Structure and Properties of Burnished and Nitrided AISI D2 Tool Steel

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D2 belongs to traditional steels, frequently used in metalworking industry. Shot peening and nitriding are known to improve the wear resistance of D2. In this work we focus on processes of slide burnishing and industrial low temperature gas nitriding. The D2 steel specimens were first subjected to heat treatments (HT) prescribed by the manufacturer, turning (T), then burnishing (B) and nitriding (N). The reason for turning was achieving appropriate surface roughness. Deformation induced in slide burnishing can be better controlled then in shot peening because of deterministic nature of this process. Four different paths to prepare surfaces were employed: HT + T, HT + T + B, HT + T + N, HT + T + B + N. D2 steel is very sensitive to the final finishing, wear rates vary up to 300 %. Two of our procedures (HT + T + N and HT + T + B + N) are much superior to the others. Moreover, in the HT + T + N case, apparently the surface fatigue scaling off takes place.

Keywords: steel slide diamond burnishing, steel nitriding, tool steel, steel wear.

1. INTRODUCTION

Burnishing of metalworking tools can lead to wear resistance improvement as well as longevity increase. Usually metalworking tools comprise entire fixtures and operate in high productivity production lines. Needless to say, long down-time means low output, high cost and loss of competitiveness of the plant. We believe that improvement of manufacturing technologies is more economical than highly praised development of new materials.

Among the popular traditional tool materials – Sverker 21 (AISI D2) is recognized as inexpensive and good for many industrial applications. Numerous publications deal with this high chromium steel and with some of its improvements such as addition of molybdenum or titanium with parallel carbon and chromium reduction [1], as well as treatment improvements (including nitriding) [2 – 6]. Laboratory testing of various kinds have been performed – but to our knowledge no testing in service; necessarily, the latter is more time consuming and more difficult to perform. Hashami and co-workers [7] have reported some benefits of shot peening. Berkowski and Borowski [8] reported some advantages of nitriding. We have worked on steel property improvement primarily by slide diamond burnishing [9, 10]. On the basis of the literature and our own results, in the present work we have focused on various combinations of heat treatment (HT), turning (T), burnishing (B) and nitriding (N). The following sequences were followed: HT + T, HT + T + B, HT + T + N, HT + T + B + N.

2. EXPERIMETAL

Specimens of ledeburitic chromium-alloyed tool steel AISI D2 (known under the trade name Sverker 21), were obtained by a conventional metallurgical process. The respective chemical composition is shown in Table 1. The specimens were machined and subjected to a heat treatment (austenizing temperature $1035 \div 1040$ °C, soaked 4 min 40 s; double tempering for 2 h at 530 °C and 520 °C) aimed at reaching the Rockwell Hardness of ≈ 60 HRC.

Table 1. Chemical composition of the studied tool steel in wt.%

C	Si	Mn	Cr	Mo	V
1.55	0.3	0.4	11.8	0.8	0.8

After heat treatment, longitudinal turning of the bar probe with a tool insert holder was performed first. The following turning conditions were maintained: turning speed $v_c = 100$ m/min, feed $f = 0.17$ mm/rev, cutting depth $a_p = 0.1$ mm. Polycrystalline cubic boron nitride (PCBN) cutting inserts made by Mitsubishi under the trade name NP-SNGA 120412GS2 MB730 were used. The surface roughness Ra is defined as the arithmetic average height of roughness-component irregularities (peak heights and valleys) from the mean line, measured within the sampling length. Our Ra values are averages of 6 measurements. Before burnishing, we obtained the Ra values between 0.72 and 0.82 μm. Turning improves the surface geometry, thus affecting the roughness.

Slide diamond burnishing process of our steel in the quenched state was carried out using diamond tools (Fig. 1) designed by us and currently produced by the Institute of Advanced Manufacturing Technology (IAMT), with the tips made of diamond composites with ceramic

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bonding phase, namely Ti_3SiC_2 [11, 12] and the shape of spherical caps with the radius $R = 1.5$ mm.

