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METHODS OF IMPROVING THE STRUCTURE AND PROPERTIES OF HIGH-SPEED STEELS

We review the works on the technologies of high-speed steels (HSSs) production. Different methods for improving the structure homogeneity of HSSs are considered. State-of-the-art techniques for controlling the structure of steels, the advantages and disadvantages of technologies are formulated. Modification methods for improving the structure of HSSs using various alkali metals, alkaline earth metals, rare-earth metals, misch metals are studied. An increase in cooling rate and the implementation of a spheroidizing treatment process to refine carbide dimensions in HSSs are considered. The sub-zero treatment for improving the fatigue characteristics, impact strength, hardness and wear resistance of HSSs are studied. Powder metallurgy is able to promote the refined and more uniform microstructures. This is their main advantage leading to improved properties and higher isotropy of HSSs. The regularities of phase and structural transformations by diffusion composition changing in the pressed powder mixture of alloys (in which the concentration of the alloying elements is similar to standard HSSs, but with different carbon content) are considered. As shown, using metal injection moulding and coating technologies are efficient ways to improve hardness and wear resistance of HSSs. The possibility of applying chemical-heat treatment to improve the structure of HSSs is shown. Diffusion changes in composition due to chemical-heat treatment allow obtaining *in situ* composite with a high level of physical and mechanical properties. The influence of additional doping on the structure and properties of composite materials of the eutectic type of binary systems, as well as the features of the structure formation of ternary colonies in the composite are considered.

Keywords: high-speed steel, structure homogeneity, modification, sub-zero treatment, powder metallurgy, coating technologies, thermochemical treatment, *in situ* composite

1. Introduction

High-speed steels (HSSs) forms a special class of highly-alloyed tool steels, combining properties such as high hot hardness, toughness and high wear resistance [1, 2].

HSSs is one of important tool materials used in the industry, which was developed more than a century ago and has been continuously improved for applications as a wear-resistant material for drills, taps, milling cutters, broaches, slotting tool and hobs [3]. HSS are ferrous based alloys of the Fe−C−X multicomponent system, where in X represents a variety of alloying elements, such as molybdenum, tungsten, vanadium, cobalt, and chromium [4, 5].

The conventional technology of HSSs production starts with the melting of pre-alloyed scrap and additions [6]. The temperature is set in the ladle furnace and the melt is cast in ingots or in the continuous casting machine. The solidified ingots are heated up in furnaces to hot forming temperatures and depending on the sizes and the grades are hot forged in the long forging machine or rolled in the blooming mill down to a cross section around 100 mm in square. Further, down, the billets are hot formed in a continuous process to the final dimensions in a multiline rolling mill. After hot rolling, an annealing process is carried out in an annealing furnace, which makes the material soft enough for machining.

By the next heat treatment, *i.e.*, hardening and tempering, the properties of the material are adjusted to the specific application.

HSSs are effective materials applied in aggressive environments where abrasion resistances are required, because they have hard carbides and relatively ductile matrix to bind carbides. However, there are many kinds of carbides in HSSs, which lead to different effect on wear properties of HSSs.

However, due to the preferential precipitation of alloy carbides from the liquid during the cooling process of HSS prepared by the traditional casting process, a coarse segregation structure of ledeburitic carbide will inevitably occur (Fig. 1) [7−9].
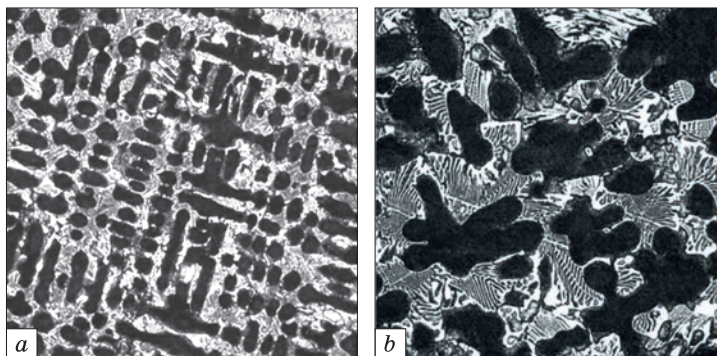

Fig. 1. Typical as cast structure of high-speed steel for two different scales: ×100 (*a*) and ×200 (*b*)

However, large amounts of networks of eutectic carbides have a decisive influence on the mechanical properties of HSSs [10–12]. The presence of segregation not only makes the forging and hot rolling of steel difficult, but also significantly reduces the strength and wear resistance of steel [13, 14].

It is well known that the mechanical properties of HSSs mainly depend on the type, shape, amount, dimensions and distribution of carbides [15–17]. Thus, how to control the distribution and dimensions of carbides is very important for HSSs.

Different methods have been used to improve the structure homogeneity of HSSs, including modification, alloying, heat treatment, and forging process [18–21].

2. Technologies of HSSs Production

2.1. Mechanical Deformation

Mechanical deformation is the most common method used to break up carbide networks; this reduces the size and improves the distribution homogeneity of carbides [22, 23]. However, this process only works when the forging ratio is extremely high. When forging ratio is low, carbides still remain coarse and are arranged in heterogeneous stringers (Fig. 2).

