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INVESTIGATION AND ANALYSIS OF THE POSSIBILITY OF DIFFUSIONLESS PHASE TRANSFORMATIONS IN THE SURFACE LAYER OF A PART UNDER THE ACTION OF GRINDING TEMPERATURES

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Досліджено та проаналізовано можливість бездифузійних фазових перетворень в поверхневому шарі шліфованої деталі під дією миттєвої температури шліфування. Це важливо, тому що фазові Feα-Feγ перетворення, які можуть мати місце при шліфуванні деталей приводять до появи так званих шліфувальних прижогів, які в 2–3 рази знижують надійність і довговічність при експлуатації деталі в працюючому механізмі. Визначено механізм фазових перетворень, критична температура цих перетворень і пов'язані з цим режими обробки, які забезпечують цю температуру. Це дозволяє обґрунтовано підходити до визначення режимів шліфування і, в разі необхідності, до застосування методу охолодження. Крім того, може бути вирішена задача оптимізації режимів шліфування, якщо продуктивність обробки взяти як цільову функцію, а як обмеження взяти температуру шліфування.

При швидкому нагріванні температурою шліфування поверхні деталі з загартованої сталі вище лінії АС1 має місце зворотне мартенситне перетворення Feα→Feγ. Мартенситний інтервал при охолодженні Мн-Мк в значній мірі охоплює негативні температури. Тому аустеніт частково фіксується в поверхневому шарі, утворюючи так званий припік гарту. Залежності для визначення температури утворення аустеніту для сталі будь-якого хімічного складу, дають можливість при шліфуванні підтримувати значення температури шліфування нижче цього рівня. Розглянуто механізм бездіффузіного зворотного мартенситного перетворення при високошвидкісному нагріванні поверхні ріжучими зернами (миттєвої температурою). Експериментально визначено швидкість нагріву і вплив тиску, яке справляє абразивне зерно на метал при знятті стружки. Таким чином обґрунтована можливість бездифузійного фазового перетворення і дається залежності для розрахунку температур утворення аустеніту, що дає в свою чергу можливість розрахувати безпечні режими обробки

Ключові слова: аустеніт, мартенсит, γ-залізо, α-залізо, швидкість нагріву, температура перетворення мартенситний інтервал, поверхневий шар, критична температура

1. Introduction

The issue of increasing the accuracy of the working surfaces of machine parts improving the quality characteristics covers a whole range of problems: technological, instrument, machine tools.

At present, high quality of the working surfaces of parts (wear resistance, heat resistance) is often provided by welding them with appropriate materials. We are talking about high-quality steels with subsequent heat treatment of such surfaces, which allows us to drastically reduce the consumption of special high-cost steels and alloys. However, these surfaces must be ground to give them the necessary accuracy and roughness.

It should be borne in mind that, under the influence of grinding temperatures, thermal grinding defects that are associated with phase-structural transformations in the ground surface layer, called grinding burns, often occur. A characteristic heat pulse, recorded by a low-inertia micro-thermocouple, is shown in Fig. 1 [1].

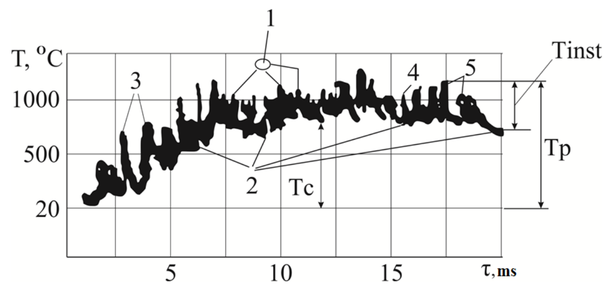

Fig. 1. Characteristic shape of the heat pulse during grinding: 1, 3, 4, 5 — temperature flares from the cutting grains, *Tc* — contact temperature, T_i —instantaneous temperature of grain cutting, T_p — pulse temperature — the sum of contact and instantaneous

Pulses, the amplitude of which is measured from the lower envelope to the upper peak values, correspond to the temperature that the given point of the ground surface acquires when cutting it with a grinding wheel grain.

The upper envelope of the oscillogram, which is mentally conducted along the vertices of the pulses, corresponds to the pulse temperature, which is the result of summing the contact and instantaneous temperatures. As can be seen from Fig. 1, the pulse temperature is higher than the temperature averaged over the contact spot, and the frequency of its action on the given point of the surface corresponds to the frequency of the instantaneous temperature.