Fig. 1. Diamond burnisher with tool holder and working parts (spherical cups)

Surface treatments involving both turning and burnishing were carried out on shaft end faces, using fixing system for tools (lathe and burnisher tool) perpendicular to the face; see Fig. 2.
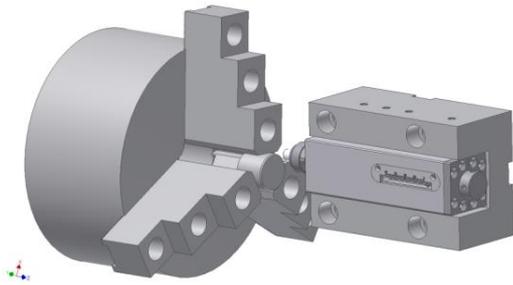

Fig. 2. The fixing of diamond slide burnisher tool

After turning or turning + burnishing process, selected surfaces were immediately nitrided by gas nitriding, under typical conditions defined in Table 2. This technology has been prescribed as one of the operations in the design and manufacturing of tools, dies, etc.

Table 2. Nitriding process parameters

Stage	Process temperature, °C	Time, h
First stage	520	5
Second stage	535	20

The surface roughness parameters were measured with the Hommel Tester T1000 profilometer and also with laboratory profilometer TOPO 01 developed at IAMT.

Surface layer microstructures and nitrogen distributions in HT + T + N and HT + T + B + N specimens were determined using a JEOL JSM 6460 V digital scanning electron microscope equipped with an energy dispersive X-ray spectrometer (EDS).

Transverse metallographic specimens were examined after earlier preparation on metallographic grinding - polisher RotoPol 21. Mounting of samples was done in thermosetting resins in a CitoPress device. The nitrogen content at a given distance from the specimen surface is a mean value for the scanned microsurfaces shown in Fig. 3. In general, such microanalytical method is not recommended for the quantitative analysis of elements with low atomic numbers, i.e. carbon, nitrogen or boron. However, we are using it for comparative purposes.

Vickers microhardness $h_{Vickers}$ was determined using a FM 7 tester from Future Tech. Corp., Japan. Microindentations were made using a 200 g load.

The abrasive wear resistance was evaluated by using the ball–on–disc method; see for instance [13]. A UMT-2MT universal mechanical tester made by CETR, Campbell, CA, USA was used.
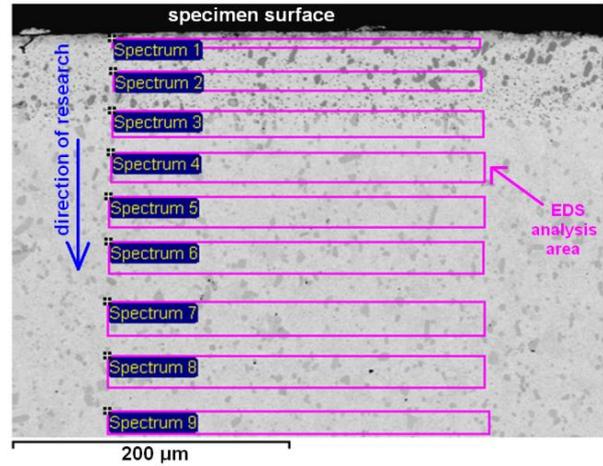

Fig. 3. Image of turned burnished and nitrided specimens with marked EDS analysis areas

The ball and disc samples were washed in ethyl alcohol and dried before the measurement. The loading mechanism applies a controlled load F_n to the ball holder while the friction force is measured continuously during the test using an extensometer. For each test, a new ball was used or the ball was rotated so that a new surface was in contact with the disc.

The size of the disc-shaped samples was approximately 30 mm diameter and 20 mm in height, with the surfaces flatness and parallelism within 0.02 mm. The following test conditions were applied: Al_2O_3 ball diameter 3.2 mm, applied load 6.0 N, sliding speed 0.1 m/s, diameter of the sliding circle 8.0 mm, sliding distance 2000 m, calculated duration of the test $2 \cdot 10^4$ s. The tests were carried out without a lubricant at room temperature. Dynamic friction μ was calculated using the standard formula: $\mu = \dfrac{F_f}{F_n}$ where F_f is the measured friction force while F_n is the applied normal force. After completing the tests following the ISO 20808:2004 E standard, the cross-sectional profile of each wear track was measured at four places, at intervals of 90°, using a contact stylus profilometer TOPO 01. Then the average cross-sectional area of the wear track was calculated. The volume of material removed was calculated as a product of cross-sectional area of the wear track and their circumference. Specific wear rate W_s was calculated by the standard formula: $W_s = \dfrac{V}{F_n \cdot L}$ where V is the volume of removed material and L is the sliding distance.

