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Surface Hardening by Turning without Chip Formation

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Abstract

The present study describes the basic principles, specific features in the implementation and technological capabilities of a new method of quench surface turning without separation of chip. The underlying process of this method is process of Deformational Cutting (DC) which is based on undercutting and deformation of the surface layers that remain on the workpiece. The energy released in the area of deformational cutting is used to heat the undercut layer up to the temperatures of structural and phase changes of the material being processed. As a result of processing, a hardened structure is formed on the surface which consists of inclined, thin undercut layers tightly fitted to each other. Options are available where the undercut layer is fully hardened in its thickness or only partially hardened. Options are presented which show structures generated on steels. Samples hardened by DC method showed a higher wear resistance compared to samples with volumetric hardening.

Keywords: *Hardening, composite, wear resistance, deformational cutting*.

1. Introduction

Surface hardening is the most efficient and economical way of increasing wear resistance of machine parts [1]. This is a real challenge for machines and mechanisms operating under high bearing pressure and abrasive wear. Currently, there have been dozens of surface hardening technologies, most of which require specialized thermal equipment to achieve thermo physical impact needed for structural and phase transformations during quenching of steels [2]. A relatively new method of surface hardening is hardening directly on metal-working machines: temperatures required for hardening are reached in the cutting process thanks to plastic deformation and friction in the contact area of tool and workpiece. The combined effect of severe deformation, high local temperatures, and rapid quenching rates causes the machined surface to undergo both physical and metallurgical changes [3].

2. State of Art

2.1. Quench Hardening with the Use of Cutting Process

Quench hardening during mechanical machining can be realized both by using edge tools and abrasive processing. The effect of increasing surface hardness during lathe machining is described in [4]. To [5] enhance friction of workpiece and tool, turning with a zero back clearance angle was used at work. Hardening of surface was observed when cutters with front negative-rake angles [6] were used for turning.

The maximum hardness of the hardened layer generated by machining hardening/grind-hardening is 50...65 HRC while the maximum penetration depth is 2 mm [3, 7].

Quench grinding of steels with a carbon content of more than 0.3% is based on the use of forced grinding modes and has a number of advantages compared to hardening based on quench turning. The thickness of the hardened layer in consideration of the removed defective layer is 0.3...0.5 mm. The heat-affected zone is up to 2 mm, hardness on the part surface is up to 50...60 HRC. Depth of cut when grinding is 0.2...1.2 mm subject to longitudinal feed of the grinding wheel 0.3...1.2 m/m. The presence of cooling liquids is not necessary since cooling is achieved by discharging heat to the underlying workpiece layers [8, 9]. Currently, the process of hardening by grinding gained momentum. DMG/Mori Seiki manufactures CNC milling and grinding machining centers which provide for quenching by using a grinding wheel. The throughput of a processing operation is 0.05...0.21 sec/cm^2. Once quench grinding is completed, the defective surface layer must be removed [10].

In the present article, an application of Deformational Cutting (DC) technology for surface hardening is presented. The main difference of quenching with the use of DC method from other methods of hardening based on the process of cutting is that chips are not separated from the workpiece and remain on the surface thus forming a special reinforced structure. Further differences include consistency, hardness quenched over its thickness and the possibility of generation of a hardened structure of composite material with alternating hardened and less

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solid (more plastic) layers. Method of turning by hardening without separation of chips is protected by RF patent No. 2556897 [11].

2.2. Method of Deformational Cutting

DC technology was invented by Zoubkov (now Nikolay Zubkov) and Ovtchinnikov [12]. A DC tool cuts and plastically deforms the surface layers of the workpiece forming a finned macrostructure since the cut layers are connected to the workpiece material (Figure 1).

The main difference between the traditional cutting process and DC is that the chips become fins and remain as a functional part of the workpiece.

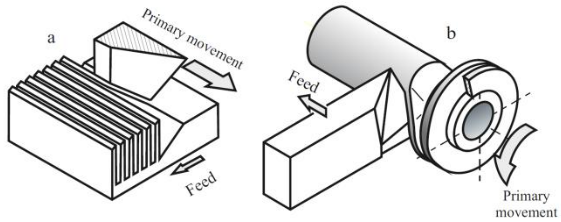

Figure 1. Concept of deformational cutting: shaping of flat surfaces (a), turning of cylindrical surfaces (b)

The DC machining can increase the surface area up to 12 times for copper and up to 6 times for steel. The main limiting factors for DC are workpiece ductility and hardness. A stable DC process can be achieved in materials with hardness smaller than HB220 and elongation larger than 18%.

