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Investigation on friction surface of high-carbon low-alloyed steel after abrasive wear

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Abstract

Samples of 120Mn3Si2 steel were water-quenched from 900 °C and tested on three-body abrasive wear laboratory machine. Microstructure, XRD investigation and microhardness measurement have been performed on worn surface. It was established three distinctive areas in-depth under surface: plastic deformation of austenite, partial phase transformation of deformed austenite, fully transformed material with martensitic structure. Practically no austenite was detected on the very surface according to XRD profile. Microhardness of worn surface was distributed in wide range of values with most probable value at 1400 HV0.05.

Key words: high-carbon low-alloyed steel, quenching, austenite, martensite, abrasive wear, microhardness, microstructure.

Introduction

Wear in its different manifestations is predominant reason for failures of machine parts or machines as a whole. The most severe wear appears under multiple scratching of friction surface by hard particles or asperities. The general trend is that the harder friction surface the less abrasive wear is. Hardness can be provided in two main ways: certain treatment of material in bulk (for example, quenching to martensite) or hardening in thin surface layer to the extent that allows significant rise in abrasive wear resistance. The most elegant way is obtaining the structure of a material that is capable for significant hardening under plastic deformation by abrasive particles in the course of wear. This way a hard surface layer is automatically generated as long as abrasive wear proceeds. In the present study discussed are the properties of such hardened layer in high-carbon low-alloyed steel quenched to predominantly austenitic structure.

Literature review

Among many works devoted to abrasive wear of steels and cast irons one may distinguish a group of investigations that try to establish general regularities of abrasive wear rather than merely reducing wear in separate practical cases. Those are in no doubts works of Khruschov and co-workers. His fundamental book published in 1960 [1] has lifted the whole science on abrasive wear to the new level of understanding. A number of regularities have been established, the most important are as follows: dependence of wear on friction distance and abrasive particle size; dependence of wear resistance on hardness of material. Lots of work was spent also to determine correct conditions of laboratory abrasive wear tests and to build laboratory testing machine which reproduced stable abrasive wear. The results of M.M.Khruschov's work were finally summarized in [2].

The main Khruschov's efforts were aimed to establish regularities of "pure" abrasive wear that was not veiled by other factors. Meanwhile many variables affect wear rate of materials in real working conditions. Extensive literature exist that deal with different cases of wear and how it is possible to save lifetime of machine parts in any given case. In this aspect one of well-known sources that may be recommended is ASM Handbook devoted to failures of machine parts and its chapter that addresses wear failures [3].

Phase transformation of instable austenite to martensite under mechanical load was firstly reported by Bogachev and Mints [4]. They have utilized this effect to increase resistance of steels against cavitation damage. Shortly it was shown that instable residual austenite may be also a favorable structure for reducing wear loss during abrasion of press-molds used in refractory bricks production [5]. This similarity of instable austenite behavior in different conditions of surface damage may be explained by similarity of damaging process: in both cases (cavitation and abrasive wear) metallic material undergoes severe plastic deformation before failure. Since 1960s the newly discovered phenomena of mechanically induced transformation of instable austenite was extensively exploited in many cases to reduce abrasive wear of machine parts [6 - 10].

Khruschov's idea to study abrasive wear in "pure" laboratory conditions has been developed and regularities of abrasive wear resistance for Fe-C alloys have been established in [11]. It was shown that possibility exists to obtain austenitic structure even in plain carbon steel at 2.1 % C and quenching from 1130 ^{o}C. This structure possesses the highest wear resistance for Fe-C compositions, much higher than high-carbon untempered martensite. Despite of high wear resistance steel with 2.1 % C is inconvenient for manufacturing because of high content of secondary carbides and high sensitivity to decarburization at quenching temperatures. Investigation on influence of alloying on abrasive wear resistance of steels have been performed further and corresponding results are presented in [12, 13]. It was established that maximum achievable level of abrasive wear resistance of retained austenite decreases with increasing of alloying. Therefore alloying of wear resistant steel should be kept as low as possible, preferably about 3 % of alloying elements in total.

According to [14, 15] optimal composition of wear resistant steel should be (in mass. %): C - 1.2; Mn – 2.8; Si – 1.5. Such alloying allows decreasing optimal quenching temperature from 1130 ^{o}C to 900 ^{o}C without significant drop in abrasive wear resistance [15, 16]. This way, steel that may be designated as 120Mn3Si2 possesses good manufacturability due to acceptable level of carbon and low alloying and obtain high abrasive wear resistance after quenching from 900 ^{o}C [15]. The next research step should be investigation on worn surface of this high-carbon low-alloyed steel after abrasive wear.