When the grinding temperature of the surface of the ground part of the hardened steel is higher than the Ac_1 line, the martensitic structure of the surface layer transforms into an austenitic structure, i. e., there is the reverse martensitic transformation or phase transition Feα→Feγ [2–5].

The transformation of austenite into martensite upon cooling does not take place completely because the martensite range M_s-M_f largely covers negative temperatures. Therefore, austenite is partially fixed in the surface layer, forming a so-called quenching burn.

Burns cause high residual stresses and cracks in the surface layer and reduce the strength, reliability and durability of the ground surface (often 2–3 times) and, consequently, of the entire part [4, 6].

At present, there are many new low- and high-alloy steels that are widely used for surfacing the working surfaces of parts. These surfaces must be ground in the future. Therefore, it is necessary to determine the safe contact grinding temperatures, which do not lead to grinding defects of the surface layer. These temperatures can be determined by an analytical study of the kinetics of phase-structural transformations during grinding. Therefore, it is important to develop a methodology for determining the austenite formation temperature for steel of any chemical composition. The need to maintain the contact temperature below this level during grinding should be taken into account. It should be noted that during grinding, super-fast surface heating takes place, as a result of which various mechanisms for the austenite formation are possible. Diffusion, diffusionless and diffusionless at high specific pressures, with the possible formation of burns under the influence of instantaneous temperature. It can be stated with a high degree of certainty that the austenite formation temperature will depend on the formation mechanism. Therefore, it is necessary to analyze all possible mechanisms.

2. Literature review and problem statement

The diffusion reverse martensitic transformation is discussed in detail in [7], but there is no information on a possible diffusionless transformation, which can occur at slightly different temperatures and at higher rates of thermal processes. If these circumstances are not taken into account, then thermal grinding defects can be obtained.

The works [2, 8] consider the issue and conclusions of adequate reflection of real processes rather deeply, however, these results need clarification and some simplification for using them in the practice of the shops of machine-building enterprises.

The reverse martensitic transformation in steels doped with Cr–Ni–Mo is investigated in [9]. The initial structure is tempered martensite and chromium carbides. The transformation of the initial coarse-grained structure into a fine-grained polygonal structure was studied. This is a purely metal research, the results of which are difficult to apply to the question under study, since it is practically impossible even to artificially create conditions similar to experimental conditions during grinding.

Now, referring to the works [10–12], one can see that in these works the phase and structural transformations (grinding burns) are deeply considered. However, neither the mechanisms of these transformations nor the temperature dependences of the formation of burns for steels of different chemical compositions are considered anywhere.

The influence of initial austenite grains on the martensitic-austenite transformation is considered in [13], but there is no information on the possibility of diffusionless transformation.

The martensitic-austenite transformation in fine-grained steels with metastable austenite was considered in [14]. However, there is no information about the mechanism of transformation.

The paper [15] considers martensitic transformations in low-alloy steels with periodic fast-flowing heating acts. In this work, there is also no mention of the mechanism of transformation.

In the work [16], the quenching processes when grinding a crankshaft are considered. Surface hardening can occur due to phase-hardened austenite. The mechanism of transformation is not mentioned.

The effect of residual austenite and residual stresses on the rolling contact is considered in [17]. The consequences of the formed austenite are considered, but not the mechanism of its formation.

In [18], the use of reverse martensitic transformation to stabilize austenite is considered. The mechanism of reverse martensitic transformation is not considered.

In [19], the phase effect of thermal cycling on the martensitic transformation is considered. However, the mechanism of reverse martensitic transformation is not considered.

The change in the structural composition and mechanical properties of chromium-nickel-molybdenum steel in the course of heat treatment is considered in [20]. The mechanism of phase and structural transformations is not described.

Thus, it should be noted that no data have been found in the literature that would explain possible diffusionless reverse martensitic transformation in the grinding of quenched steels and austenite formation temperatures.