There are a number of different application areas of DC technology. The main application area is heat exchange intensification [13], for example, finning of tubes for heat exchangers [14] including internal finning [15]. DC can be used for making boiling surfaces and capillary structures for heat pipes [16]. Other DC application areas are electrical joints manufacturing [17, 18].

2.3. Analysis of the Possibility to Use DC Method for Surface Hardening

It is well known that chips when turned may be heated up to the temperatures exceeding the temperatures of phase transformations in steels which may lead to hardening of chips at relevant cooling rates. During turning process by cutting, virtually all the power of the main drive measured in kilowatts is released in the cutting zone which has a volume of several cubic millimetres. Mechanical energy applied externally is localized in the plastic deformation area and in places where tool is touching the chips and workpiece and is converted into heat energy and latent energy of deformation. The material of chips is affected by such factors as shear strain, shear strain rate, high heating rate, high cooling rate and local environmental conditions. For example, when workpiece material is turned: C45E with speed of cut V=160 m/min the cutting temperature may be 1030 °C, shear strain may reach 400%, shear strain rate - 10^4 c^{-1}, heating rate - 10^6 °C/s, cooling rate - 10^3 °C/c, average normal stress - 350 MPa, and average shear stress - 250 MPa [19, 20].

When deformational cutting is performed, the cooling rates of the fin material necessary for hardening are achieved thanks to the conductive heat sink through the fin base to a colder workpiece core. A similar method of achieving hardening cooling rates without the use of cooling mediums is used in the following methods of heat treatment: induction and laser hardening.

Figure 2 demonstrates the principle of quench turning by using the method of deformational cutting without chips formation. Photograph of the treatment area and quenched shaft are shown in Figure 3.

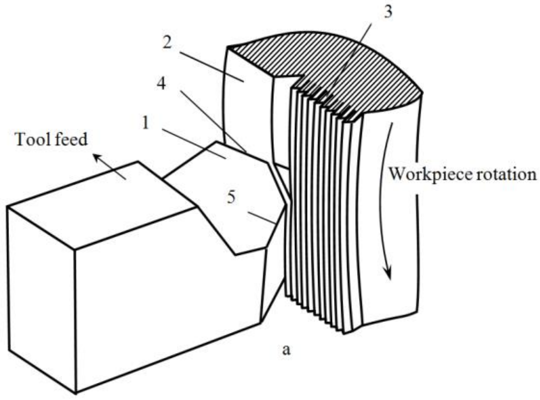

Figure 2. Concept of DC hardening. 1- DC tool, 2-surface to be hardened, 3 – hardened surface, 4 - cutting edge, 5 - deforming edge

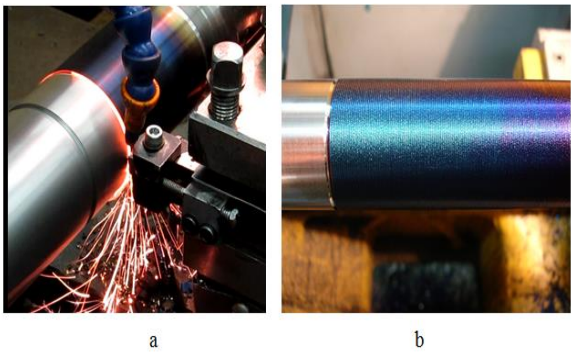

Figure 3. a - Process of DC hardening, b - hardened shaft

When deformational cutting is performed, the undercut layer may remain on the workpiece both with the retained interfin gaps and without gaps, i.e., tightly packed. Let us consider the case when interfin gaps remain at generation of finning. Figure 4 shows the plan view of the DC zone. The initial and final positions of the DC tool within one spindle revolution are marked as *I* and *II*, respectively. The cross-section of the future fin *ABCD* is cut by the cutting edge BE and moves on the tool rake surface. The tool deforming edge BF determines the final position of the fin marked as $A_1BCC_1D_1$. The slot width b depends on the undercutting angle, φ bending angle φ_1, and axial tool feed per revolution p.