As expected, the roughness of the tested surface before wear testing was dependent on the type of surface treatment used; see Table 3.

Table 3. Type of surface treatment and resulting roughness

Surface treatment	Sample code	Mean roughness Ra, μm
HT + T	S.1	0.8
HT + T + B	S.2	0.24
HT + T + N	S.3	0.72
HT + T + B + N	S.4	0.23

3. RESULTS AND DISCUSION

In Fig. 4 we display a typical microstructure of quenched and tempered AISI D2 steel; we see carbide particles in a fine tempered martensite structure.
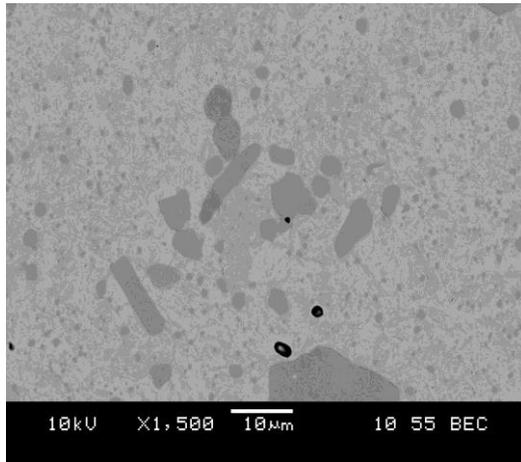

Fig. 4. SEM micrographs of AISI D2 tool steel structure after quenching and tempering

The results of surface roughness measurements and the resulting K_{Ra} index (the ratio of the roughness after turning to burnishing) after the surface treatment processes are presented in Table 4; parameters listed are determined according to ISO 4287: Lt – 4.8 mm (tranverse length); Ra – arithmetical mean deviation of the assessed profile; Rz – the average maximum profile height of the ten largest peak-to-valley separations in the evaluation area; Rp – the maximum profile peak height, i.e. the distance from the mean line/surface to the highest point in the evaluation length/area; Rt – total height of the profile; $Rmr (c)$ – relative material ratio of the profile. The ratio is determined by the intersecting line which separates the protruding peaks from the surface profile. The term bearing area curve (BAC) is also used for the ratio. Lowering the line into the surface results in increasing percentages of the length of the line intersecting protruding peaks. Here results in the last column of the Table pertain to c = 50 %.

We see that slide burnishing favourably affects the surface geometric structure (SGS) of the tool steel. The optimised burnishing parameters ($F = 180$ N, $f = 0.02$ mm/rev) substantially affect the surface characteristics and thus K_{Ra}. The respective parameters are defined at the bottom of Table 4. It is seen from the roughness profiles in Fig. 5 that the height of the profile decreases after burnishing. There is reduction, by more

than a factor of two, of the parameter c%, namely Rt for $Rmr'(c) = 50$ %; we see also a concurrent increase in the material ratio (Fig. 6), what substantially increases the area of tool/workpiece contact.

Fig. 7 shows the cross-sectional microstructure of our D2 steel subjected to various surface treatment processes. The presence of the compound layer can be clearly observed. In the case of the turning+burnishing+nitriding series (Fig. 7 b), the thickness of the nitrided zone is almost double as compared to turned and nitrided only.

We have also determined the Vickers microhardness $h_{Vickers}$, a quantity we have used before and we find convenient to characterize also other types of materials and coatings [14]. In the case of nitrided surfaces of D2 steel, we observe a significant increase of the microhardness (Fig. 8). That increase, in particular down to a 80 μm depth below the surface, is in range $4 \div 44$ % for burnished surfaces – as compared to surfaces nitride only.
Nitrogen content at a given distance from the sample surface is the average value for an area of about 260 x 8 μm. A method of data collection was shown in Fig. 3. The results are summarized in Fig. 9.