The mechanism of diffusion formation of austenite from martensite (reverse martensitic transformation) in iron-carbon alloys at heating rates up to 10.10^8 °C/s is considered in [3, 4, 6, 9, 21–25]. However, when the metal is heated by an instantaneous or pulsed temperature, when the heating rates are even higher and when the diffusion processes are suppressed, a variant of diffusionless reverse martensitic transformation is entirely possible. In this case, the austenite (grinding quenching burn) formation temperature will be different. Therefore, in order to select the parameters of the grinding process that would exclude the appearance of burns, it is necessary to determine at what temperatures the diffusionless martensite→austenite transformation can occur.

3. The aim and objectives of the study

The aim of the work is to establish the possibility and regularity of diffusionless phase transformations α→γ in the quenched surface layer of the polished part under the action of the instantaneous grinding temperature. This will allow us to evaluate the joint influence of high-speed thermal processes during grinding and the chemical composition of the ground surface, for assigning safe temperatures, and, consequently, processing regimes.

To achieve this aim, the following objectives were set:

– to determine the surface heating rate when the contact temperature is lower and above the point Ac_1;

– to establish the possibility of diffusionless reverse martensite transformation under the martensite-austenite scheme for high-speed surface heating, on the basis of which it is necessary to determine the formation temperatures of austenite for various steels.

4. Materials and methods for studying phase-structural transformations in the surface layer of the ground part

The investigations were carried out using experimental measurements of heating temperatures and rates using embedded microthermocouples and electronic oscilloscopes. As materials, pre-eutectoid steels-40H; 40A (0.4 % carbon), eutectoid steel U8 (0.8% carbon), hypereutectoid – cemented and hardened steels 12H2N4A, 20HN3A (1.2 % carbon) were used.

5. Analytical and experimental studies

The peculiarities of the process of metal heating during grinding should be attributed to the small dimensions of the thermal source and the considerable power of this source, which ensures a high intensity of heat flow and a short time of thermal exposure of this source to the metal.

In principle, the formation of the austenite structure (quenching burn) in the surface layer is possible as a result of three processes.

1. Diffusion path – by high-speed tempering of martensite according to the M→P→A scheme (martensite→perlite→austenite).

2. Diffusionless path (when a short pulse of the instantaneous or pulsed temperature is applied to the metal), when an instantaneous rearrangement of the crystal lattice occurs according to the M→A scheme.

3. Diffusionless path at a high contact pressure of the cutting grain, leading to a decrease in the temperature of the point A_{C1}.

The heating rates during grinding are estimated as 10^6–10^{10} °C/s [8, 21].

In a number of cases, under the condition of heating rates of 10^6–10^8 °C/s, martensite can decay with the formation of ferritic-pearlite structures. In [22], the heating rates and temperature ranges for which this is possible are given (Fig. 2).

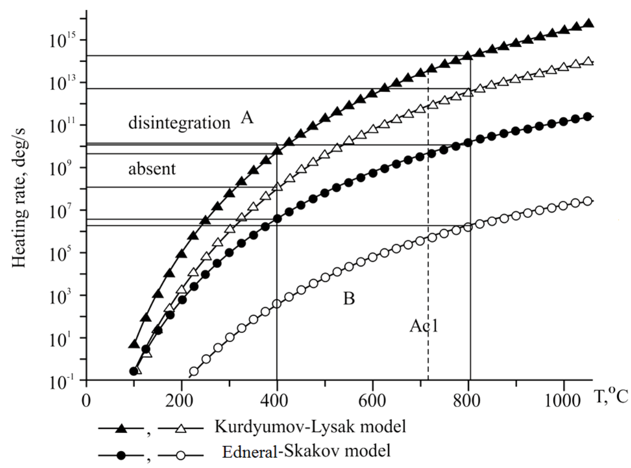

Fig. 2. Areas of possible diffusion decay of martensite as a function of the heating rate

As can be seen from Fig. 2, during heating at about 400 °C, which is typical for the temperature of the third tempering transformation, the diffusion decay of martensite can occur at heating rates of 1.8·106–1.6·107 °C/s.

At the heating temperature of about 800 °C, which is much higher than the point Ac_1, the diffusion decay of martensite can occur at heating rates of about $1.3 \cdot 10^6$–$1.1 \cdot 10^7$ °C/s. At higher heating rates, the diffusion decay of martensite is impossible. The experimental measurement of the heating rates was carried out from oscillograms of the temperatures measured by embedded microthermocouples with recording on an electronic oscillography.