2.2. Modification

Several other methods, such as modification, alloying, and heat treatment, [24, 29] proved to be effective. After modification with alkali metal [24], alkaline-earth metal [25] or cerium [26, 27], the networks of eutectic carbides are refined and changed into discontinuous networks. By heat treatment, continuous networks change into isolated massive blocks that refine carbide dimensions to a certain degree [28, 29]. Unfortunately, these carbides are still too large to satisfy material requirements. The unsatisfactory effects of heat treatment on carbide dimensions are essentially attributed to the unfavourable morphologies of eutectic carbides. They generally maintain a lamellar or plate-like shape, which are kinetically unfavourable for carbide spheroidization during heating. It is expected that eutectic carbides can adequately be refined by heat treatment if they possess a more 'kinetically favourable' shape [30, 31].

The rare earths have a great influence on HSSs, such as increasing the hot plasticity, refining the matrix structure and networks of eutectic carbides, and promoting the spheroidization of eutectic carbides during heating. In addition, research shows that rare earths could promote the formation of fishbone like M_6C carbides [32, 33], where M denotes a metal.

Fig. 2. Microstructure of the hot-deformed high-speed steel (optical microscopy) [6]
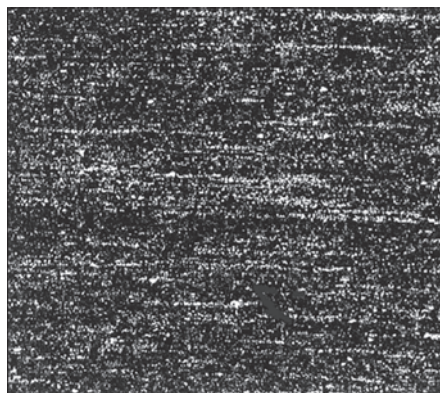
Authors [34] investigated the effects of rare-earth metals on the morphology of γ-M_2C, γ-M_6C, and γ-MC eutectics of as cast $M2$ high speed steel. Rare-earth metals favoured the formation of the M_6C eutectic, at the expense of the M_2C eutectic, and promoted the formation of the duplex M_2C/MC and M_6C/MC eutectics. The formation of these duplex eutectics was attributed to the decrease in the MC eutectic temperature.

To improve the mechanical properties of HSSs, different contents of rare-earth Y (0.047, 0.096, 0.229, and 0.310 (wt.%)) are added, and the microstructure and mechanical properties of as-cast HSSs are systematically studied [35]. As the Y content increases from 0 wt.% to 0.229 wt.%, the strength, elongation and impact toughness of HSSs are improved from 516.7 MPa, 0.29% and 3.8 J to 820.9 MPa, 0.47% and 5.2 J, respectively. This provides a new idea for the design and application of HSSs, and has a practical reference value for the development of other wear-resistant materials.

Authors [26] studied the effects of Ce–La addition on the microstructure and mechanical property of as-cast M2 HSS. The results showed that the Ce and La could make the carbides microstructure change from net-like to isolated or circular. Ren *et al.* [36] found that Ca element could adsorb on the carbide surface of boron–carbon HSS, inhibiting the oriented growth of carbide as a result.
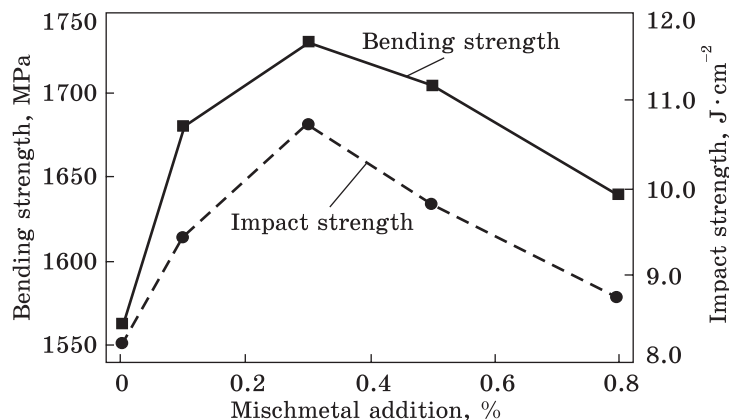

Fig. 3. Effect of misch metal addition on bending strength and impact strength after quenching and tempering [26]

The addition of misch metal refines the dendrites in M2 high-speed steel, decreases the total eutectic carbides content and makes the distribution of eutectic carbides in discontinuous networks. The weak connection of the network is broken. When the adding contents of misch metal is about 0.3%, nearly all of the networks of eutectic carbides at the vicinity of grain boundaries are broken, and eutectic carbides tend to be separated and spheroidized [26]. The impact toughness and bending strength of M2 HSS can be improved greatly by modification with misch metal. When the adding contents of misch metal is about 0.3%, the impact toughness and bending strength are greatly increased by 27% and 10.76% compared with that without adding misch metal, respectively (Fig. 3).

2.3. Spheroidizing Treatment

Authors [37] proposed to refine carbide dimensions in HSSs, namely through an increase in cooling rate and the implementation of a spheroidizing treatment process. With increasing cooling rates, M_2C eutectic carbides, the prevailing carbide type in M42 steel, change from a lamellar shape into a curved rod shape. In comparison with lamellar carbides, curved rod M_2C carbides formed at higher cooling rates are much easier to decompose and spheroidize during heating. This considerably refines the carbide dimensions. Hence, it is concluded that the combination of increased cooling rates and spheroidizing treatment is favourable to both the microstructural homogeneity and overall performance of M42 HSS.

2.4. Sub-Zero Treatment

The sub-zero treatment is a well known and an effective method to improve dimensional stability [38], fatigue behaviour [39], toughness [40–44] and wear resistance [45–65], which is commercially used to improve the performance of many metallic materials for decades. Figure 4 shows a typical heat treatment cycle of sub-zero treatment.