There are substantial differences in nitrogen content between cross-sections in T + N and T + B + N samples. At ≈ 100 μm below the surface, the differences exceed 150 %. These observations correlate with the microstructure, in which a clear difference is observed between the thickness and uniformity of the nitriding of the tool steel. A similar trend is evident also in the microhardness profiles (Fig. 8).

The dynamic friction μ, is shown in Fig. 10 as a function of the testing time. After turning, the friction increases with sliding time up to about 60 min.; at that time μ reaches a practically constant value of about 0.9. A similar trend can be observed after burnishing, but then the friction settles at a lower value of approximately 0.8. A different trend is observed after turning and nitriding. Two degradation stages occur after about 2 h and 4.5 h. They seem to correspond to surface fatigue scaling off. A similar phenomenon has been observed by Staia et al. [15]. Sequential processing: turning + burnishing + nitriding results in the lowest value of the dynamic friction of approximately 0.75.

Wear rates calculated as explained above are displayed in Fig. 11. We find significant differences between the results for different treatment sequences. Turning alone does not improve much wear resistance of our D2 specimens. Further surface treatments like nitriding or/and burnishing provide better results. Burnishing alone can increase by almost 40 % the wear resistance of the turned specimens.

Table 4. Mean values (averages from 6 measurements) of surface geometric characteristics parameters

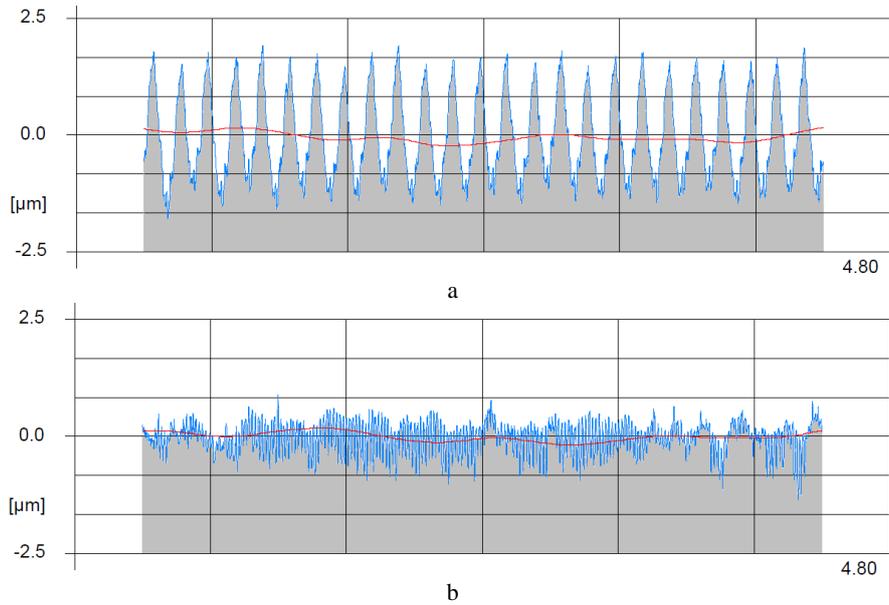| Sample Code	Burnishing Force, N	Feed, mm/rev	SGS parameters after turning					SGS parameters after burnishing					K_{Ra}
			Ra', μm	Rz', μm	Rp', μm	Rt', μm	c', % Rt' for $Rmr'(c)$=50%	Ra, μm	Rz, μm	Rp, μm	Rt, μm	c, % Rt for $Rmr(c)$=50%	
S.1	Turning		0.79	3.31	1.91	3.49	59.9	–	–	–	–	–	–
S.2	180	0.02	0.82	3.51	2.21	4.02	59.7	0.24	1.70	0.90	2.11	39.8	3.38
S.3	Turning		0.72	3.14	2.01	3.52	64.8	–	–	–	–	–	–
S.4	180	0.02	0.75	3.33	2.10	3.62	64.9	0.23	1.56	1.24	2.21	54.8	3.22