Goal of research and tasks to be performed

The goal of research was determining microstructure and properties of friction surface of 120Mn3Si2 steel quenched from 900 ^{o}C and abraded by hard particles under high pressure of abrasive medium. Microstructure investigations, XRD analysis and microhardness measurement had to be performed to achieve the goal of present work.

Material and methods

The material used in this study was 120Mn3Si2 steel of chemical composition: 1.21 wt% C, 2.56 wt % Mn, 1.59 wt % Si. The steel was industrially produced by conventional metallurgical cycle in a form of strips 5 mm thick. Abrasive wear tests were performed using sample with dimensions 30*90 mm^2. Sample was quenched in water after 15 min austenitization at 900 ^{o}C in electric air furnace. Decarburized layer was removed after quenching by grinding about 1.5 mm of material from one side.

For three-body abrasive wear tests the testing rig was used as described in [13]. The abrasive was silicon carbide with grit size of about 0.60-1.00 mm. The sample was abraded during 200 strokes to ensure complete adaptation of wear surface to working conditions. Pressure of abrasive medium was 5 MPa.

The XRD investigation was performed on the worn surface using a Bruker D8 Discover apparatus with CuKα-radiation. Microhardness was measured directly on worn surface without any grinding or polishing by means of computer controlled Wilson® Hardness tester at 0.05 kg load. Special care was taken to choose proper location for microhardness indentation i.e. areas that were big enough to made single measurement and obtain good print after indentation. Cross-sections of worn sample and friction surface were investigated using SEMs JEOL JSM-7000F and TESCAN.

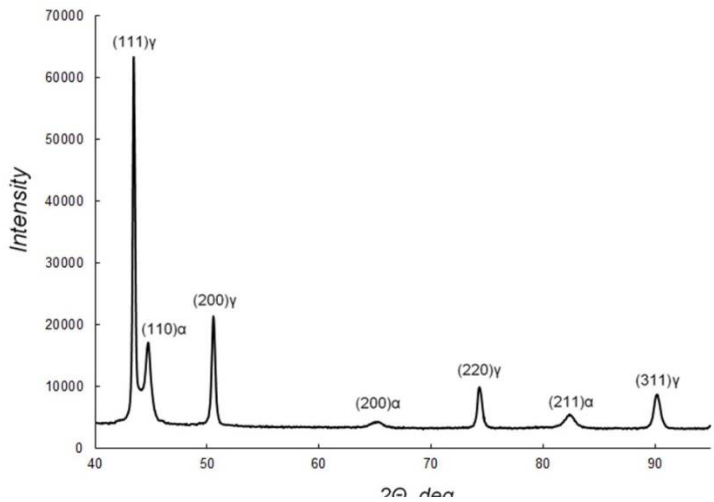


Fig. 1. XRD pattern of 120Mn3Si2 steel after quenching from 900 ^{o}C

Results and discussion

XRD profile of as-quenched material after deleting decarburized layer is shown on Fig. 1.

According to XRD pattern austenite is predominant structure constituent after quenching from 900 ^{o}C. Taking into account (110)α peak intensity the amount of martensite may be roughly estimated as 30 vol %. It means that matrensite start point (Ms) is slightly higher than room temperature, thus retained austenite is very instable and sensitive to phase transformation under mechanical impact of abrasive particles.

High resolution panorama view of friction surface compiled from several x5000 SEM micrographs is shown on Fig. 2 and XRD profile of worn surface is presented on Fig. 3.

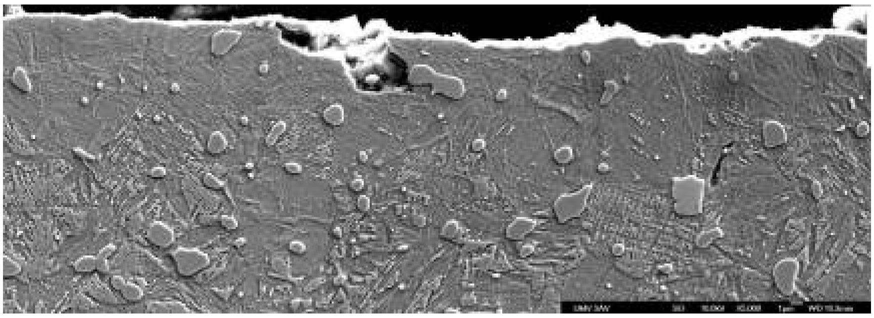


Fig. 2. Microstructure of cross-section in near surface region of 120Mn3Si2 steel quenched from 900 ^{o}C after three-body abrasive wear