$$b = p - a \cdot \sin(\varphi_1) = p \cdot (\sin(\varphi) - \sin(\varphi_1)) \quad (1)$$

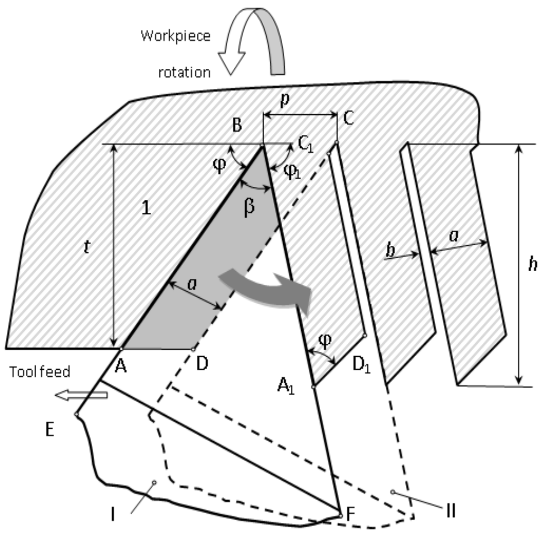

Figure 4. Fin shaping scheme by the deformational cutting method

To analyse the impact of angular parameters of the tool, we must transform (1)

$$b = 2S_o \cdot \sin\left(\frac{\Delta\varphi}{2}\right) \cdot \cos\left(\frac{180° - \beta}{2}\right) \qquad (2)$$

where Δφ - the difference between the angles of bending and undercutting $\Delta\varphi = \varphi_1 - \varphi$, β – tool wedge approach angle $\beta = 180^{\circ} - (\varphi + \varphi_1)$.

As can be seen from Equation (2), the value of interfin gap, subject to a constant feed *p*, is affected not only by the difference of angles *Δφ*, but also by the tool wedge approach angle β. The more β, the lesser is the interfin gap all other factors held equal.

As can be seen from Equation (1) and (2), if φ and φ_1 are equal, the slot width *b* will theoretically be zero. This means that the method of deformational cutting allows obtaining a non-porous, densely packed structure without interfin gaps subsequent to treatment.

Since no chips are removed, one may derive a formula for the height *h* of the obtained finned structure based on the principle of material volume retention:

$$h = t \cdot \frac{\sin\varphi_1}{\sin\varphi} - \frac{p}{2} \cdot \left[\frac{(\sin\varphi_1 - \sin\varphi)^2}{\sin\beta} - \sin\beta\right] \qquad (3)$$

For narrow and zero interfin gaps, when ≈1 the expression for the microrelief depth will be simplified:

$$h = t + \frac{p \cdot \sin\beta}{2} \qquad (4)$$

For quench hardening it is reasonable to use finning with interfin gap equal to zero, i.e., densely packed ribs. Modifications of such structures on different steels and with different pitches are shown in Figure 5.

Plastic deformations and friction of the undercut layer on the tool working surfaces function as sources of heat dissipation in the deformational cutting area. If the temperature of undercut layer exceeds the critical value and the cooling rate is high, the undercut layer undergoes hardening (Figure 6a). The undercut layer has the highest temperature in the area which is touching the tool face. Such uneven heating may be used to obtain a quenched fin partially hardened over its thickness (Figure 6b). Alternation of fully hardened layers and softer interlayers might be interesting from the point of view of enhancing score resistance of the friction knot.