Representative optical and scanning electron microscopy (SEM) micrographs of shallow cryogenically treated specimens are depicted in Fig. 5. The primary carbides are large, elongated and dendritic-type having non-uniform distribution [41]. The amount, size, morphology and distribution of primary carbides are expected to be identical among the differently heat-treated specimens and the observations are in line with this expectation. In the optical micrographs (Fig. 5, *a*), the secondary carbides appear either as small white regions (marked by area 1) or tiny black patches (marked by area 2). Comparison of optical micrograph (Fig. 5, *a*) with SEM micrograph (Fig. 5, *b*) reveals that the 'tiny black patches' in optical micrograph are secondary carbides of smaller
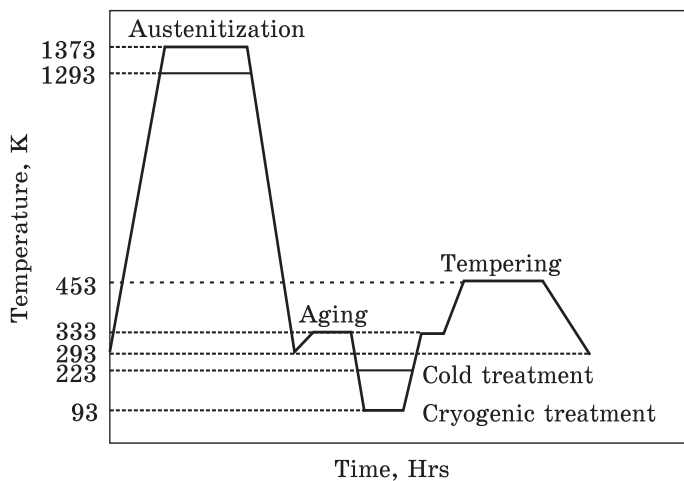
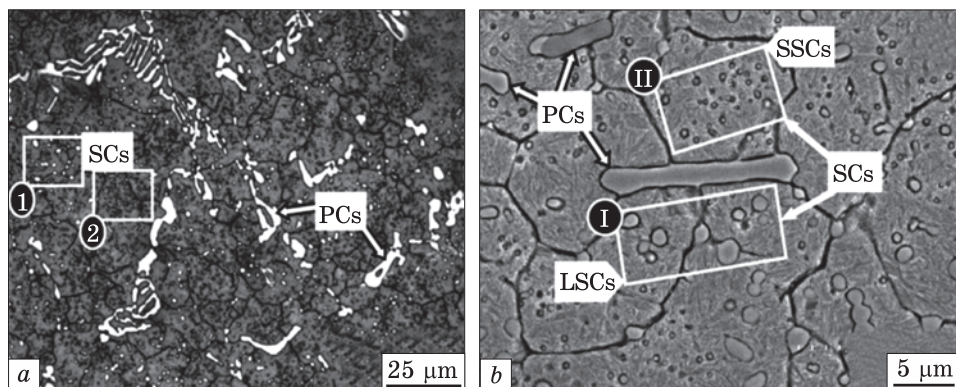*Fig. 4.* Sketch of the heat-treatment process [43]

Fig. 5. Representative (*a*) optical and (*b*) SEM micrographs of shallow cryogenically treated specimens [41]
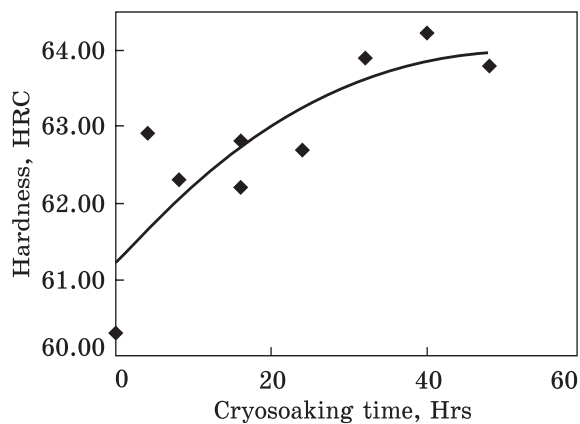

Fig. 6. Hardness *vs.* the cryogenic-soaking time [61]

size. The secondary carbides are categorized here as 'large' and 'small' based on their size.

The great efforts were made for considerably improved fatigue behaviour, toughness, hardness and wear resistance of HSS using the sub-zero treatment (Fig. 6). Leskovsek *et al.* [48] investigated the Influence of deep-cryogenic treatment procedure on the wear resistance of HSS and showed that different cryogenic treatment procedures resulted in different combinations of hardness and fracture toughness, leading to an order-of-magnitude difference in the wear resistance of samples under study.

However, Kelkar *et al.* [50] observed that the cryogenic treatment followed by tempering eliminated residual strain to a large degree, which is beneficial to the fracture toughness. By coupling the deep cryogenic treatment with conventional vacuum heat treatment, Pellizzari *et al.* [52] reduced the wear rate of AISI-M2 HSS up to 42 %. Firouzdor *et al.* [66] reported 77 % and 126 % improvement in drilling life of M2 steel by cryogenic treatment and cryogenic tempering treatment, respectively. Many studies have demonstrated that an appropriate combination of soaking temperatures and tempering treatment, mechanical and tribological properties of HSSs can be significantly improved [44, 45, 47, 55, 58, 67].