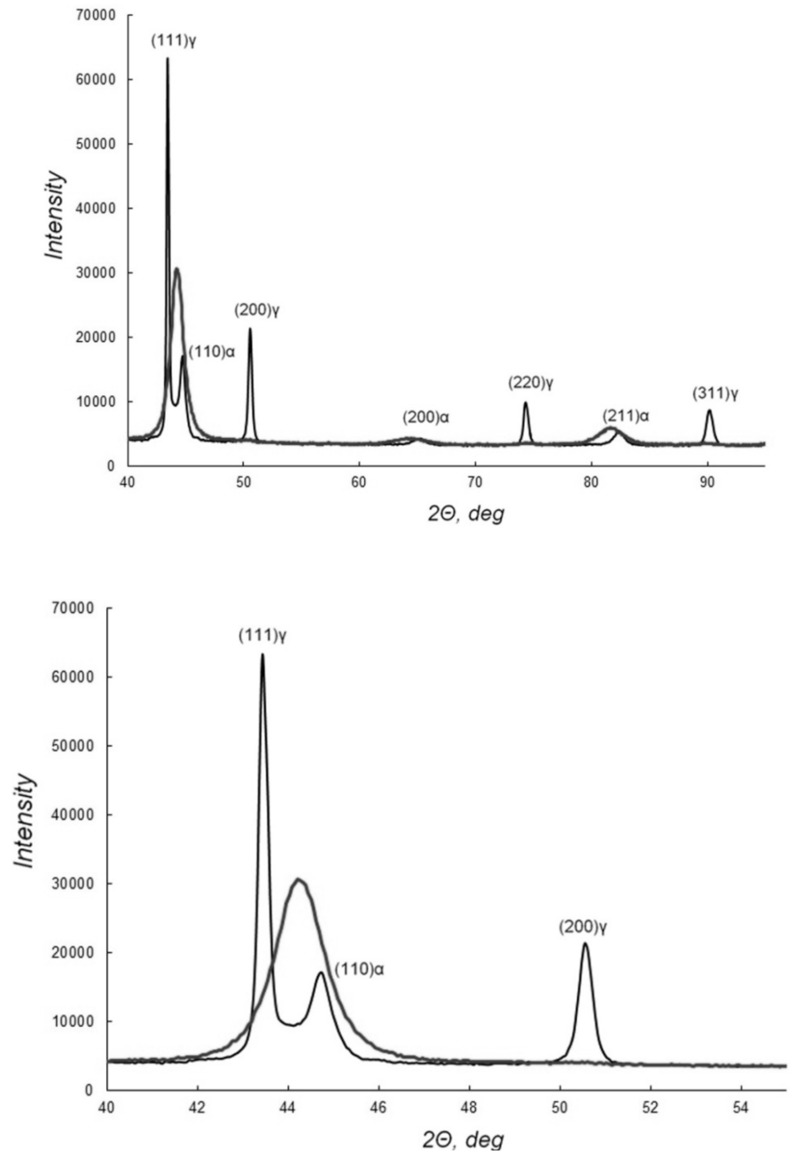


Fig. 3. XRD patterns of 120Mn3Si2 steel: black line – as-quenched from 900 ^{o}C; red line – friction surface after abrasive wear

According to XRD profile of worn surface (see Fig. 3, red line), austenite is absent in thin surface layer about 3 μm depth; that is penetration depth for CuKα-radiation. This conclusion could be drawn from disappearing of (200)γ, (220)γ and (311)γ alone standing diffraction peaks after wear. At that alone standing (200)α and (211)α peaks are present after wear and become much wider. Widening of α peaks in comparison with same peaks after quenching means that surface martensite has much more distorted crystal lattice.

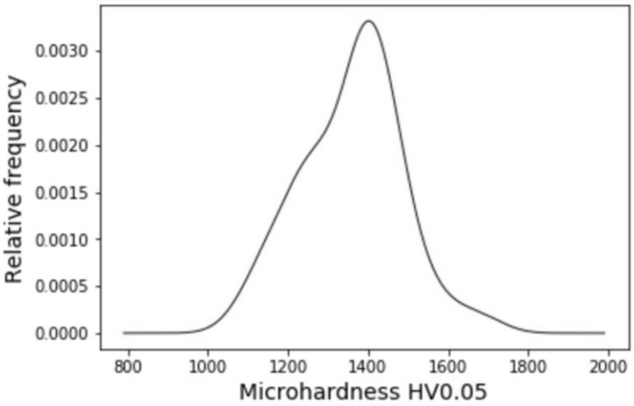


Fig. 4. Distribution of microhardness of friction surface after abrasive wear

Special attention should be paid on the most intensive XRD peak for worn surface (red line, see Fig. 3) which is located right between (111)γ and (110) α peaks for as-quenched material (black line). According to absence of all alone standing γ peaks for worn material this most intensive peak should correspond to (110)α peak which is significantly widened and shifted to lower angles in comparison with that for as-quenched state. Widening and shifting of (110)α peak means significant distortion of crystal lattice and increasing interplanar spacing. Such a state of martensite should manifest itself in significant increase in microhardness.

