| 120                       | 1962                 | 31.7                 |

Figure 7 shows the SEM micrographs and EDX analysis results of the sliding portion after the abrasion test. As a result of elementary analysis outside of the sliding portion, oxygen was detected from abrasion powder. Therefore, it is inferred that oxidative wear occurred in all processing time. When the processing time was more than 5.4 ks, a scratch marks came to be observed. From the investigation results of the cross sectional microstructure and hardness (refer Figure 4 and Figure 5), it is thought that abrasive wear occurred after FeB layer peeled from a processed surface. Moreover, on the basis of the depth profile of the sliding portion, it was revealed that abrasion was controlled in layers consisting of Fe$_2$B. From the above results, it was suggested that optimization of the processing time according to an applicable part is required.

4. Conclusions
The conclusions of this study are summarized as follows.
(1) As a result of a hardness measurement, it was found that the most suitable processing time was less than 3.6 ks to form a layer having the high surface hardness and toughness.
(2) When the processing time was more than 5.4 ks, the abrasion was controlled in Fe$_2$B layer, although the abrasive wear occurred after FeB layer peeled.

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