To obtain a wide range of contact temperatures, a CBN grinding wheel was chosen: LO 180/150V1 100% and grinding modes V_w=35 m/s, V_p=V_u=0.66 m/s, grinding depths t=0.015; 0.02; 0.04 mm.

The corresponding contact temperatures will be: 430 °C, 770 °C, ~1000 °C.

By measuring the heating rates in the temperature range from 400 °C to Ac_1, the following values can be obtained: $V_{0.04}$=3·106 °C/s; $V_{0.02}$=2·106 °C/ s; $V_{0.015}$=0.3·106 °C/ s.

Consequently, the surface heating rates can fall within the range of diffusion transformation rates shown in Fig. 2.

The higher the temperature, the faster the diffusion process of carbon redistribution in austenite [14].

A number of academic sources, for example, [23] indicate that the diffusionless shear reverse martensitic transformation in steels is hardly possible due to the high diffusion rate. This is, of course, true at the heating and cooling rates occurring during conventional heat treatment. However, when grinding, when such combinations of processing regimes can be created, when the heating rates are incomparably greater than the diffusion rates, such transformation is possible, which is proved by experiments on measuring heating temperatures and rates from single grains.

Fig. 3 shows a part of the heat pulse "cut-out" from the contact temperature, consisting of pulses from several grains (instantaneous temperature) at a scanning speed of about $2.5 \cdot 10^{-7}$ s/cell and at a vertical scale of 150 °C/cell (a memory oscilloscope C8-9A).

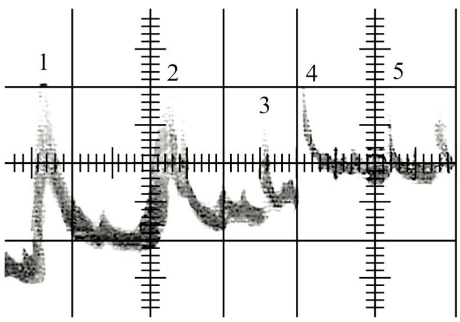

Fig. 3. Cut-out from the heat pulse of contact temperature

Comparing the half-width of the pulse (heating time) and the height of the pulse (heating temperature), it is possible to obtain the average rate of metal heating by the temperature of grain cutting (instantaneous temperature). If we consider the pulses 1; 2; 3; 4; 5, then using the scale we can compile Table 1.

Table 1

The values of instantaneous surface temperatures, heating time and heating rate

Pulse No.	1	2	3	4	5
T_{sf} – surface temperature, °C	390	300	195	255	180
τ_h – heating time, s	$2.5 \cdot 10^{-8}$	$2.5 \cdot 10^{-8}$	$1.25 \cdot 10^{-8}$	$1.75 \cdot 10^{-8}$	$1.25 \cdot 10^{-8}$
V_h – heating rate, °C/s	$1.56 \cdot 10^{10}$	$1.71 \cdot 10^{10}$	$1.56 \cdot 10^{10}$	$1.46 \cdot 10^{10}$	$1.44 \cdot 10^{10}$

The average heating rate will be $1.546 \cdot 10^{10}$ °C/s. Processing of 20 such "cut-outs" gives the heating rate range of $1.675 \cdot 10^{10}$–$1.446 \cdot 10^{10}$ deg/s. Comparing these data with Fig. 2, it can be seen that the rate of metal heating by instantaneous temperature comes into the region where diffusion transformations are impossible. Thus, if diffusion transformations are impossible, and austenite does exist, then it can be asserted that it was formed without diffusion, due to the shift of the crystal lattice. On microsections, such austenite can be seen as small spots of irregular shape (Fig. 4, 5)

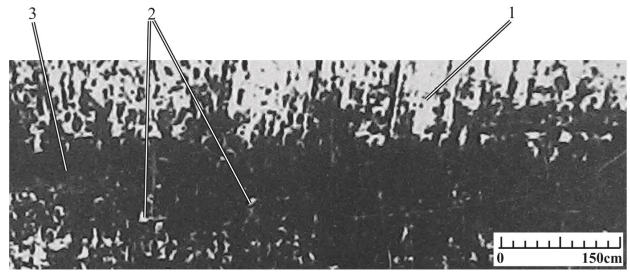

Fig. 4. Microsection of type "oblique cut" 5°. 1 — the end of the ground surface, 2 — small austenite spots, 3 — tempered layer. ×150

Fig. 5. Microsection of the polished surface. Dark tempering field and white austenite spots. ×150

Thus, the diffusionless reverse martensitic transformation during grinding is possible and can occur under the action of high-speed heating by instantaneous temperature.