As demonstrated in [68], the mechanical properties of the cryogenically treated samples were superior to those of conventionally treated ones. The cryogenically treated samples with subsequent tempering performed better than cryogenically treated samples that experienced prior tempering. The lower temperatures for sub-zero treatment were more effective in improving the mechanical properties.

2.5. Powder Metallurgy

In order to distribute uniformly carbides, the most ideal method is to use powder metallurgy (PM) technology. Due to the extremely fast cooling rate of the alloy droplets (>104 °C/s) during the atomization process, the coarsening process of the first precipitated carbides in the droplets is inhibited, resulting in fine and dispersed carbides in the final particles (Fig. 7) [69, 70].

Various processes may produce PM HSS, being the most usual the ASP, CPM and APM process. The differences in PM processes mainly regards to hot isostatic pressing (HIP) techniques. The APM process has some advantages, since it is able to produce as-HIPed PM HSS free from porosity and with no segregation of S, O or C [71, 72]. This is possible thanks to a cold loaded mega-HIP system, where pressure and temperature are raised simultaneously. As APM steel is not subjected to any later forming process, it is considered the only truly isotropic PM high-speed steel [71].

Fig. 7. Microstructure of HS 6-5-3 powder metallurgy high-speed steel [70]
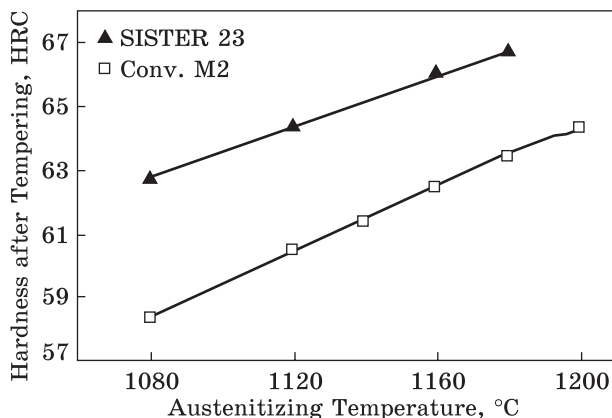

50 μm
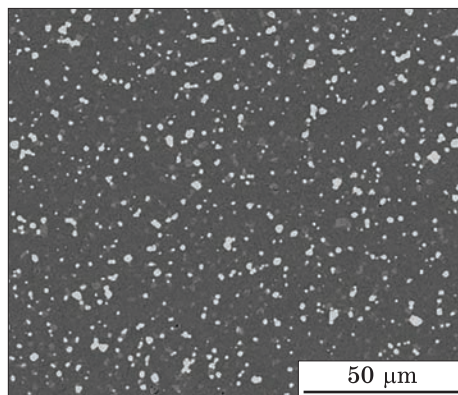
In recent years, the preparation of PM HSS by cold pressing and sintering with carbide and iron powder as raw materials has attracted much attention [69, 70, 73]. Using carbides as raw materials can, not only avoid the oxidation of active metals such as V and Cr during milling, but also prevent grain growth due to the pinning effect of undissolved carbides during sintering.

In the preparation of casting HSS, the addition of rare-earth elements can refine the carbides in the coarse ledeburite and improve the mechanical properties [74, 75]. La and Ce are the most commonly used rare-earth elements in alloys, and the role of those elements in HSSs has been extensively studied and evaluated [71, 75, 76].

The osprey process is unique in combining a rapid solidification process (gas atomization) with a direct method for making bulk components [77−79]. There are four main stages in osprey process, including melting and dispersing, gas atomization, deposition and collector manipulation.

The results show that the as-HIPed PM material presents finer and more uniform carbide distribution, leading to a complete isotropy and higher toughness than the conventional steel (Figs. 8, 9). In the Osprey material, carbides are also finer, well distributed and the isotropy is considerably higher than that for conventional HSS [80].

Work [81] shows that the specimens are densified rapidly *via* supersolidus liquid phase sintering mechanism. When vacuum sintering was employed, a near full density was obtained at 1210 °C after 60-min holding. Sintering above the critical temperature of 1210 °C and prolonged isothermal sintering in the presence of liquid

Fig. 8. Hardness after tempering at 560 °C *vs.* the austenitizing temperature [72]
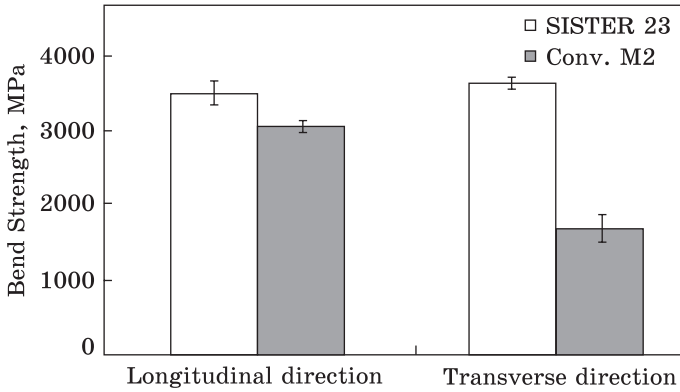
Fig. 9. Longitudinal and transverse bend strength for wrought 91 mm M2 and as-HIPed 76 mm SINTER 23 [72]

species result in rapid growth in the grain size, and coarsening of Mo, W rich M_6C carbides.

The vacuum sintering characteristics of cold compacted M2 and M3/2 types of water-atomised high-speed steel powders are investigated in [82]. Optimal sintering temperatures were established as 1255 and 1250 °C for M2 and M3/2 respectively. It is shown that optimal sintering takes place on heating to within a four-phase austenite + M_6C + + MC + liquid region.