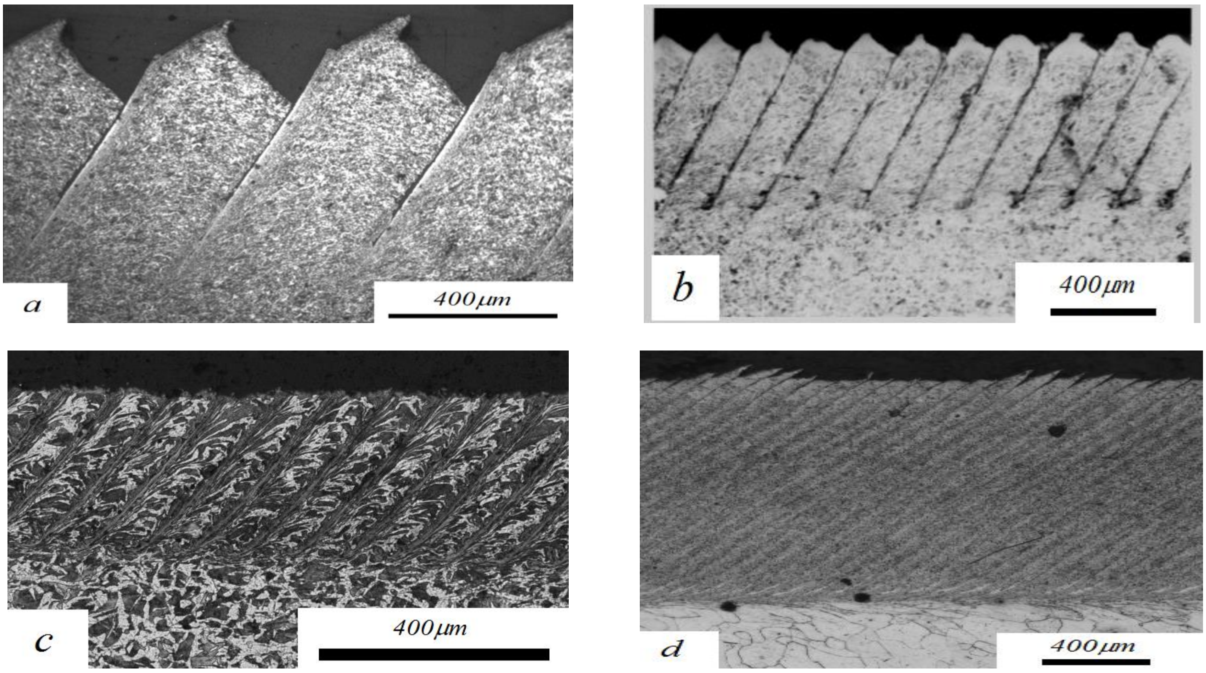

Figure 5. Examples of deformational cutting on steels with a zero interfin. a- steel 30HGSA, *p* = 0,4 mm; b – steel 20KH13, *p* = 0,2 mm; c – steel 35, *p* = 0,1 mm; d - Armco iron, *p* = 0,1 mm.

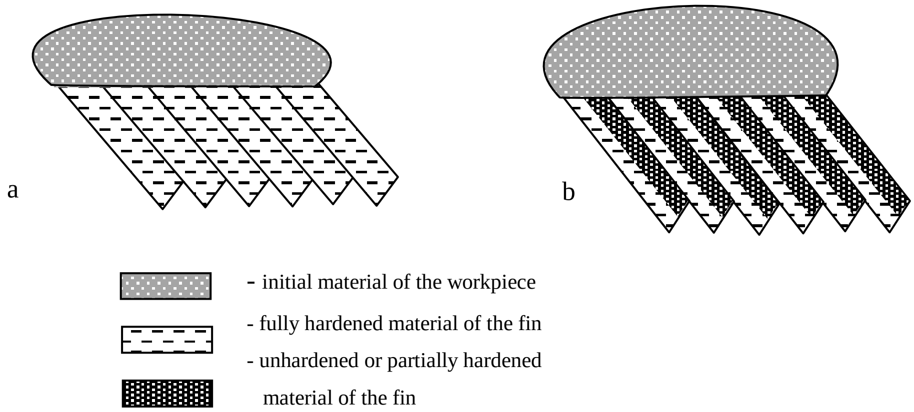

Figure 6. Modifications of structures obtained during quenching deformational cutting: a- fully hardened over the thickness of fin, c - partially hardened over the thickness of fin

3. Experimental Procedure

Cylindrical samples with a diameter of 60...80 mm made of steel after normalization were processed: steel 40H (0.4% C, 1.0,% Cr), steel 20, (0.2% C), steel 35, (0.35% C), ShH15 (1.0 % C, 1.5 % Cr).

