Special Case of Destruction of the End Mill Made of High-Speed Steel Powder

E P Nikolaeva
Irkutsk National Research Technical University, 83, Lermontov str., Irkutsk, 664074, Russia

E-mail: nicolaeva-ep@yandex.ru

Abstract. Comparing with cast steels high-speed steel powder S390 Böhler MICROCLEAN® has better properties, which is determined by the technology of its manufacture: this steel is high-alloyed, contains an increased amount of carbon and carbide-forming metals. In contrast to cast steels, its microstructure has no carbide inhomogeneity. Despite many advantages and long life of steel S390, explained by its balanced microstructure and chemical content, sometimes early tool failures occur. The article provides the grounds for tool failure connected with the peculiarities of heat treatment conduct. The authors establish the influence of a heat treatment mode on the number and content of carbide phases. The authors give recommendations for increasing the tool service life. This article gives the results of the steel macro- and microstructure research. In the course of research hardness was measured and the content of chemical elements was determined. The phase composition was defined with the help of the X-ray diffractometer Shimadzu XRD-6000. The amount of retained austenite was defined by means of the X-ray method of “four peaks” at the diffractometer Xstress 3000. The distribution of chemical elements was studied with the help of a microprobe X-ray analyzer Camebax SX50 while the surface topography was studied with the help of a scanning electronic microscope with the 100-3000-fold magnification.

1. Introduction

High-speed steels (HSS) are frequently used for manufacturing metal treatment facilities. For example, HSS are used to make end mills for aviation material machining [1, 2]. The mill resistance is influenced by physical&chemical processes occurring in the cutting area, high contact voltages, intense heat action due to the emission of heat during cutting [3–5]. When a tool is heated, its microstructure is subject to undesirable changes because of the abrasive action of the treated material. The mill material is influenced by high cutting forces, thus, significant temperature causes softening and increased cutting edge wear.

The metal cutting tool material should meet a number of requirements: high hardness and red-hardness. Also, it should have sufficient flexure strength, compressive strength and shearing strength. But as a rule, one and the same HSS grade cannot have all these properties at the same time. The cause is a non-homogeneous microstructure of cast HSS [6–8].

The methods of hardening treatment of a cutting tool can be divided into 5 groups: superficial plastic deformation (SPD), heat treatment, superficial alloying, coating, combined treatment. For a metal cutting tool superficial plastic hardening is not applied frequently as it causes irregular stress field and roughness increase. Hardening methods, based upon deformative action, are most frequently applied for
engineering materials [9–13]. Heat treatment hardening remains the main part of a technical process during the tool manufacture from HSS [6, 8].

At heat treatment hardness is the parameter to be measured most frequently. Hardness is the main steel characteristic used for evaluating the steel quality. Heat treatment, conducted to obtain the maximum hardness, causes significant decrease in crack resistance. When there are structural stress concentrators inside a tool (grooves, cavities, holes for delivering lubricating cooling liquid) unstable failure occurs more frequently.

Some technological properties of HSS alongside with the mechanical ones are predetermined by the method of steel manufacture. Powder technology for manufacturing high-speed steels provided the solution for many problems, caused by structural imperfections. Powder HSS of the new generation are highly-alloyed and contain the increased amount of carbon, their microstructure has no carbide inhomogeneity.

The design of end mills, intended for high-efficiency treatment of high-duty aviation materials, takes into account the end mill geometry as well as the need of internal cooling during cutting, vibration influence on the precision and quality of the treated part surface [14–18]. Tool manufacture is followed by quality control [6, 19, 20]. The combination of chisel steel powder with optimal geometry of a cutting tool should facilitate the efficiency increase. However, sometimes tool failure occurs. The purpose of this research is to find out the causes of destruction of the end mill, made of steel S390.

2. Materials and methods

This paper studies the end mills with a wave-shaped cutting edge, used for rough machining of the parts made of titanium alloys and high-resistance steels [1, 2, 8]. Mills were withdrawn from a technical process after 10 and 20 minutes.