The formation of austenite from martensite is diffusionless, and in the transformation range the composition of the phases is constant. The temperature range of the reverse martensitic transformation (A_s–A_f), which depends primarily on the composition of the alloy, is higher than the equilibrium temperature T_0 (when the free energies of austenite and martensite are equal). This is well shown in [25]. The work is theoretical and the lines A_s and M_s are derived from thermodynamic laws. Calculations were made on low-carbon steels with different nickel contents, since nickel has a significant effect on the character of martensitic transformation [23].

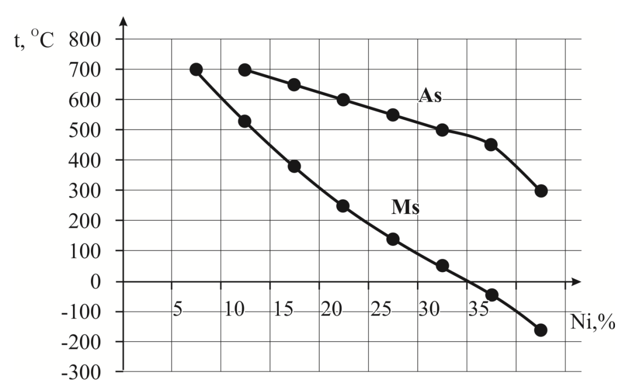

Fig. 6. Temperatures of the start of direct M_s and reverse A_s martensitic transformation [23]

In the paper [25], low-carbon steel with different Ni contents is obviously chosen by the authors as an example, since on such a steel the reverse diffusionless martensitic transformation is realized at relatively low heating rates characteristic for industrial heat treatment regimes.

Assuming (from the grinding results given above) that the diffusionless reverse martensitic transformation is possible, it must be borne in mind that, as indicated in [23], there is a temperature hysteresis of about 150–200 °C. That is, martensite is formed at a below-equilibrium temperature, and austenite is formed at an above-equilibrium temperature. In this case, the well-known martensite formation diagram [23] with the application of the line T_0 and the line A_s can presumably look as shown in Fig. 7. Thus, in the superfast heating, presumably the austenite formation temperatures for pre-eutectoid steels about 700 °C, for eutectoid steels about 550 °C, and for hypereutectoid steels about 450–500 °C should be expected.

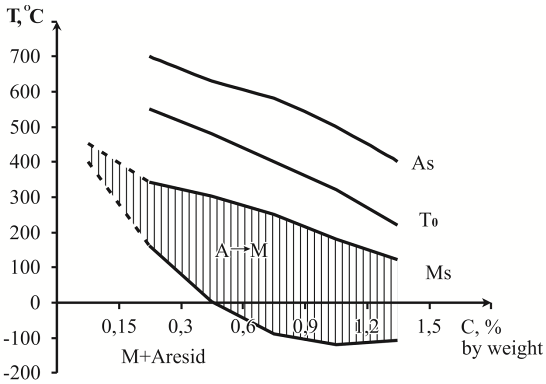

Fig. 7. Assumed position of the lines T_0 (equilibrium temperature) and A_s (austenite formation start temperature)

This assumption is confirmed to some extent by the data of [26], although without graphs, but mathematically.

Grinding of samples from steels 40A, U8, cemented and hardened steels 12H2N4A, 20HN3A was carried out, in each sample there was a microthermocouple [1], the grain size of the wheel was not less than 25–40 for obtaining large pulses on the screen, 5 samples were taken for each steel. The grinding modes were selected in such a way that the lower envelope of the contact temperature pulses did not exceed 450 °C (the boundary temperature at which the 3rd tempering transformation begins), and the large pulses were 100–300 °C higher. After grinding the samples (5 samples from each steel, for each wheel speed – 20, 35, 50 m/s), the microsections was prepared from each sample according to the scheme used in any metallographic laboratory [27]. The resulting microsections were viewed on a well-known MIM-7 metal microscope [28] to determine the presence of austenite. Thus, the average instantaneous grinding temperature was determined from the magnitude of the pulses (for example, Fig. 2), and the microsections from the same sample gave an answer about the presence of austenite, without any quantitative values, but by the "yes" or "no" principle. The task of determining the amount of austenite was not set, since this is an independent, very voluminous study. Mean temperatures were calculated by the method of [29]. The results of the measurements and observations were summarized in a table, an example of which is shown below for the first series of five samples for a wheel speed of 35 m/s (Table 2).