The effect of carbon content on the vacuum-sintering characteristics of annealed and cold compacted water-atomised type T1 HSS powders is reported by [83]. It was found that increasing carbon content from 0.8 to 1.4 wt.% resulted in significant improvements in sinterability; optimum sintering temperatures were lowered from 1320 to 1240 °C whereas the sintering window expanded from ≈10 to ≈40 K.

A technology, which was characterized by the vacuum solid-state sintering, was developed for powder metallurgy high speed steels production [70]. During sintering, both the WC and Mo_2C reacted with Fe and transformed to W and Mo rich M_6C carbides, which were the common hard phases in HSSs. In addition, a high number of W, Mo and Fe were dissolved in VC, forming the MC carbides. The densification of the material mainly relied on the solubility effect during the M_6C and MC carbides formation. By alloying with a 0.1 wt.% of LaB_6 to the steel, the bending strength and the fracture toughness were improved. Moreover, the deoxidization effect caused by the LaB_6 addition promoted the sintering at a high-temperature period, which contributed to the bending strength and fracture toughness improvement.

The high cost of PM associated with complicated process and low yield restricts its extensive application [84]. In the past decades, spray forming has been proved an efficient way to fabricate high-alloyed HSS with no segregation and fine distributed carbide [85−88]. It was reported that the microstructure of spray-deposited HSS comprised of homo-
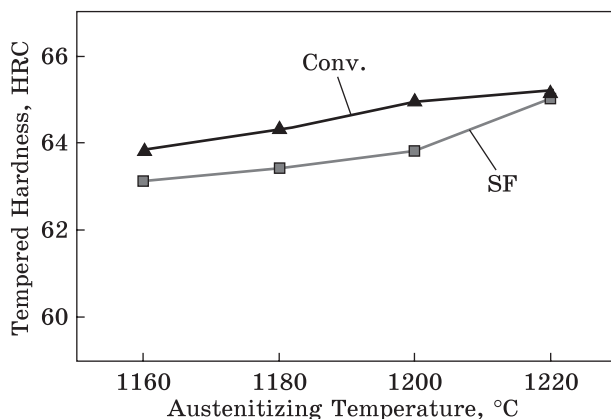
Fig. 10. Hardness after double tempering at 560 °C *vs.* austenitizing temperature for conventional and spray formed M3:2 [90]

geneous equiaxed grains and small-size carbides of MC (vanadium carbide VC), M_2C (in particular, Mo_2C, W_2C) or/and M_6C (Fe_3W_3C, Fe_4Mo_2C). Moreover, this material exhibits excellent mechanical properties comparable with those produced by PM and far better than those do by conventional technology (Fig. 10) [89, 90].

The effect of YH_2 addition on the microstructure and mechanical properties of sintered and heat-treated HSS was studied by [91]. The results show that due to the addition of YH_2, submicron spherical Y_2O_3 particles dissolved with a certain amount of sulphur and other alloying elements are formed at the grain boundaries and inside the grains. Compared with the samples without YH_2 addition, the bending strength of the samples with 0.1 wt.% YH_2 is increased by 6.7%, reaching 3425 MPa. However, excessive addition of YH_2 results in the formation of large-sized Y_2O_3 particles at the grain boundaries, resulting in de-
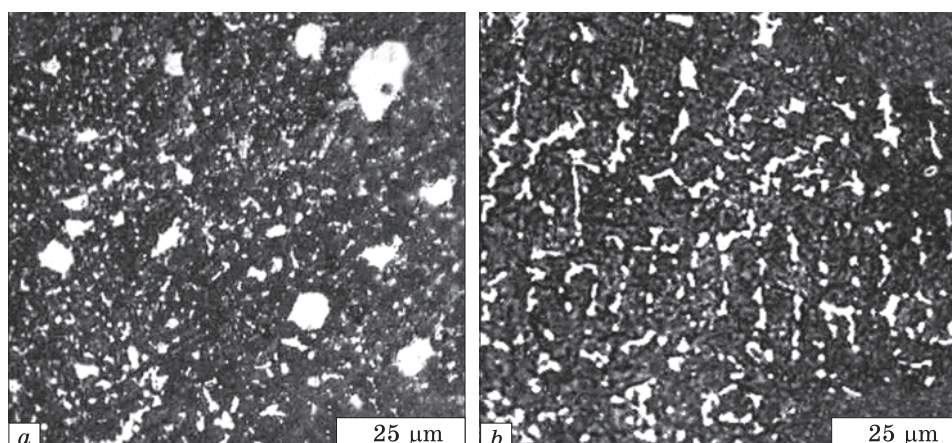

Fig. 11. Microstructure of the powder mixture under analysis during the sintering process, where (*a*) initial state, (*b*) after 30 min of sintering [92]

creased mechanical properties. With the increase of YH_2 addition, the hardness, tempering softening resistance and *in situ* hot hardness gradually increase.

The results reported in Ref. [92] made it possible to elucidate a number of issues of structure formation and phase transformations during liquid-phase sintering of a mixture of powders of low-carbon HSS and a high-carbon alloy alloyed according to the principle of HSS. Sintering in combination with crystallization and spheroidization makes it possible to obtain a material without carbide inhomogeneity (Fig. 11). In addition, the presence of about 70% of the ferrite component in the composition of the powder mixture allows excluding softening annealing before pressing from the technological scheme. The data obtained will make it possible to more flexibly control the final structure of specific products, and, consequently, successfully solve practical problems of improving the technological and operational characteristics of powder cutting tools.

