Effects of Pulsed Magnetic Field Treatment on Microstructure and Mechanical Properties of M42 High-Speed Steel Cutting Tools (Postprint)

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Abstract

Pulse magnetization treatment was applied to M42 high-speed steel tools to investigate the influence of pulsed magnetic fields on microstructure and properties, and to analyze the mechanism through which pulsed magnetic fields modify microstructure and mechanical properties. Transmission electron microscopy (TEM) and laser confocal microscopy were utilized to examine variations in dislocation configuration, carbide distribution, and microstructure of the high-speed steel before and after pulsed magnetic field impact. The results indicate that following pulsed magnetization treatment, the high-speed steel experiences lattice distortion, precipitation of numerous dispersed carbides within the matrix, refinement of the microstructure, and grain refinement. These microstructural transformations induce changes in mechanical properties, with both Rockwell hardness and microhardness of the material exhibiting significant enhancement; the Rockwell hardness can be increased by up to 2.9 HRC. The strengthening mechanism of high-speed steel under pulsed magnetic field action was analyzed based on dislocation theory; the force exerted by the magnetic field on dislocations is sufficient to overcome the resistance arising from dislocation line tension and the crystal lattice, thereby enabling dislocations to multiply and slip via the Orowan mechanism, leading to increased dislocation density.

Full Text

Influence of Pulsed Magnetic Treatment on Microstructures and Mechanical Properties of M42 High Speed Steel Tool

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Abstract

Magnetic treatment of tools is a novel method to increase tool life in which the tool is magnetized before cutting or the cutting is performed in a magnetic field. The method has many attractive features, such as short treatment time and no pollution. However, this approach has not been widely applied yet, since the mechanism of magnetic treatment of tools is not clear and treatment results are affected by many factors. Therefore, it is important to study the mechanism of magnetic treatment of tools. This work aims to study the influence of pulsed magnetic treatment on microstructures and mechanical properties of M42 (W2Mo9Cr4VCo8) high speed steel, which is a typical tool material that contains high amounts of cobalt, enabling it to exhibit stronger magnetism during pulsed magnetic treatment. Changes in dislocation configuration, carbide distribution, and microstructure before and after magnetic treatment were characterized by TEM and laser scanning confocal microscopy. Moreover, Rockwell hardness and micro-hardness were measured to quantitatively investigate the influence of magnetic treatment on mechanical properties. Results showed that after pulsed magnetic treatment, the lattice of the material was distorted, carbides were precipitated, and the microstructure and crystalline grain were refined. These microstructural changes led to significant increases in Rockwell hardness and micro-hardness, with the maximum increase in Rockwell hardness reaching 2.9 HRC. Ultimately, the strengthening mechanisms of high speed steel were analyzed based on dislocation theory. It was shown that the force acting on dislocations due to magnetic treatment could overcome the centripetal restoring force and the Peierls stress, enabling dislocations to proliferate via the Orowan mechanism and increasing dislocation density. The dislocation configuration determined from TEM micrographs was in good agreement with the discussion of dislocation mechanisms.

Keywords: pulsed magnetic treatment, high speed steel, microstructure evolution, dislocation strengthening

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1. Introduction

Magnetic treatment of cutting tools is a recently developed method for tool strengthening that reduces tool wear and extends tool life by magnetizing tools before cutting or performing cutting in a magnetic field. This new approach offers high application value due to its short treatment time, pollution-free process, and ability to be completed at room temperature. Magnetic treatment can be categorized into three types based on magnetization current: DC magnetization, AC magnetization, and pulsed magnetization. Compared with DC and AC magnetization, pulsed magnetization can achieve higher magnetic field strengths more conveniently. During pulsed magnetic field impact, eddy currents continuously appear inside the material, and the interaction between these currents and the magnetic field generates Lorentz forces, creating magnetic pressure within the material [1] that can more substantially alter mechanical properties. Studies [2-4] have confirmed that appropriate magnetic treatment can effectively improve tool life. However, this method has not been widely adopted due to unclear mechanisms of property alteration and numerous factors affecting treatment outcomes.