The results were somewhat unexpected, since the formation of austenite occurred at a temperature of about 550±28.6 °C (sample size 10, of the total number of measurements and observations 25).

It is necessary to answer the question why such low temperatures of A_s were obtained. For this, it is necessary to remember that when cutting a metal by grain, a system of two forces P_z and P_y appears, which are components of the cutting force. The first force is called the chip formation force, and the second is the force of the pressure of the cutting grain on the metal: (Fig. 8 [30]). The rounded cutting edge radii of the grain are extremely small. For grains of electrocorundum, these values are 10–15 μm. The area of contact between the grain and the metal is extremely small and amounts to $S_s=2\pi R_s h$ as the surface of the spherical sector, the values of which are cut off by the value of h, in other words, the depth of grain penetration into the metal (Fig. 8).

Table 2

The results of comparison of instantaneous temperatures and the presence of austenite

Steel	40H	40A	U8	12H2N4A	20HN3A
T_{inst} – average instantaneous temperature, °C	530	530	520	515	520
The presence of austenite on microsections	+	+	+	+	+
τ_h – average heating time, s	$2.0\cdot10^{-8}$	$2.0\cdot10^{-8}$	$2.2\cdot10^{-8}$	$1.9\cdot10^{-8}$	$2.1\cdot10^{-8}$
V_h – average heating rate, °C/s	$2.65\cdot10^{10}$	$2.65\cdot10^{10}$	$2.36\cdot10^{10}$	$2.7\cdot10^{10}$	$2.4\cdot10^{10}$

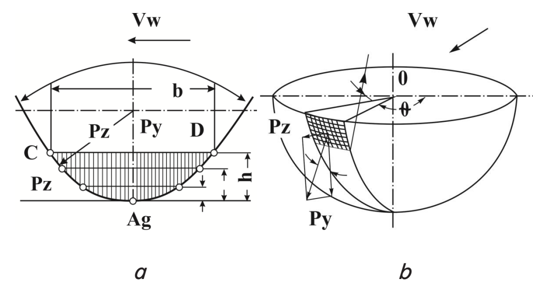

Fig. 8. Schemes of rounded edges of cutting grains [30]: *a* – the projection of the section of the rounded cutting edge of the grain on the plane, *b* – the view in the axonometry of the rounded cutting edge of the grain

For round and flat grinding conditions with the grinding depth of 0.02–0.05 mm and grain size of 16–25, the rounded cutting edge radius of the grain are 10–15 μm, the depth of grain penetration into the metal is 2–4 μm, the strength P_y is 15–20 N [30]. For such a case, the pressure at the grain-metal contact site amounts to

$$P_з = {P_y}\Big/{2\pi R_z \cdot h}, \tag{1}$$

where P_z is the value of the pressure on the metal "under grain"; P_y is the force, N; R_z is the rounded cutting edge radius the grain, m; h is the average value of grain penetration into metal, m.

For the above conditions, P_z will be $2.17.10^{10}$ N/m^2 or 21.7 GPa. Consequently, the diffusionless austenite formation during grinding must be considered not only under the action of instantaneous temperature, but also under the action of high pressure.

To take into account the pressure of the cutting grain on the metal during the austenite formation due to heating by the instantaneous temperature, one can use the relationships presented in [24, 31], where it is shown that under pressure conditions the equilibrium line of the modifications α→γ has the form of Fig. 9 [24, 31].

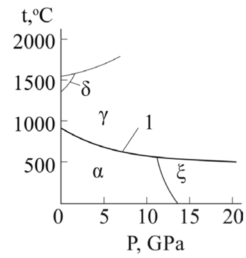

Fig. 9. Equilibrium line α→γ for iron, depending on temperature and pressure [24, 30]

As can be seen from Fig. 9, the equilibrium line between the phases γ and α decreases significantly with increasing pressure. However, in the pressure range of about 15–20 GPa, the equilibrium line is stabilized at a temperature of about 500 °C. It is this pressure that the cutting grains have on the metal when grinding.