The mills were made of steel powder S390 Böhler MICROCLEAN®. According to the data of optical emission&spectral analysis, the mill parts contain the elements (% wt): 1.6 C; 10.6 W; 7.7 Co; 5 V; 4.7 Cr; 1.9 Mo; 0.5 Si; by 0.3 Mn and Ni; 0.02 P; less than 0.01 S.

During the mill manufacture its material was hardened by heat treatment. At first, workpieces (bars) were annealing to remove residual stress at the temperature 600°C for 2 h. The hardening used after produce end mill which shape is needed. Due to low heat conductivity before quenching HSS was subject to two pre-heatings for temperature equalization along a whole mill section and conducting phase changes for a whole volume. Heating temperature: 1st heating – 560°C, for 2 h; 2d heating – 860°C, for 12 min. Final heating was conducted in a salt bath. The hardening temperature is 1,185°C, hold time – 4 min. 10 sec, cooling - in the oil, heated up to 60°C. Next was to three-stage tempering at the temperature 560°C, each tempering lasted 2 hours.

To study the microstructure, the authors selected the fractures of end and inside mill parts in the region of a cooling channel. The sites of sample cutting for microstructure research are shown in figure 1. At the end part one can observe the tracks of plastic deformation and the cutting edge fracture occurred because of high contact stresses (figure 1, a).

![Figure 1. Stereoscopic Picture: (a) cutting edge of the mill end part; (b) fracture surface.](image-url)
On the fracture of the mill internal part one can observe beach marks and cracks, propagating from the surface of cooling channels (figure 1, b).

The samples were prepared for their microstructure research with the help of a kit for sample preparation, which contains a cutoff machine Discotom-10, abrasive and polishing system Tegramin-25, STRUERS. Micro-structure research was conducted with the help of the microscope OLYMPUS GX51 with the 500-fold magnification.

The distribution of chemical elements was studied on a microprobe X-ray analyzer Camebax SX50. The examination of the sample surface was conducted with the help of a scanning electronic microscope at 100–3.000-fold magnification. The study of sample topography was conducted with the application of secondary electrons (SEI), chemical composition – in back-scattered electrons (BSE) as well as in characteristic X-ray beams of elements. The analysis was conducted with the help of wave X-ray spectrometers and energy-dispersive spectrometer KEVEX.

Finding out the phase composition of high-speed steels was conducted by means of the X-ray diffractometer Shimadzu XRD-6000 in Cu-K-alpha radiation.

Retained austenite was defined by the diffractometer Xstress 3000 with the “method of four peaks”. The authors compared integrated intensities of the diffraction peaks of austenite and martensite in the range of angles 2 theta 79.1…156.4 degrees [21]. The measurements and calculations were conducted automatically by the software of the tool XTronik. The peculiarities of measurements: instead of the shooting mode “modified” [5, 6, 11, 12, 22, 23], used at the measurement of residual stresses in a superficial layer, the authors used the mode “omega”. The authors applied a spheric detector arc (figure 2).

At the treatment of diffraction peaks Lorentz correction was made. On the basis of the measured intensity the authors calculate the content of retained austenite according to the formula 1:

\[
V_r = \frac{(1-V_c) \cdot ((q)^{-1} \cdot \sum_{j=1}^{q} ((I_{qj}) \cdot (R_{qj})^{-1}))}{(p)^{-1} \cdot \sum_{i=1}^{p} ((I_{ai}) \cdot (R_{ai})^{-1}) + (q)^{-1} \cdot \sum_{j=1}^{q} ((I_{qj}) \cdot (R_{qj})^{-1})}
\]

where \(V_r\) – volume fraction of austenite phase; \(V_c\) – volume fraction of carbide; \(q\) – number of austenite peaks (hkl); \(I_{qj}\) – integrated intensity of specific (hkl) austenite diffraction peak; \(R_{qj}\) – parameter of the theoretical austenite integrated intensity; \(p\) – number of martensite peaks (hkl); \(I_{ai}\) – integrated intensity of specific (hkl) diffraction martensite peak; \(R_{ai}\) – parameter of theoretical integrated intensity of martensite.