The mechanisms by which magnetic treatment increases tool life can be broadly divided into two categories [5]. The first involves potential changes in cutting mechanisms. Some research [6] suggests that during magnetic field-assisted cutting, the combination of magnetic force and cutting force can alter the shear angle, thereby affecting chip formation mechanisms. Other studies [7-10] propose that during friction and wear processes, magnetic fields can enhance carbon layer transfer and oxidation rates on worn surfaces, changing wear patterns of tools or workpieces. Additionally, research [11] has found that magnetic field-assisted machining can improve surface roughness and increase material removal rates. The second category involves changes in material mechanical properties after magnetic treatment. Research in this area is still in its early stages. Some studies [12-14] suggest that magnetic treatment can reduce residual stress, while others [15,16] indicate it can decrease material wear rates. Additional perspectives [17,18] propose that magnetic treatment can improve material fatigue life. However, detailed and fundamental mechanistic explanations for these experimental phenomena have not yet been reported.

This work investigates M42 (W2Mo9Cr4VCo8) high speed steel using a self-designed pulsed magnetic treatment experimental platform. M42 high speed steel is a widely used cobalt-containing super-hard high speed steel with excellent comprehensive properties. Its high cobalt content enables it to exhibit strong magnetism during magnetic treatment. Microstructural changes such as dislocation configuration and carbide distribution before and after pulsed magnetic field impact were analyzed using transmission electron microscopy and laser confocal microscopy. The effects of pulsed magnetic treatment on mechanical properties were examined by measuring changes in Rockwell hardness and micro-hardness. Finally, the transformation of microstructure and mechanical properties of high speed steel after pulsed magnetic strengthening treatment was analyzed based on dislocation theory.

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2. Experimental Methods

The experimental materials consisted of heat-treated M42 high speed steel plate and fully annealed M42 high speed steel rod, with chemical composition (mass fraction, %) of: C 1.08, W 1.5, Mo 9.5, Cr 3.95, V 1.15, Co 8.0, Si 0.2-0.3, Mn 0.2-0.3, Fe balance. Plate samples were cut into 10 mm × 10 mm × 3 mm blocks using wire electrical discharge machining. Surfaces were sequentially ground with water sandpaper, mechanically polished to a scratch-free finish, ultrasonically cleaned in absolute ethanol, and dried. To minimize the influence of martensite on dislocation configuration observation, fully annealed M42 high speed steel rod was used to prepare TEM samples. Samples were first cut into 0.3 mm thick slices, then mechanically ground and polished to 100 m thickness. The samples were divided into two groups: one group received pulsed magnetic treatment while the other served as a control group. All TEM samples were finally thinned using a GATAN-691 ion mill.

Magnetic treatment experiments were conducted on a self-designed pulsed magnetic treatment platform, schematically shown in [Figure 1: see original paper]. The platform consists primarily of a pulsed power supply, magnetic field generation system, and cooling circulation system. The power supply can generate three current waveforms: sine wave, unidirectional square wave, and alternating square wave, with continuously adjustable frequency from 5-200 Hz. The magnetic field generation system comprises a movable iron core, fixed iron core, coil, and adjustment handle. Samples are placed in the air gap between the movable and fixed iron cores, with gap spacing adjustable via the handle to produce continuously adjustable pulsed magnetic fields from 0-1.7 T. After calibration with a Gauss meter, the system was found to produce stable, continuous, high-intensity pulsed magnetic fields when using unidirectional square wave current at low frequencies. The pulsed magnetic treatment parameters used were: unidirectional square wave current at 10 Hz frequency, 3 mm fixed air gap spacing, 2 min treatment time, and magnetic field intensity ranging from 20-1500 mT.