Screw-cutting lathe 1K62 was used to obtain hardening structures. Tool for deformational cutting was turned using two tooling materials: oxide ceramic of CM332 grade (Al_20_3+0.8% MgO), cemented carbide T15K6 (79% WC, 15% TiC, 6% Co), SiAlON of CC6060 grade (Sandvik Coromant) and CBN with the major cutting edge angle equal to φ=42º and rake angle equal to γ=-18º. The cutting speed V ranged from 3 to 5 m/s, advance of tool per shaft revolution was S_0=0,05...0,4 mm/Rev, cutting depth was t=1,0...2,0 mm.

The main component of the cutting force was measured by help of Kistler dynamometer, model 9257 (Switzerland), measurement data were displayed on the PC.

The cutting force measurement was carried out with a Kistler three-component piezoelectric dynamometer, type 9257B. The dynamometer was placed under the tool holder and connected to Kistler charge amplifiers, type 5011, with a frequency limit of 200 kHz.

Temperatures in the area of deformational cutting were measured by natural thermocouple method. Temperatures on the surface of the treatment area were measured by IRTIS-2000S thermograph (Russia).

For metallographic studies and microhardness measurement, transverse finning microsections were prepared: they were cut from a hardened shaft by using EDM processing technique. Metallographic analysis was carried out on the Olympus GX51 microscope with 1000x magnification on the polished surface of transverse sections pre-treated with 4% solution of HNO3 in C2H5OH. Microhardness was automatically measured on the hardness tester EMCOTEST DuraScan 70 (Germany) using an indenter in the form of a diamond pyramid of a regular quadrihedral shape with a 100 kg load. The microstructure was examined with the help of an optical metallographic microscope Olimpus GX51 (Japan).

4. Results and Analysis

During machining using oxide cutting ceramics on steels 20, 35 and 40H, samples were obtained with a through hardened fin. The hardness of a fully quenched layer on through-hardened samples on steel 35 for the finning pitch p=0.05 mm was $650HV_{0.1}$ (58HRC), for p=0.15 mm the hardness is 670 $HV_{0.1}$ (59HRC), provided that initial hardness HV is $217_{0.1}$ (207HB) (Figure 7a). The hardness on steel 40H was 720..800HV0.1 (61..64HRC) with finning pitch 0.1 mm and on the average $680HV_{0.1}$(59HRC) with finning pitch of 0.05 mm. The hardness for low-carbon steel 20 was 438...$489HV_{0.1}$ (44...48HRC).

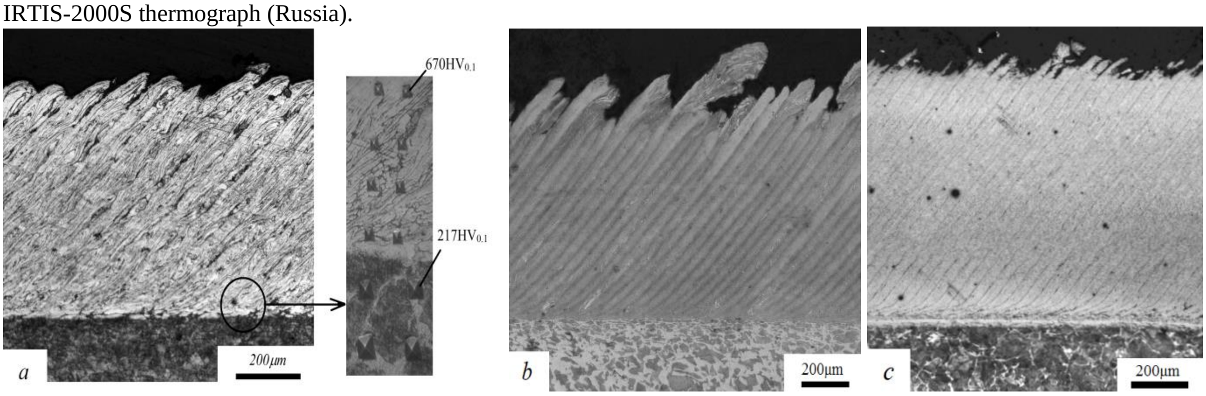

Figure 7. Total hardening over the thickness of fin. *a*- steel 35, pitch of the structure 0.15 mm, $740HV_{0.1}$, *b* - steel 35, pitch of the structure 0.05 mm, $650HV_{0.1}$, *c* - steel 40H, pitch of the structure 0.05 mm, 680HV0.1.

