Friction stir processing as a method of hardening cutting tools

I K Chernykh, E V Vasil'ev, A M Badamshin, A G Kushnareva
Omsk State Technical University, 11 Mira ave., Omsk, 644050, Russia

e-mail: vnchnkh@gmail.com

Abstract. One of the most perspective methods of hardening is friction stir processing. The study shows processing methods based on the friction stir principle. The results of hardening of tool steels 1089 (Fe97%, C0.8%), 3343 (Fe80%, C0.9%, Cr4%, Mo5%, W6%, V2%), 440C (Fe78%, Cr18%, C0.95%) are presented. As a result of hardening, it was possible to increase the microhardness of carbon tool steel by more than 3 times, and also to achieve a decrease in the average grain size in the treated area by more than 10 times in relation to the base material. It is proposed to use the FSP in the manufacture of cutting tools from tool steels to increase physical and mechanical properties.

1. Introduction

The friction stir processing (FSP) is akin to the friction stir welding (FSW) process. The Welding Institute (Cambridge) made a tangible contribution to the development of the FSW method, and it was invented by TWI specialists [1]. Most researchers refer to the 1991 patent as the first mention of the FSW process in the scientific literature. Some researchers note that the process was known in the USSR in the 60s [2-4], which is proved by the copyright certificate [5]. In any case, it was TWI that started active research into the process. In the early 2000s, the study and active development of a new metal processing method based on the principles of friction stir welding - friction stir processing began.

Nowadays FSP allow us to produce composites, hardening and shaping of a material, which is implemented using a special rotating tool that exerts a thermomechanical effect on the material being processed. In the FSP, a rotating tool, which has a shoulder and (not in all cases) a pin, exerts axial pressure on the surface of a solid workpiece, or a workpiece with added particles. As a result, the following can be formed: altered microstructure with smaller grains; zone with the addition of particles (composite); layer of another (homogeneous or heterogeneous in relation to the base) material; technological tunnel; structure with a reduced degree of heterogeneity. Technologies based on the FSP principle are shown in Fig. 1. In more detail, all the technologies presented will be considered in other study.
Figure 1. Technologies based on the FSP principle

The first mentions of FSP as a separate technology date back to 1999. The first researchers to study FSP include the R. S. Mishra, M. W. Mahoney, Z. Y. Ma, Indrajit Charit, T. W. Nelson, N. Saito and others [6-11]. Among Russian studies, there are few works devoted to FSP [12, 13]. In general, FSP is carried out according to the scheme shown in Fig. 2. In this case, a diagram of FSP by tool with a pin is shown. In fig. 2 blank - one-piece (one half is shown transparent for illustrative purposes).

Figure 2. FSP using tool with a pin principal scheme: a) – before processing; b) – at the beginning of the processing (after plunging); c) – the position near the end of processing; d) – after processing
2. Formulation of the problem
The aim of the study is to determine the effect of friction stir processing on the hardness and microhardness of tool steels.

3. Theory
The analysis of studies shows that after FSP, the results of changes in physical and mechanical properties are varying of material to material. For example, FSP of aluminum alloys, one can often observe a drop in hardness in the nugget zone [12]; FSP of some steels, one can observe both a significant increase in hardness [14] and an insignificant one [15], while wear resistance and corrosion resistance often increase [15].

The change in hardness and wear resistance is explained as a consequence of a change in the microstructure of the material. Researchers note that after FSP of steels the formation of micrograins takes place, the size of which can be an significant smaller than the grain size of the base material. For example, after FSP of the aluminum plate the average grain size decreased from 45 to 6.8 [16], and after FSP pure iron from 130 to 6.2-2.1 [17]. Along with a change in the grain size, the hardness (microhardness) also increases, and the increase can be more than 3 times than that of the base metal, as, for example, in the study [16] (the hardness increased from 173±15 to 900 ± 50 HV). These factors make the technology a promising method of hardening, in addition to the low cost of its implementation.

To determine the effect of processing on the hardness of tool steels, it is necessary to conduct an experiment, during which hardened samples will be obtained using a carbide tool under various conditions. Steel 1089 (Russian grade U8: Fe97%, C0.8%), 3343 (Russian grade R6M5: Fe80%, C0.9%, Cr4%, Mo5%, W6%, V2%), 440C (Russian grade 95Kh18: Fe78%, Cr18%, C0.95%), T1 (Russian grade R18: Fe73%, C0.8%, Cr4%, W18%) were selected as the material under study.

4. Experimental results
Some of the processed samples are shown in Fig. 3.

![Figure 3. Image of samples: a) – 440C (Russian grade 95Kh18: Fe78%, Cr18%, C0.95%); b) – 1089 (Russian grade U8: Fe97%, C0.8%); c) – T1 (Russian grade R18: Fe73%, C0.8%, Cr4%, W18%); d) – 3343 (Russian grade R6M5: Fe80%, C0.9%, Cr4%, Mo5%, W6%, V2%)](image-url)
An image of the cross-section of a sample made of 440C steel is shown in Fig. 4 (sample height 4 mm). Here you can see a clear delineation of the already known zones - the nugget zone, the thermomechanical affected zone, the heat affected zone and the base material.