A Tecnai G2 F20 field emission transmission electron microscope (TEM) was used to observe changes in dislocation configuration before and after magnetic treatment, and high-resolution TEM (HRTEM) was employed to observe atomic structure. Metallographic etching of pre-ground and polished samples was completed using two etchants: first, 4% nitric acid alcohol solution (volume fraction) to reveal martensite phase and carbides, followed by picric acid mixture (5-8 g picric acid + 8-12 mL detergent + 100 mL water) to reveal grain boundaries. Samples were then blow-dried and examined using a KEYENCE VK-X100 laser confocal microscope to observe carbide distribution, morphology, and microstructure. The pulsed magnetic treatment parameters for these observations were 10 Hz frequency, 2 min treatment time, and 1500 mT magnetic field intensity.

Rockwell hardness of samples before and after pulsed magnetic treatment at various magnetic field intensities was measured using an HR-150A Rockwell hardness tester. For each treatment parameter, three samples were tested, with five measurements taken on each sample before and after treatment, and results averaged. Micro-hardness was measured using an FM-300 micro-hardness tester with a load of 0.98 N and dwell time of 15 s.

2.1 Effect of Pulsed Magnetic Field Impact on Dislocation Configuration

TEM images of dislocation configuration in M42 high speed steel before and after pulsed magnetic field impact are shown in [Figure 2: see original paper]. Compared with untreated samples, the magnetically treated samples exhibit significantly increased dislocation density, with the formation of dislocation tangles and dislocation cell structures. M42 high speed steel is a ferromagnetic material with spontaneous magnetization and domain structure. Inside ferromagnets, the material divides into numerous spontaneous magnetization regions (magnetic domains) with essentially uniform size and orientation, as shown in [Figure 3a: see original paper]. For different domains, the directions of spontaneous magnetization intensity vary. When ferromagnetic material is placed in a magnetic field, domain rotation or domain wall displacement occurs until alignment with the external magnetic field direction is achieved, as shown in [Figure 3b: see original paper]. This process changes the equilibrium distance between atoms. However, due to magnetocrystalline anisotropy in ferromagnetic materials, the change in magnetization intensity with magnetic field varies by direction. In other words, certain directions are easily magnetized (easy axes) while others are not (hard axes). For example, the easy magnetization direction for Fe single crystal is <100>, while the hard direction is <111> [19]. Therefore, changes in equilibrium atomic distance caused by the external magnetic field are lattice-direction dependent, meaning the distance change along easy axes differs from that along hard axes, resulting in lattice distortion, as shown in [Figure 4: see original paper].

During this process, the primary role of the magnetic field is to provide the driving force for lattice distortion. Under continuous pulsed magnetic field impact, the equilibrium state of the material’ s internal lattice is repeatedly disrupted, generating new lattice defects—dislocations. From an energy perspective, magnetic fields can reduce dislocation nucleation energy, increase dislocation mobility, and accelerate residual stress release through enhanced dislocation motion [20]. Consequently, under pulsed magnetic field action, dislocations in the crystal continuously generate, multiply, slip, and climb, forming high-density dislocation cells and thereby increasing dislocation density.

2.2 Effect of Pulsed Magnetic Field on Microstructure

Carbide distribution morphologies in M42 high speed steel before and after pulsed magnetic treatment are shown in [Figure 5: see original paper]. Compared with untreated samples, magnetically treated high speed steel shows significantly increased carbide content. High-magnification carbide morphologies before and after treatment are shown in [Figure 6: see original paper]. Two types of carbide changes are observed after pulsed magnetic treatment: first, precipitation of new fine carbides in areas previously lacking carbides; second, fragmentation of some existing blocky carbides into finer particles. During magnetization, the spin moments of atoms in the material tend to align in the same direction, altering the equilibrium distance between crystal lattice points and causing lattice distortion. This leads to smaller magnetostrictive deformation of austenite. Under continuous pulsed magnetic field impact, the material undergoes repeated lattice distortion and austenite experiences continuous small deformations. Deformation pressure can significantly reduce carbon solubility in austenite [21], causing massive precipitation of dispersed carbides from the austenite matrix. Simultaneously, as dislocations continuously move and encounter carbides, they can shear through carbides, causing morphological changes or fragmentation. Both newly precipitated and fragmented dispersed carbides can strengthen the martensite matrix and enhance wear resistance, representing another reason why pulsed magnetic treatment can increase tool life.