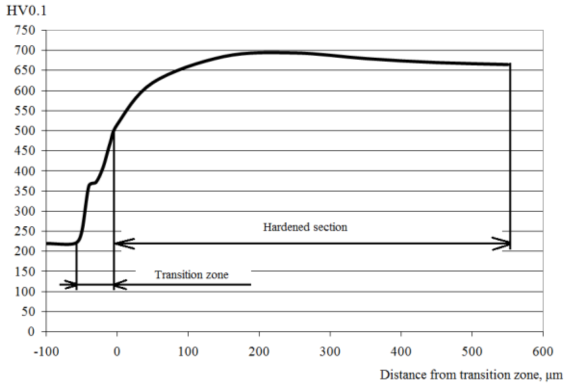

Figure 8. Distribution of microhardness over the thickness of the hardened layer. Steel 35, pitch of the structure p=0.05 mm.

If advance of tool per part revolution S is changed, or the cutting speed V *and* grade of tooling material is modified, one may achieve different ratios between the thickness of hardening zones and finning interlayers without any structural transformations. The ratios of thickness of fully hardened layer to the total thickness 1:6 (Figure 9a), 1:4 (Figure 9b), 1:2 (Figure 9c) and 1:1 (Figure 9d) were obtained on steel 40H.

The hardness of a fully hardened interlayer on steel 35 was 670 HV0,1 (55...59 HRC). Hardness of partially hardened fin material is about 40 HRC. Increase in hardness can be explained both by partial hardening, and strain-hardening under the influence of high deformations in the course of deformational cutting.

During processing of SHKH15 (ShH15) grade steel with a pitch p=0.2 mm layers of fully quenched material were obtained which were 48 mm thick and had microhardness of the quenched zone of up to 950HV0.1 (68HRC) considering the initial hardness of the workpiece 220HB.