The results of the experiment showed that all the materials being selected for processing may be hardened using carbide tool, with the exception of T1. When processing T1 steel, heightened temperature is observed (more than 1000 ºC, even at low tool rotational and transverse speed) and it is lead to the extensive tool wear. Subsequently, that material should be processed using a tool with higher heat and wear resistance.

![Image of the cross-section of the processed sample from 440C steel](image)

**Figure 4.** Image of the cross-section of the processed sample from 440C steel

The obtained hardness data of the processed zone for comparison with that of the base material are shown in Fig. 5. To draw up the graph, the average values of hardness were used, measured on several samples (for 440C - 10 samples, 1089 and 3343 - 5 samples each). The graph is for informational purposes only; more detailed data will be presented in further studies.

![Graph of average values of samples microhardness](graph)

**Figure 5.** Average values of samples microhardness in the nugget zone and in the base material

Microstructure analysis shows significant changes in the nugget zone in comparison with the base material, in particular: the grain size, the carbide size and its distribution being changed, and in some cases (1089 grade) the steel structure itself is being changed. An image of the microstructure of the 440C alloy in the nugget zone is shown in Fig. 6. In the base material, the average size of carbides is...
much larger and their distribution is less uniform. After processing, the "breaking" of large carbides into smaller ones takes place, and as a result of stirring, they are more evenly distributed over the volume of the processed material.

**Figure 6.** Microstructure of 440C steel after FSP: a) nugget zone; b) - base material (without processing)

With the FSP of 1089 steel, a change in the structure is also observed; images of the processed and unprocessed area are shown in Fig. 7.

**Figure 7.** Microstructure of 1089 steel after FSP: a) nugget zone; b) - base material (without processing)

The microstructure of the sample without processing is rather heterogeneous. In addition to the grains of lamellar pearlite, there is also the presence of ferrite with cementite inclusions of a spherical shape (granular pearlite). The presence of granular pearlite is undesirable, since it leads to an uneven distribution of microhardness in the samples and a decrease in the total value of hardness [19]. FSP leads to significant structural and phase changes in samples from steel 1089. As a result of heating to temperatures exceeding the recrystallization temperature (above 900 °C), phase recrystallization occurs in a thin surface layer of the samples. Heating, followed by accelerated cooling, contributes to the grinding of the ferrite-cementite mixture (large-lamellar perlite is converted into sorbitol), a decrease in the total grain score and an increase in the overall homogeneity of the microstructure. All the above-described structural changes as a result of FSP lead to an increase in the mechanical characteristics of samples made of 1089 steel and can contribute to an increase in wear resistance.
5. Discussion
Specimens of steel 440C, 3343 and 1089 showed an increase in hardness and a change in the microstructure after processing, and processing of a specimen of steel T1 led to the destruction of the carbide pin of the tool. As a result, FSP was able to increase the hardness by 220%, 20% and 170% compared to the initial value for steels 440C, 3343 and 1089, respectively, while the hardened areas when using the optimal modes do not have significant defects.

Based on the data obtained, it can be argued that the FSP allows local hardening of the material, and it can be more effective than heat treatment. In addition, it is possible to strengthen both the stock material and the heat-treated material, which will also increase its hardness (the authors managed to increase the hardness from 600 HV to 780 HV when processing the heat-treated steel 440C).

It was also found that hardening can be carried out using a carbide tool, while, despite the adhesion of the processed material to the pin and shoulder of the tool, it retains its operability. Hardening can be carried out using universal milling machine. During the experiments, it was found that the process temperature under optimal conditions does not exceed 950 °C, and the axial force does not exceed 15 kN (on average, 5-8 kN at the optimal temperature). Unlike other hardening methods, this method does not require specialized equipment, is the most environmentally friendly and easy to implement.

6. Conclusion
It is shown that the FSP technology is effective in hardening tool steels. It is proposed to use it as a hardening technology in the manufacture of cutting tools, while hardening is performed only in the area of the cutting edge. The easiest to implement will be the hardening of flat tools such as guillotine knives, while the depth and width of the treated area will depend on the size of the pin and the shoulder of the tool. Thus, it is possible to manufacture a tool with a microhardness in the cutting edge zone 3 or more times higher than in the base material, while other parts of the tool will not be exposed to thermal effects, internal stresses, etc., since the hardening process occurs only in the zone processing, and the rest of the metal heats up slightly. As a consequence of the increased hardness of the material, there will be an increase in wear resistance. The tool made according to the hardening technology under study will have a significantly higher resource of work. To refine the technology to an industrial level, it is necessary to conduct research on the effect of processing on wear resistance, the appearance of defects inside the treated area and to make prototypes of cutting tools hardened using this method.

7. References
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