2.6. Metal Injection Moulding

Metal injection moulding (MIM) has established itself as an important alternative for the manufacturing of high-speed steel (HSS) [93, 94]. One of the main advantages of the MIM is the freedom offered regarding component shape and size. However, the use of large amounts of polymer (35 to 40 vol.%) causes large stresses during debinding and limits the possible component size [95].

The vacuum cast M2 HSS exhibited significantly refined as-cast microstructure, regarding the size and morphology of eutectic carbides and the matrix grain size as well as reduced volume fraction of eutectic constituent, compared to that of the gravity cast one [96].

The refinement of the eutectic carbides and colonies as well as the formation of the more discontinuous and thinner interdendrite network of eutectic carbides and the metal cleanliness were the determining factors that provided enhanced toughness and strength properties of the vacuum cast HSSs compared with that of the gravity cast one.

2.7. Coatings Technology

Another efficient way to improve hardness and wear resistance is production of various coatings on a HSS substrate [97–106]. The optimisation of some microstructural parameters or even the design of the tailored microstructure may lead to a significantly enhanced wear resistance of HSSs, and therefore, a longer tool life. For this reason, some attempts have been made to investigate the effect of certain microstructural characteristics on a wear response of the HSSs manufactured by different routes.

Fig. 12. Results of disc wear in the wear test with the alumina ball for both coated and uncoated AISI D2 discs, where typical wear track for coated steel is presented as well [107]

It is an established fact that in most applications, coated cutting tools exhibit superior performance as compared to uncoated tools in machining operations (Fig. 12) [107]. Owing to the enhanced wear-resistance, self-lubricating properties, high thermal stability, and lower coefficient of friction, researchers have been drawn to this area in an on-going quest to develop and evaluate novel coating materials and configurations [108].

Kalss *et al.* [109] found harder and more brittle TiCN coating to be better than TiAl-based hard coatings by a factor of two in terms of abrasion resistance. Same work reported AlCrN coating to be even better (by a factor of 3–5) in comparison to TiAl-based coatings [110].

Santos *et al.* [111] employed MoS_2-TiAlN multi-layer-coated HSS twist drills for machining GH 190 cast iron at a maximum rpm of 400. They reported this multi-layer coating had low wear coefficient and further reported relatively better cutting performance in comparison to TiN- and TiAlN-coated tools. Okada *et al.* [112] evaluated the effect of different coatings on carbide tools by measuring temperatures, wear and thermal conductivity for low and high-speed machining. They reported that tool flank wear depended on hardness and oxidizing temperature of the coating material. In another work [113], multi-layer-coated tools exhibited better life as compared to single-layer coatings. Their TiAlN/TiAlVN multi-layer-coated milling tools exhibited twice the tool life against the performance of mono-layered TiAlN tool. They further reported TiAlN/TiAlBN and TiAlN/TiAlTaN coatings performance was bettered by a factor of four as compared to the TiAlN in drilling and turning operations. The reasons for the improved performance of multi-layering are multiple interlayer boundaries that divert the orientation of fractures thus resisting the growth in other parts of the coating [114]. This characteristic is absent in monolayer coatings where fracture growth is imminent.
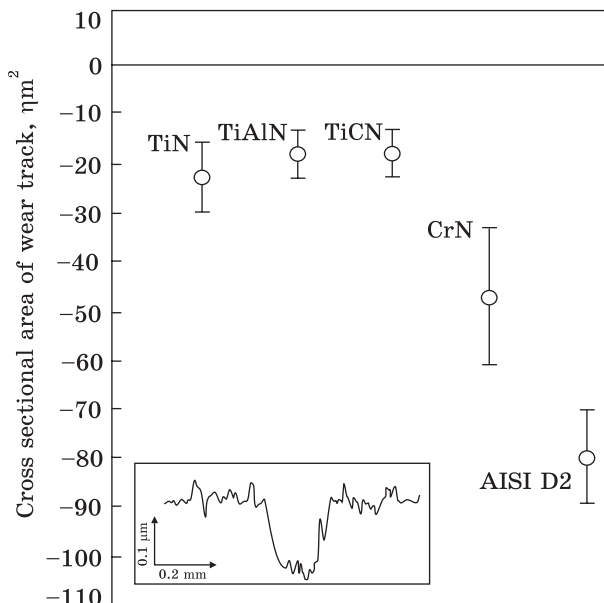
Recently, nanocomposite coatings (nanostructured coatings or super hard coatings) have been developed where a nanocrystalline phase is embedded in a matrix phase of different materials/components (like Ti, Cr, Al, and Si) [115, 116]. One factor that contributes towards an increase in hardness of the coating is the presence of nanoscale constituents due to Hall–Petch strengthening mechanism [117]. Excellent wear resistance coupled with high nanohardness, good heat and chemical resistance, good adhesion, and lower coefficient of friction make them better choice for high-speed machining [118–120].

Research reveals improved machining behaviour of thicker coatings compared to thinner ones [121–130]. These investigations show further that by increasing the film thickness, the tool life is prolonged almost proportionally with the coating thickness augmentation, thus compensating for higher coating cost [121–123].