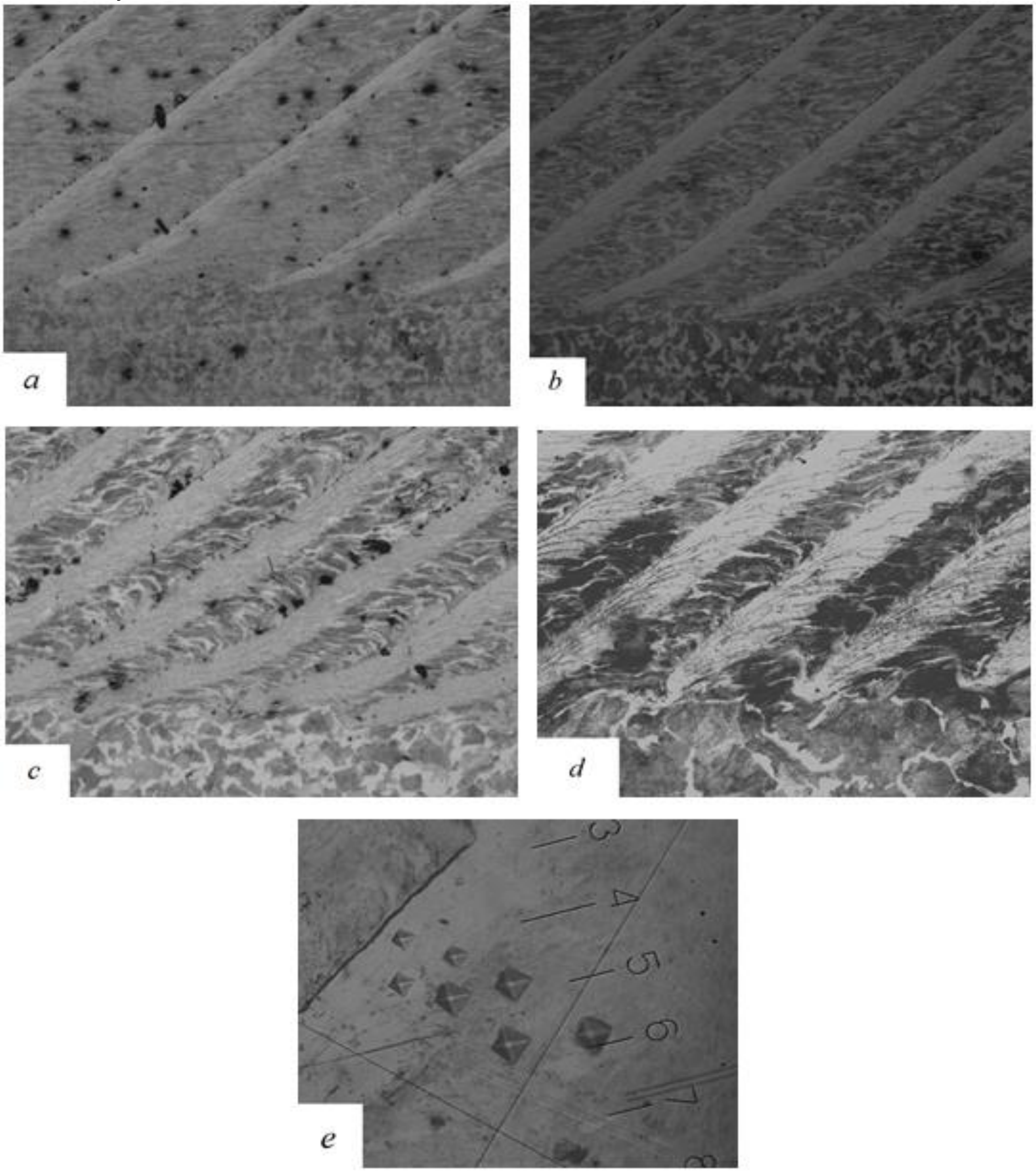

Figure 9. Hardened structures on steel 35 with various ratios of fully hardened and partially hardened material of fin. a - tool material ZM332, p=0.15 mm, b - tool material SiAlON, p=0.1 mm, c - tool material SiAlON, p=0.1 mm, d - tool material CBN, p=0.1 mm, e- comparison of dimensions of imprints in fully and partially hardened fin area

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Tribotechnical tests of samples which were performed with hardening by using the declared method confirmed their operational capability in sliding friction knots. We compared wear intensity and friction coefficient (Figure 6) of samples made of 40H steel with volumetric hardening in water and oil and subsequent low tempering (according to the modes recommended by reference books) to samples which were hardened by deformational cutting method without tempering and with low tempering at a temperature of 200^0C within 40 minutes. The tests were carried out on Amsler A135 friction machine according to the friction scheme "disc on disc", with slippage velocity 0.08 m/s and load of 185 N. The material of the counterbody is cemented carbide VK8 (92% WC, 8% Co). As can be seen from the histogram (Fig. 10), samples hardened by the proposed method have a 10 to 40 % higher wear-resistance compared to the samples quenched by volumetric hardening.

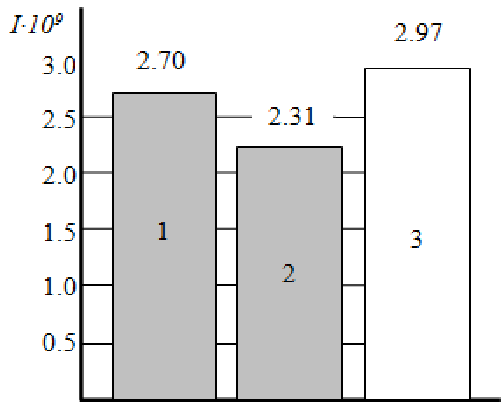

Figure 10. Wear intensity. Steel 40H. 1 – after DC without tempering, 2 – after DC with low-temperature tempering, 3 – after standard volumetric tempering with low-temperature tempering

5. Discussion

Let us analyse the examined option of deformational cutting of a cylindrical workpiece made of 40H steel and with diameter 48 mm, with advance p=0.1 mm/Rev, cutting depth t=1.0 mm, cutting speed V=3 m/s. (rotation speed of lathe spindle n=1200 RPM). Measurement of the main component of the cutting force using Kistler dynamometer revealed that P_z=800 N. Measurement of the temperature in the cutting zone by using natural thermocouple method showed that T=1100°C.