Microstructures of M42 high speed steel before and after pulsed magnetic treatment are shown in [Figure 7: see original paper]. After pulsed magnetic field impact, the microstructure becomes noticeably finer and denser, likely due to transformation of retained austenite to martensite. The external magnetic field causes magnetostriction in the metallic material, resulting in isotropic expansion of austenite and reducing the activation energy for its transformation to martensite. Thus, the energy generated during domain rotation and domain wall displacement may induce retained austenite transformation to martensite [22,23]. Additionally, original large grains become partially subdivided and refined after magnetic treatment because newly precipitated black acicular bainite can partition original austenite grains, refining austenite grain size and martensite packet or lath dimensions. Therefore, grain refinement after pulsed magnetic field impact treatment further increases material strength and toughness.

2.3 Effect of Pulsed Magnetic Treatment on Hardness

The effect of pulsed magnetic treatment on Rockwell hardness of M42 high speed steel is shown in [Figure 8: see original paper]. Rockwell hardness increases significantly after treatment, with a maximum increase of 2.9 HRC. Generally, higher magnetic field intensity produces greater hardness increases because the magnetic field provides the driving force for dislocation motion during pulsed magnetic impact. Stronger magnetic driving forces more readily cause dislocation multiplication and slip, forming high-density dislocation cells within the material and significantly increasing hardness.

Micro-hardness measurement results for M42 high speed steel (annealed state) before and after pulsed magnetic treatment are shown in [Figure 9: see original paper]. Micro-hardness also increases significantly after treatment. All test samples were obtained from the same plate, but due to variations in microstructure and heat treatment degree at different plate locations, the Rockwell hardness of samples before magnetic treatment shows some differences. Additionally, different microstructures on sample surfaces have varying resistance to dislocation motion due to differences in crystal lattice, dislocation network nodes, grain boundaries, and carbides. Consequently, dislocation motion under magnetic driving force varies among samples, leading to different hardness increase magnitudes.

2.4 Effect of Pulsed Magnetic Treatment on Surface Temperature

When analyzing the mechanism of pulsed magnetic treatment effects on high speed steel microstructure and properties, temperature changes during treatment must be considered. [Figure 10: see original paper] shows the temperature variation of a sample surface measured with a temperature sensor attached to the sample during 1 hour of pulsed magnetic treatment. The sample surface temperature increased by approximately 5 °C during the 1-hour treatment, which is insufficient to cause changes in material microstructure and mechanical properties. Heat generation during magnetic treatment primarily comes from two sources: first, the coil generates substantial heat when pulsed current passes through it, but this heat is essentially removed by the experimental platform' s cooling water circulation system, so the iron core temperature remains essentially unchanged; second, eddy current effects in the sample during pulsed magnetic treatment also generate some heat, but because the power supply frequency used in this experiment is very low, the heat generated by eddy current effects is minimal.

2.5 Analysis of Dislocation Motion Mechanism

The mechanism by which pulsed magnetic field impact alters material mechanical properties involves continuous lattice distortion within the material, increased dislocation density, reduced carbon solubility in austenite, decreased martensite activation energy, and increased martensite nucleation rate. These effects lead to massive precipitation of dispersed carbides in the matrix after magnetization, significantly finer microstructure, and ultimately transformed mechanical properties—namely increased Rockwell hardness and micro-hardness. Thus, pulsed magnetic strengthening of high speed steel results from combined strengthening mechanisms including dislocation strengthening and dispersion strengthening. The root cause of this series of strengthening effects lies in lattice distortion under magnetic fields that subjects dislocations to forces, causing their multiplication, slip, and climb. Therefore, analysis of forces on dislocations, resistance, and multiplication/slip mechanisms under magnetic fields is necessary.