In study [131], TiAlN, TiN, AlCrN, (TiN + AlCrN) and (AlCrN + TiAlN) coatings were successfully performed on HSS single point cutting tool using PVD (physical vapour deposition) coating technique. The coated tools hardness is higher than uncoated HSS tool. It is because of the nitrides present on the coated tool surface. The coated tools have low wear rate because of the hard ceramic material coating on the surface. The (AlCrN + TiAlN) bilayer coating on HSS tool has better corrosion resistance property because of the protective coating. The mild steel work piece was machined with uncoated and PVD coated HSS tools. The work-piece surface roughness is better when machined with coated tools, since the coating material is acting as lubricant in the dry machining. The protective alumina layer acts as a tribofilm during the metal cutting process.

2.8. Chemical-Heat Treatment

Chemical-heat treatment at a constant temperature promotes multiphase transformations for iron alloys [132]. In this case, phase transformations are stimulated by diffusion change of concentration. The regularities of phase and structural transformations during a diffusion change in carbon composition are considered in the series of works [133–148]. The presence of multiphase regions on the isothermal state diagram is a condition for the implementation of these transformations. It is also necessary that the composition of the alloy, which varies with carbon concentration, pass through these areas [133]. The eutectoid transformation is carried out by isothermal carburization of ferritic alloys of iron with carbide-forming elements. Joint directed growth of austenite and carbide occurs during the carburization of ferritic iron alloys containing carbide-forming α-stabilizers. This promotes the formation of *in situ* austenite-carbide composite (Fig. 13). The joint growth

Fig. 13. Micro-structure of *in situ* austenite–carbide compos-ite (×400) [141]
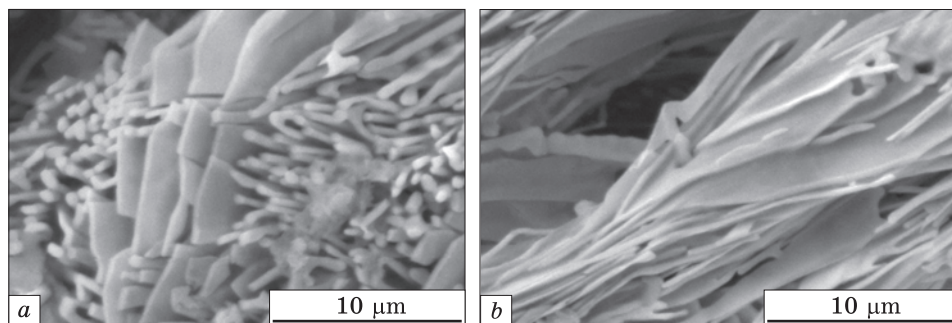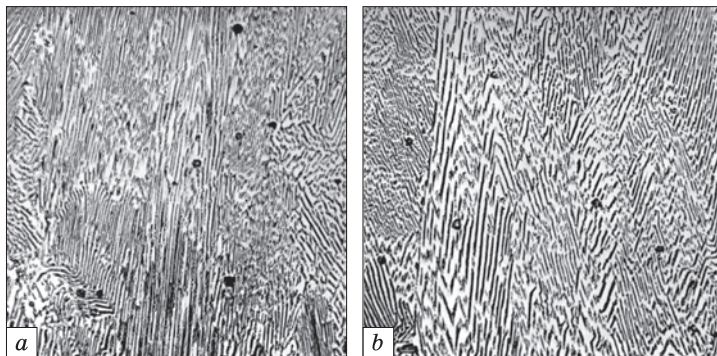

Fig. 14. SEM images of the carbide component of colonial structures after complex chemical and thermal treatment [142]

of these phases is possible if the composition of the ferrite subjected to carburization corresponds to the three-phase equilibrium ferrite–aus-tenite–carbide at the carburizing temperature. The conversion is accom-panied by a redistribution of alloy components between the transforma-tion products. As a result, a regular plate or rod austenitic carbide colonies growth is established [134–136]. The colonies grow mainly di-rected in the direction of carbon flow (Fig. 14). Composite growth of austenite–carbide colonies was observed during carburizing of binary alloys Fe–W, Fe-Mo, Fe–Cr, Fe–V, Fe–Ti [136–142]. The mechanism of cooperative transformation during diffusion change of carbon content is similar to eutectic or eutectoid transformations.

The phase and structural changes of Fe–W–Cr–C and Fe–Mo–Cr–C alloys during the carburization were researched [133, 144, 146, 147]. The four-phase equilibrium $\alpha + \gamma + M_6C + M_{23}C_6$ is invariant in Fe–W–Cr and Fe–Mo–Cr alloys at constant temperature during carburizing. The correspondence of the initial concentration of the matrix alloy to the equilibrium concentration of the α-phase in the four-phase region is the condition for the joint growth of austenite and carbides. The trans-formation of ferrite into three phases, namely, austenite and two car-
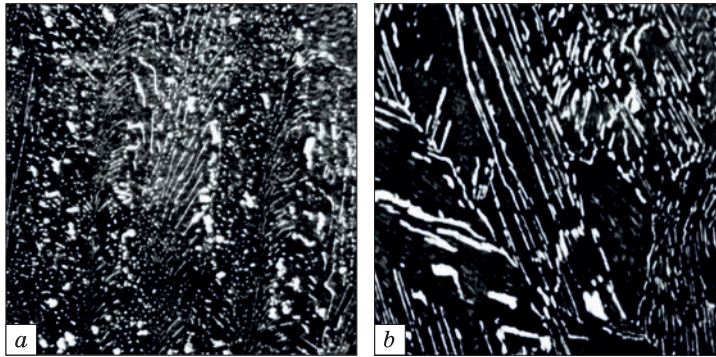
Fig. 15. Microstructure of *in situ* composite based on the (*a*) Fe−W−V−C [147] and (*b*) Fe−V−Cr−C [148] systems (×500)

bides, is possible. The *in situ* composite material, namely, austenitic matrix reinforced with two types of carbides, was formed (Fig. 15). According to x-ray microanalysis data, large plates in both alloys are $M_{23}C_6$ carbide, with thin M_6C carbide fibres located between them [147].