Fig. 4 shows the result of measurement microhardness of worn surface. The relative frequency distribution profile has a peak near 1400 HV 0.05. This is much higher than usual microhardness of as-quenched high-carbon martensite (usually 900 - 1000 HV).

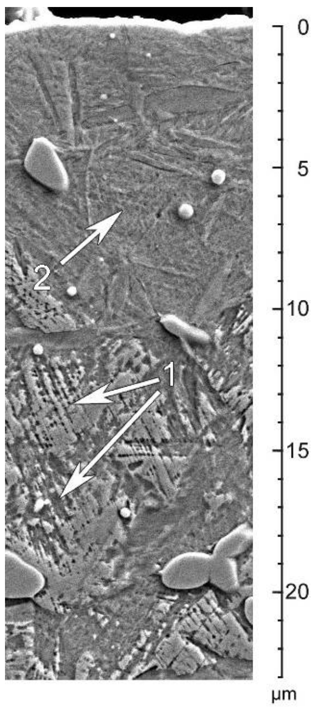


Fig. 5. Sites of severe plastic deformation in austenite 1 and martensite 2 in subsurface after wear

Results of XRD investigation and microhardness measurement help in explaining the structure presented on Fig. 1. Solid layer of uniform structure is located at the very surface and is about 10μm deep. The only second phase that may be observed is undissolved secondary carbides. Widened α-peaks on XRD diffractogram, absence of γ-peaks and very high microhardness indicate that the solid surface layer should be mechanically induced martensite.

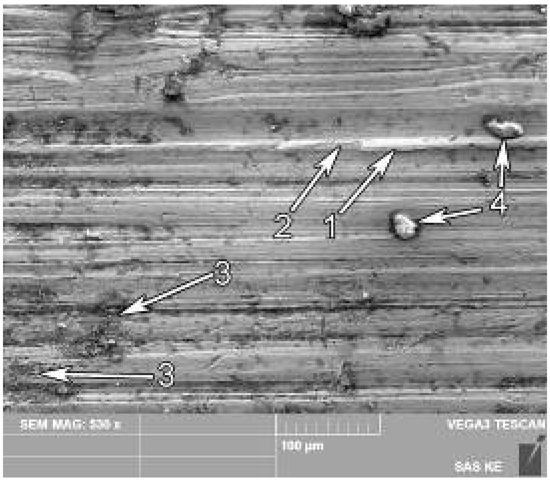
Even more close view of friction surface microstructure is shown on Fig. 5. Multiple crossing slip bands in area 1 indicate highly deformed austenite just before phase transformation. More darker gray sites in area 1 are presumably mechanically induced martensite; those sites are identical to the whole structure on the very surface.

Highly deformed state of austenite is inevitably inherited by mechanically induced martensite after phase transformation. Hence dislocation density in this martensite should be the same as in austenite just before transformation. Multiple crossing dots in area 2 are visually similar to those in area 1 and may serve as the evidence of inheritance of deformed state by martensite after transformation.

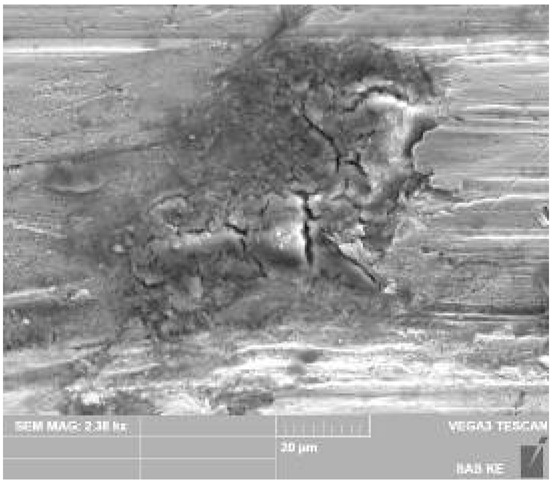
This way, comparing microstructure, XRD profile and microgardness of worn surface, it may be stated than very hard solid martensitic layer about 10 μm depth is developed in course of abrasive wear on the friction surface of quenched 120Mn3Si2 steel with a retained austenite structure. Such a high level of microhardness, i.e. 1400 HV0.05 and even higher, was not previously seen in literature.