Analysis of forces on dislocations in magnetic fields is shown in [Figure 11: see original paper]. The force τ acting on a dislocation of unit length L in a magnetic field can be calculated by [24]:

$$\tau = \frac{m_0 M_s H \sin\theta}{L}$$

where m_0 is the vacuum permeability (4π$×10^{-7}$ T•m/A), M is the saturation magnetization, H is the magnetic field intensity, and   is the angle between the magnetization direction and magnetic field direction.

To activate dislocation sources, the driving force from the magnetic field acting on dislocations must overcome resistance caused by dislocation line tension. The critical driving force τc required to activate a dislocation line of unit length L can be calculated by [25]:

$$\tau_c = \frac{Gb}{2L}$$

where G is the shear modulus and b is the magnitude of the Burgers vector.

According to dislocation theory, dislocation motion driven by magnetic fields must also overcome resistance from the crystal lattice. The Peierls-Nabarro (P-N) force σc is the maximum resistance from the crystal lattice to dislocation motion and can be calculated by [25]:

$$\sigma_c = \frac{2G}{1-\nu} \exp\left(-\frac{2\pi d}{b(1-\nu)}\right)$$

where   is Poisson' s ratio and d is the interplanar spacing.

For Fe-C alloys: M = 1.7$×10^{6}$ A/m, G = 7.94$×10^{4}$ MPa, b = 24.8$×10^{-11}$ m,   = 0.25-0.33, d = 3.51$×10^{-10}$ m. At a magnetic field intensity of 1500 mT, the magnetic force acting on dislocations calculated from equations (1)-(3) is 2.5 MPa, while the resistance caused by dislocation line tension is only 20 Pa, and the maximum resistance to dislocation motion (P-N force) is only 1.5 MPa. These results demonstrate that the magnetic force acting on dislocations is sufficient to overcome both the resistance from dislocation line tension and the maximum lattice resistance (P-N force), establishing the prerequisite condition for pulsed magnetic treatment to activate dislocation sources in high speed steel. However, dislocation motion in practice is also affected by many factors such as long-range elastic interactions, jog formation from intersection with forest dislocations, and blocking from converging dislocations. Theoretical estimation of these resistances remains challenging. Nevertheless, the TEM experimental results shown in [Figure 2: see original paper] demonstrate that both dislocation density and morphology changed after pulsed magnetic treatment, consistent with experimental results from in-situ TEM observations by Li Hongqi et al. [26]. This analysis confirms that after pulsed magnetic treatment of M42 high speed steel, dislocation sources are activated, producing dislocation multiplication, slip, and other dislocation motions.

Analysis of dislocation motion mechanisms under pulsed magnetic fields is shown in [Figure 12: see original paper]. During pulsed magnetic treatment, dislocation lines begin moving forward under the combined action of magnetic force τ and critical stress τc (FIG. 12a). During this process, dislocations encounter newly precipitated carbide particles. When carbide particle strength is sufficient to resist local stress from dislocations without shearing or fracturing, dislocation lines can only bypass the particles, become bent, and continue moving forward, leaving a dislocation loop around the carbide particles. Typical loop-shaped dislocation morphology around carbide particles can be observed in FIG. 12b. Therefore, dislocation strengthening in high speed steel under pulsed magnetic fields manifests as Orowan strengthening.

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3. Conclusions

1. After pulsed magnetic treatment of M42 high speed steel, dislocations in the crystal continuously generate, multiply, slip, and climb, forming high-density dislocation cells that increase dislocation density. Massive precipitation of dispersed carbides occurs in the matrix, the microstructure becomes finer and denser, and grains are refined.
2. Both Rockwell hardness and micro-hardness of high speed steel increase significantly after pulsed magnetic treatment. Under certain treatment conditions, Rockwell hardness can increase by 2.9 HRC.
3. Strengthening of high speed steel mechanical properties by pulsed magnetic treatment results from combined strengthening mechanisms including dislocation strengthening and dispersion strengthening. Under pulsed magnetic fields, dislocations in high speed steel can overcome resistance from dislocation line tension and lattice resistance, multiplying, slipping, and climbing via the Orowan mechanism.

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