Fig. 5. Examples of the profilographs for the specimens surface after: a – turning; b – turning + burnishing.
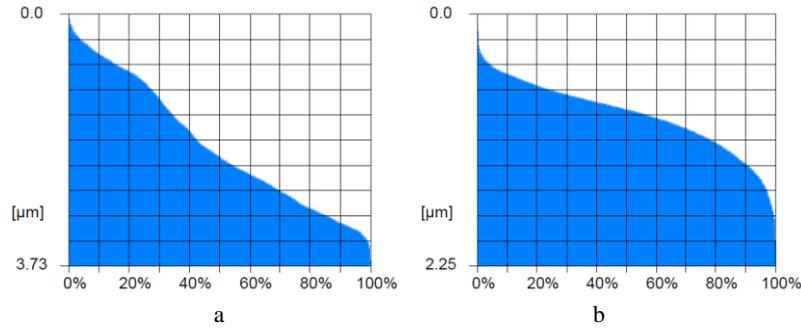

Fig. 6. Examples of the material ratio of the profile for the specimens surface after: a – turning; b – turning + burnishing
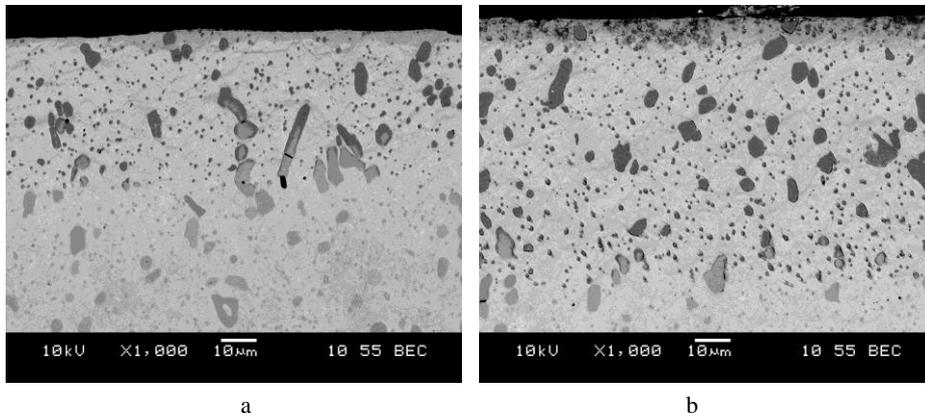

Fig. 7. Cross-sectional SEM micrographs of the surface layer: a – turning + nitriding; b – turning + burnishing + nitriding
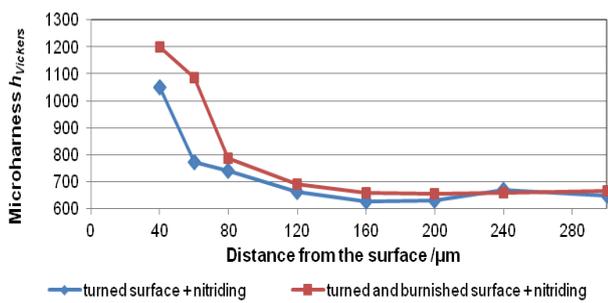

Fig. 8. Microhardness of D2 specimens after turning, slide diamond burnishing and nitriding
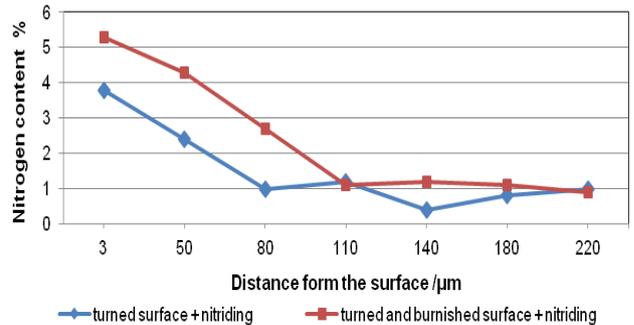
Fig. 9. Distributions of nitrogen content of D2 specimens after turning, slide diamond burnishing and nitriding