Micrograph for top view of friction surface in SEM after abrasive wear is shown on Fig. 6. Multiple scratches may serve as the evidence of wear in low-cycle mode, i.e microcutting or ploughing by hard particles, when abrasives plastically deform the surface of material. Besides of scratches there are other signs of ploughing: ledges of plastically deformed material along the edges of the scratches (1 on Fig. 6, a). These ledges are fragilely broken in some places (2); it is sure sign of high level of hardness and high brittleness of a material.

Despite of predominantly low-cycle wear mode, some sites of a friction surface have traces of high-cycle fatigue failure (3). Combination of signs of low-cycle and high-cycle wear modes may be explained as follows. On the very first stage of wear the surface material is in predominant austenitic state, therefore is quite soft and capable for plastic deformation. This initial deformation manifests itself as multiple scratches and grooves on friction surface. Initial plastic deformation leads to extensive phase transformation (see Fig. 3) and, hence, material becomes very hard and brittle. The harder is the material the less is the probability of cutting or ploughing; elastic deformation with subsequent fatigue failure of micro volumes becomes predominant wear mode. Places that are in pre-failure condition after multiple cycles of elastic deformation appears in SEM as a darker sites (3). Closer view of place of fatigue erosion is shown on Fig. 6, b.



a



b

Fig. 6. SEM micrograph of friction surface after abrasive wear:
a – general view;
1 – ledge of plastically deformed material;
2 – broken ledge;
3 – place of high-cycle fatigue failure;
4 – embedded abrasive particle;
b – closer view of place of high-cycle fatigue failure

Presented results of SEM and XRD examination of friction surface along with measurement of its microhardness may serve as confirmation of hypothesis concerning specific microstructure of friction surface [5]. It was suggested in [5] and other works that in the course of abrasive wear of instable retained austenite a specific honeycomb substructure is developed, namely extremely hardened austenite being "sealed" by mechanically induced martensite. Sites 1 and 2 in Fig. 5 confirm validity of this hypothesis. Moreover, it appeared that even austenite with high dislocation density is able to undergo phase transformation, therefore the whole structure appears to be martensite-sealed-by-martensite and no austenite is retained at all at the very surface after abrasive wear (see Fig. 2 and red line on Fig. 3).

XRD pattern of worn surface contains lots of information that is not discussed here, for example, dislocation density, interplanar spacing etc. Revealing this information may be taken as the direction of future investigations.

Conclusions

Results of investigation on friction surface properties after abrasive wear of high-carbon low-alloy steel 120Mn3Si2 with unstable austenite structure lead to the following conclusions.

1. Solid layer of mechanically induced martensite is developed on the very surface in the course of abrasive wear. The depth of fully martensitic structure is not less than penetration depth of CuKα-radiation. According to SEM micrographs the depth of martensite layer may be estimated as 7 - 10 µm.

2. Maximum value of relative frequency distribution for microhardness measured on top of friction surface is 1400 HV0.05. This level of microhardness for mechanically induced martensite was not previously seen in literature.

3. According to XRD profile no austenite is retained on friction surface after abrasive wear. Significant widening of α peaks is detected also, this clearly indicates that mechanically induced martensite inherits lattice imperfections which appears in austenite in the course of plastic deformation by abrasive particles.

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Хессе О., Калінін Ю.А., Петришинець І., Кунерт М., Єфременко В.Г., Андрущенко М.І., Осіпов М.Ю., Бриков М.М. Дослідження поверхні тертя високовуглецевої низьколегованої сталі після абразивного зношування.

Зразки сталі 120Г3С2 загартовано у воді від температури 900 °С та піддано абразивному зношуванню на лабораторній установці. Проведено мікроструктурні та рентгенівські дослідження, а також вимірювання мікротвердості на зношеній поверхні. Встановлено, що існують три характерні області по глибині від поверхні: пластична деформація аустеніту, часткове фазове перетворення деформованого аустеніту, повністю перетворений матеріал із мартенситною структурою. Згідно з результатом рентгеноструктурного аналізу на самій поверхні тертя аустеніт практично відсутній. Мікротвердість зношеної поверхні розподілено у широкому діапазоні з максимально вірогідним значенням 1400 HV0.05.

Ключові слова: високовуглецева низьколегована сталь, гартування, аустеніт, мартенсит, абразивне зношування, мікротвердість, мікроструктура.