It should be noted that the rounded cutting edge radii of the grains and the average grain penetration depth with changes in the grinding conditions will still be within the above limits, therefore, the process of diffusionless austenite formation will occur at a pressure of about 20 GPa and, as a consequence, at temperatures of about 500 °C.

For practical use, Table 3 of temperatures, above which austenite is detected for steels that are used in this study was compiled.

Table 3

The approximate temperature of austenite formation in the case of diffusionless α→γ transformation under the influence of instantaneous temperature taking into account the pressure at the grain-metal contact point

Initial data		A_{si}		
V_w, m/s	V_h, °C/ s	Pre-eutectoid steel 40H and steel 40A – 0.4 % C	Eutectoid steel U8 – 0.8 % C	Hyperectoid cemented and hardened steel 12H2N4A and 20HN3A – 1.2 % C
20	$4{\cdot}10^9$	528	521	524
35	$12{\cdot}10^9$	530	522	525
50	$25{\cdot}10^9$	531	524	527

Note: the average heating rate is calculated in the range of 500...1000 °C

The results obtained can be regarded as indicative in the practice of mechanical shops where grinding of critical parts from hardened steel is carried out.

6. Discussion of the results of the study of the possibility of diffusionless phase transformations in the surface layer of the hardened steel part

The investigations carried out in the present work show that, with certain parameters of the grinding operation, surface heating rates of about 1.5·1010 °C/s and higher are possible. At such heating rates, it is the diffusion martensite→austenite transformation is impossible, but there is the possibility of diffusionless shear reverse martensitic transformation. This transformation on the grain paths can occur at an elevated pressure of the grains on the ground metal, which reduces the A_s point, as a result of which the formation of austenite can occur at lower temperatures, which naturally should be taken into account when assigning grinding regimes. It should be noted that the conditions for the prevailing influence of instantaneous temperature (grain cutting temperature) can be created relatively rarely, when it is necessary to remove minor allowances of about 0.01–0.025 mm with a relatively coarse-grained wheel (for example, grain size 400/250).

As the results of the study showed, the diffusionless mechanism of reverse martensitic transformation is possible when grinding hardened steels under the action of instantaneous grinding temperature. The pressure of the cutting grain when cutting on the steel surface, the value of which under the action of the force P_y can reach the values of about 20 GPa has a significant influence in this process.

A significant difference of the hardening burn in the diffusionless transformation of martensite into austenite is that it does not lie on the perlite layer (since pearlite transformation does not have time to occur).

Since the austenite formation temperature under the action of the grain pressure is lower, it is advisable to use the data of Table 3 for the design of grinding operations.

The results of the research make it possible to design the grinding operation of critical parts from hardened steel more competently, excluding those parameters of the grinding process with which the diffusionless phase transformation M→A is possible.

Despite the large number of works devoted to burns, the issue of burns caused by instantaneous temperature when grinding parts from hardened steels is not considered and there are no recommendations for preventing such thermal defects.

The disadvantage of this study is that the experiments were performed only on low-carbon steels and on chromium-nickel cemented and hardened. The experiments were carried out in a minimum volume because of the very high laboriousness of the latter.

In the work, it would be worthwhile to apply physical modeling with the help of a plasma beam. At present, there are quite a lot of studies in the field of plasma quenching, the heating rates in which are comparable with the heating rates of the instantaneous temperature, but in these studies the M→A transformation is not considered.

7. Conclusions

1. The rates of surface heating by the instantaneous grinding temperature at which the diffusionless reverse martensitic transformation is possible, are about $1.5–2.0{\cdot}10^{10}$ °C/s. The diffusionless mechanism of the transformation of martensite into austenite in steels of different chemical compositions is possible due to the high heating rate at which the diffusion processes are suppressed.

2. The limiting instantaneous temperatures, at which the formation of austenite can already begin, are 500–550 °C, the temperature being further reduced by the high pressure exerted by the cutting grain on the metal. The heating rates at which diffusion processes are suppressed as a result of the action of instantaneous temperature are most often produced when grinding with sufficiently coarse-grained wheels at small cutting depths. The grain size of the wheel is about 400/250 and the grinding depth is about 0.01–0.02 mm, the wheel speed is about 30 m/s.

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