The parameter of theoretical integrated intensity (R) depends on the interplanar spacing (hkl), the Bragg angle, crystal structure and composition of the phase being measured. It is calculated by the main principles (see the standard ASTM E975-13).
3. Results and Discussion

The steel hardness, measured after tempering (66.5...67.5 HRC) falls in the range suitable for end mills, intended for highly efficient metal machining. At the microslice of the end surface of the cutting edge, one can observe the sections of partially strained metal. The formed build-ups of the machined material have the thickness from 6 um to 36 um (figure 3a).

![Figure 3. Mill cutting edge: (a) treated material adhesion; (b) region of heat influence and crack in the superficial layer.](image)

The region of heat influence and microcracks, not characteristic for the material (figure 3, b), are clearly observable. The initiation of micro-cracks, developed in the direction from the surface towards the core, is obviously caused by excessive stresses during cutting.

The steel microstructure consists of fine-needled martensite quenching and multiple disperse carbides characteristic for steel powder. The steel structure is homogeneous, finely dispersed with the uniform distribution of carbides. Carbides have a round shape, equiaxial, small - their sizes are approximately 1.5 um. The sample microstructure is normal for the HSS heat treatment mode “quenching and three-stage tempering”. Cooling channels are covered with scale and remnants from heat treatment process (figure 4, b).

![Figure 4. Cooling channels surface: a) scale and oxidation products are evident; (b) polished specimen, oxidation products and corrosion are evident in cooling channels.](image)

The content of retained austenite does not exceed a permitted norm and falls within the range 1.4...1.8%. A larger part of analyzed chemical elements (Cr, Ni, Co) is contained in martensite. The distribution of carbide-forming alloying elements (W, Mo, V) is uniform.

The phase composition of the steel S390 is defined after various quenching temperatures. It is defined that martensite saturation with the alloyed elements increases at the growth of quenching temperatures from 1172 to 1193°C. Figure 5 shows the comparison of the diffractograms of steel S390 quenched at various temperatures and tempered at 560°C.

Irrespective of the quenching temperature in steel S390 the X-ray phase analysis detects ordered vanadium carbide – V₆C₇ [24], complex tungsten carbide – Fe₃W₃C и Co₃W₃C [25]. Cobalt is detected in the composition of complex tungsten carbides – Co₃W₃C and molybdenum – Co₆Mo₆C₂
At the quenching temperature 1193°C steel S390 demonstrates the increase in the share of a stronger carbide-forming element – vanadium (V₈C₇), increase in the carbide share Co₆Mo₆C₂ and decrease in the amount of tungsten carbides.

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![Diffractograms of steel S390 after heat treatment](image)

**Figure 5.** Diffractograms of steel S390 after heat treatment: red line – quenching temperature 1182°C; blue line – quenching temperature 1193°C.

In this steel no carbides of the type Mé₂₃C₆, Mé₇C₃, Mé₂C are detected (these carbides are most frequently found in cast high-speed steels) [6, 25]. It is likely that some deviations from the recommended heat treatment modes [20] facilitate the occurrence of dispersed carbides of the specific composition in the microstructure of steel S390.

### 4. Conclusion

The conducted research makes the authors draw a conclusion that one of the causes of early failure of the end mill is the state of material of cooling channel superficial layers. At all studied fragments along the inside surfaces of cooling channels one observes a fragile zone with the increased carbon content. Carburization occurs at the stage of hardening heat treatment. Carburization occurred because of oil use during hardening. In addition to carburization in these regions, one can also observe massive layers of oxides (scale) there. Hard and fragile carburization surface in combination with oxides (scale) depositions - these inside superficial defects are the cause of micro-cracks formation and, subsequently, the cause of tool destruction during high-speed treatment. Potential optimization of the service life of end mills, made of high-speed steel grades, consist in conducting heat treatment eliminating the formation of any deposits or carburization regions along the inside surfaces of cooling channels. This can be implemented at the application of modern heat equipment with cooling in vacuum or inert gas. Mechanical damage of the cutting edge during tool operation under high external load occurs because of high temperature action. Such temperatures
are caused by friction and adhesion of the treated material. In this case one should select more favourable conditions of treatment under which it is possible to provide sufficient tool cooling for preventing defect occurrence.

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