Nitriding can have a very strong influence, 150 % improvement. On the other hand, very high hardness of the upper surface layer favours formation of microfractures; the consequences are seen in Fig. 10. The best results are seen for T + B + N specimens (green line in Fig. 10): no scale offs, low value of friction and more then 200 % higher wear resistance in tribometry. Those results confirm the expectation that the synergy effect exists in multistage treatments, as contrasted with single nitriding or burnishing.
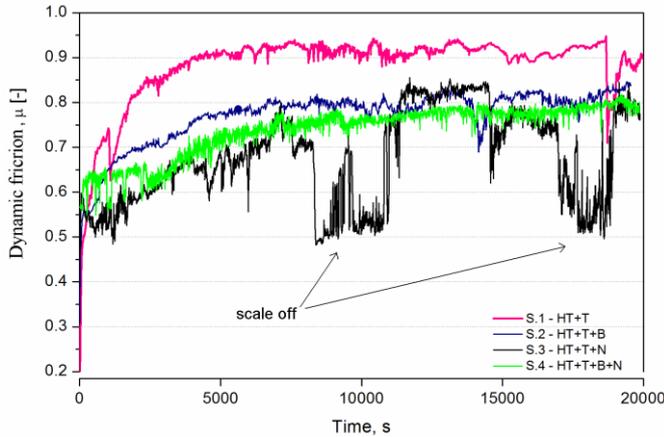

Fig. 10. Changes in the dynamic friction μ for D2 tool steel after various surface treatments

4. CONCLUDING REMARKS AND A SURVEY OF RESULTS

Quite understandably, much research effort is expended in providing steels with a protection from corrosion [16]. The issue of wear concerns only applications when moving parts are involved [17]. However, in those cases we have a similar situation as with corrosion: an otherwise usable part has to be replaced by a new one—while later on the replacement will have to be repeated periodically. Aydin, Bayram and Topçu [18] studied effects of nitriding on AISI 430 ferritic stainless steel. They have performed nitriding in gas mixtures and also in salt baths. Clear effects of the nitriding mediumand also of the temperature on dynamic friction have been reported. Important conclusions from our work can be summarized as follows:

1. Diamond slide burnishing before gas nitriding improves wear abrasive resistance of D2 tool steel by nearly 20 %;

2. Burnishing alone increases the abrasive wear resistance by 37 % in comparison with heat treated and turned specimens;

3. Although HT + T + N samples have a good wear resistance in ball–on–disc testing (only 18 % below the best HT + T + B + N combination), two sudden falls of μ which correspond to scaling off upper layers of the surface (debris formation) occur. Needless to say, peeling the surface is unacceptable for many engineering applications since under dynamic loads a sudden fracture of manufactured elements becomes possible;

4. Comparison with the results of Berkowski and Borowski [8] shows that even less advantageous conditions (higher nitriding temperatures) lead to property improvement in diamond slide burnishing followed by ordinary gas nitriding process.

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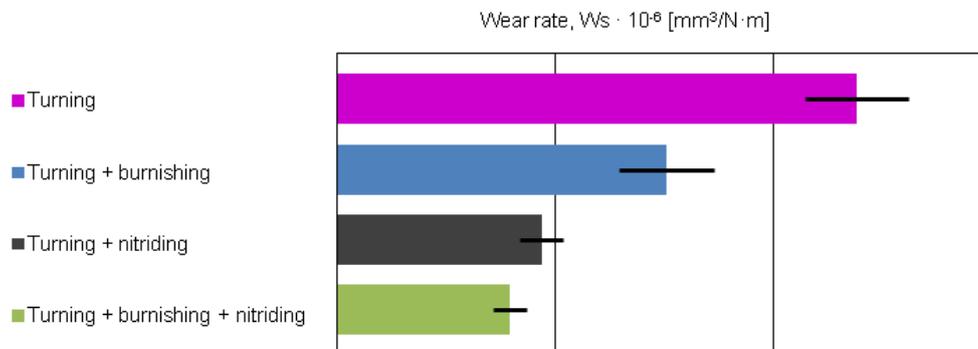
Fig. 11. Wear rates for D2 tool steels after different surface treatments (load: 6.0 N, speed: 0.1 m/s, sliding distance: 2.0 km)

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