Volumetric flow of metal q passing through the treatment area will be:

$$q = t \cdot p \cdot V = 0{,}3 mm^3/s \tag{5}$$

Mass flowrate of metal passing through the treatment area will be:

$$G = \rho \cdot q = 2{,}36 g/s, \tag{6}$$

where ρ=7,85·10³ kg/m³ – is specific weight of 40H steel.

Power which is released in the treatment area will be:

$$N = P_z \cdot V = 2{,}4kV \tag{7}$$

Assuming that all the heat generated in the treatment area is used for heating of the undercut layer, the fin temperature will be:

$$T = N/(C_p \cdot G) = 1533^\circ C, \tag{8}$$

where C_p = *663 J/(kg·K)* - is a mean specific heat capacity for the temperature range 20...1500 °C for steel 40H.

The calculated temperature value doesn't coincide with the temperature measured by using natural thermocouple method. This is due to the fact that not all the power generated in the treatment area is used for heating of the undercut layer. Some part of the heat flow passes into the tool, into the surrounding environment thanks to convective heat transfer and radiation, some part of heat flow goes directly into the workpiece, bypassing the undercut layer. When cutting is performed, energy is also consumed for elastic deformations, shattering of grains (increase in interface boundaries between grains), formation of new surfaces, formation of dislocations and their motion [21], and phase transformations.

Time period t during which metal remains in the heating area (in the area of contact with tool face) was estimated over the length of contact between undercut layer and tool face and cutting speed. For processing conditions mentioned, the length of the contact zone is 1.2 mm. Therefore,

$$t = l/V = 4 \cdot 10^{-4} s \tag{10}$$

Rate of τ metal heating in the treatment area up to 1100°C will be:

$$V_{heat} = \Delta T/t = 2.7 \cdot 10^6 K/s \tag{11}$$

This value exceeds the heating rates which are typical for laser quenching and are up to 10^6 K/s [22].

Energy to volume ratio Q generated in the treatment area due to plastic deformations, internal and external friction is determined as:

$$Q = N/q = 8.0 kJ/cm^3 \tag{12}$$

Heated layers, as with laser quenching, are cooled down through transfer of heat to the workpiece body. The cooling rate during quenching deformational cutting was assessed based on the temperature difference on the cutting area surface which was 900 °C, and on the temperature of adjacent fin every other revolution of the workpiece. The differential temperature was 450°C. The measurements were carried out by using IRTIS-2000S thermograph. If frequency of rotation of the workpiece is 1200 rpm, 0.05 s is required for one revolution of the workpiece which brings a cooling rate V_{cool}= 9.0·10³ °C/c. This is an assessment of the minimum cooling rate since the thermograph recorded the temperature of outer layers. For layers located closer to the fin bottom, the cooling rate should be even higher. The cooling rate is also higher than the cooling rate during laser quenching which is about 10^3 °C/c. [23].

The authors didn't manage to obtain a defect-free surface of the hardened shaft. As it is seen from the photographs showing transverse sections of hardened surface Figure 7a, the top layer has defects featuring delamination and sagging. This fact is still a substantial disadvantage since the defective layer needs to be removed by hard turning on the same machine which was used for hardening or by a separate grinding operation to remove about 1/4 of the thickness of the hardened layer.

The throughput of the operation for the case considered - where the shaft with diameter of 48 mm is hardened by deformational cutting method - is 0.12 m of the length of the hardened shaft surface per minute and the depth of a hardened layer is up to 1 mm.

6. Conclusion

1. A new method of surface hardening was developed and put to an evaluation test: the subject of method is machining without formation of chips.
2. When deformational cutting is made, heating temperature, heating and cooling rates are sufficient enough to ensure phase transformations of the undercut layer material.
3. Unlike laser quenching, phase transformations occur at higher degrees and rates of deformation.
4. Hardened surface layers showed more uniform hardness over thickness compared to other methods of surface hardening.
5. It has been demonstrated that it is possible to obtain laminated structures with inclined layers and that is also possible to control the ratio of thickness values of hardened and unhardened areas.
6. The adoption of DC hardening method may have economical and higher productivity benefit due to its increased integration level. The new method improves efficiency of the quenching operation, allows abandoning transport operations for heat treatment, reduces energy intensity of quenching, and makes specialized thermal equipment unnecessary.

Acknowledgment

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