3. Conclusions

High-speed steels (HSSs) have the characteristics of high hardness, toughness, and wear resistance, which have been widely applied. However, the carbides of as-cast HSSs show continuous net-like microstructure. Once formed, microcracks will rapidly spread along net-like carbides, leading to early failure of as-cast HSSs. Therefore, it is necessary to look for ways to improve the microstructure of net-like carbides and then extend the service life of HSSs.

Many methods to improve the structure homogeneity of HSSs, including modification, heat treatment, powder metallurgy, metal injection moulding, coating technologies, chemical-heat treatment *etc*. have been considered.

Mechanical deformation does not destroy completely the carbide networks. In addition, it is a very energy-intensive process.

Material researchers have tried to control the growth of carbide by adding some modified elements in the HSSs. Various alkali metals, alkaline-earth metals, rare-earth metals, misch metal are used as modifying elements for HSSs. it will be observed that modification cannot significantly change the structure of HSSs. The eutectic carbides are still too large to satisfy material requirements. However, the impact toughness and bending strength of HSSs can be improved greatly by modification with misch metal.

It is possible to reduce the size of carbide in HSSs, namely by increasing the cooling rate and implementing the process of spheroidizing processing.

The sub-zero treatment can significantly improve the fatigue characteristics, impact strength, hardness and wear resistance of HSSs. Many works have demonstrated that an appropriate combination of soaking temperatures and tempering treatment, mechanical and tribological properties of HSSs can be significantly improved.

Powder metallurgy and spray forming have been reported as important alternative routes for tool steel production. The ability to promote refined and more uniform microstructures is their main advantage, leading to improved properties and higher isotropy. PM allows to get completely rid of carbide inhomogeneity; however, this is an expensive and difficult-to-control technology.

The results of studying the regularities of phase and structural transformations during diffusion changes in the composition of powders of low-carbon HSS and high-carbon alloy alloyed according to the principle of HSS. Sintering in combination with crystallization and spheroidization makes it possible to obtain a material without carbide inhomogeneity.

Metal injection moulding (MIM) has established itself as an important alternative for the manufacturing of HSSs. One of the main advantages of the MIM is the freedom offered regarding component shape and size. Another efficient way to improve hardness and wear resistance is production of various coatings on a HSS substrate. It is an established fact that in most applications, coated cutting tools exhibit superior performance as compared to uncoated tools in machining operations.

Thermochemical treatment at a constant temperature promotes multiphase transformations for iron alloys. The mechanism of cooperative transformation during diffusion change is similar to eutectic or eutectoid transformations. Joint directed growth of austenite and carbide occurs during the carburization of ferritic iron alloys containing carbide-forming α-stabilizers. This promotes the formation of *in situ* austenite–carbide composite. The influence of additional doping on the structure and properties of composite materials of the eutectic type of binary systems, as well as the features of the structure formation of ternary colonies in the composite are considered.

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МЕТОДИ ПОЛІПШЕННЯ СТРУКТУРИ
ТА ВЛАСТИВОСТЕЙ ШВИДКОРІЗАЛЬНИХ КРИЦЬ

Оглянуто роботи з технологій виробництва швидкорізальних криць. Розглянуто різні методи підвищення однорідности структури швидкорізальних криць. Сформульовано сучасні методи контролю структури криць, переваги та недоліки технологій. Досліджено методи модифікування для поліпшення структури швидкорізальних криць із використанням різних лужних металів, лужноземельних металів, рідкісноземельних металів, мішметалів. Розглянуто вплив збільшення швидкости охолодження та впровадження процесу сфероїдизації для поліпшення розмірів карбідів у швидкорізальних крицях. Досліджено кріогенне оброблення задля поліпшення втомних характеристик, ударної в'язкости, твердости та зносостійкости швидкорізальних криць. Порошкова металургія здатна сприяти поліпшенню та більшій однорідності мікроструктури. Це її головна перевага, що приводить до поліпшених властивостей і більш високої ізотропії швидкорізальних криць. Розглянуто закономірності фазових і структурних перетворень через зміну дифузійного складу пресованої порошкової суміші стопів (у яких концентрація леґувальних елементів подібна до стандартної швидкорізальної криці, але відрізняється вмістом Карбону). Показано, що використання технологій литтля під тиском металу та нанесення покриттів є ефективними способами поліпшення твердости та зносостійкости швидкорізальних криць. Показано можливість застосування хеміко-термічного оброблення для поліпшення структури швидкорізальних криць. Дифузійні зміни складу внаслідок хеміко-термічного оброблення уможливили одержання *in situ*-композит з високим рівнем фізико-механічних властивостей. Розглянуто вплив додаткового леґування на структуру та властивості композиційних матеріалів евтектичного типу бінарних систем, а також особливості структуроутворення потрійних колоній у композиті.

Ключові слова: швидкорізальна криця, однорідність структури, модифікування, кріогенне оброблення, порошкова металургія, технології нанесення покриттів, хеміко-термічне оброблення, *in situ*-композит.