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

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Abstract

Pulse magnetic treatment was performed on M42 high-speed steel cutting tools to investigate the effects of pulsed magnetic fields on material microstructure and properties, analyzing the mechanism through which pulsed magnetic fields modify microstructure and mechanical properties. Transmission electron microscopy (TEM) and laser confocal microscopy were employed to analyze changes in dislocation configuration, carbide distribution, and microstructure of the high-speed steel material before and after pulsed magnetic field impact. Research indicates that following pulse magnetic treatment, the high-speed steel material experiences lattice distortion, precipitation of numerous dispersed carbides within the matrix, microstructural refinement and densification, and grain refinement. These microstructural changes result in modified mechanical properties, with both Rockwell hardness and microhardness exhibiting significant enhancement; the Rockwell hardness can be increased by up to 2.9 HRC. The strengthening mechanism of high-speed steel materials under pulsed magnetic fields was analyzed based on dislocation theory. The force exerted by the magnetic field on dislocations is sufficient to overcome resistances arising from dislocation line tension and the crystal lattice, thereby enabling dislocation multiplication and slip via the Orowan mechanism and consequently increasing the material' s dislocation density.

Full Text

Preamble

ACTA METALLURGICA SINICA

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 represents a novel method for enhancing tool life, wherein tools are magnetized prior to cutting or machining is performed within a magnetic field. This approach offers numerous attractive features, including short treatment duration, environmental cleanliness, and the ability to be conducted at room temperature, thus holding significant potential for industrial application. Magnetic treatment modalities can be categorized into three types based on magnetizing current: direct current magnetization, alternating current magnetization, and pulsed magnetization. Compared with DC and AC magnetization, pulsed magnetization facilitates attainment of higher magnetic field intensities. Moreover, during continuous pulsed magnetic field impact, eddy currents are repeatedly generated within the material, and the interaction between these currents and the magnetic field produces Lorentz forces, thereby generating magnetic pressure within the material [?] and enabling more substantial modification of mechanical properties. Research has confirmed [?] that appropriate magnetic treatment can effectively improve tool life. However, this method has not yet achieved widespread adoption due to unclear mechanisms underlying the modification of material properties and the numerous factors influencing treatment efficacy.

The mechanisms by which magnetic treatment enhances tool life can be broadly classified into two categories [?]. The first involves potential alterations to the cutting mechanism itself. For instance, some studies [?] suggest that during magnetic-field-assisted cutting, the combination of magnetic forces and cutting forces can modify the shear angle, thereby affecting chip formation mechanisms. Other research [?] proposes that magnetic fields can enhance carbon atomic layer transfer and oxidation rates at wear surfaces during friction and wear processes, consequently changing wear modes of tools or workpieces. Additionally, some investigations [?] have found that magnetic-field-assisted machining can improve surface roughness and increase material removal rates. The second category concerns changes in material mechanical properties following magnetic treatment. Research in this area remains in its infancy, with some studies [?] suggesting that magnetic treatment can reduce residual stresses, others [?, ?] indicating decreased wear rates, and some [?, ?] demonstrating improved 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 tool material with excellent comprehensive properties. Its high cobalt content enables strong magnetic

response during pulsed magnetic treatment. Through transmission electron microscopy (TEM) and laser scanning confocal microscopy, we analyze changes in dislocation configuration, carbide distribution, and other microstructural features before and after pulsed magnetic field impact. By measuring variations in Rockwell hardness and microhardness, we assess the influence of pulsed magnetic treatment on mechanical properties. Based on dislocation theory, we analyze the mechanisms underlying microstructural evolution and mechanical property changes in high-speed steel following pulsed magnetic strengthening treatment.

Experimental Materials and 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. Plate specimens were cut into 10 mm × 10 mm × 3 mm blocks using wire electrical discharge machining. Surfaces were progressively ground with waterproof abrasive paper, mechanically polished to a scratch-free finish, ultrasonically cleaned in anhydrous ethanol, and dried for subsequent use. To minimize martensite interference in dislocation configuration observation, fully annealed M42 high-speed steel rod was used for TEM sample preparation. Specimens were first cut into 0.3 mm thick slices, then mechanically ground and polished to 100 m thickness. Samples were divided into two groups: one subjected to pulsed magnetic treatment and the other serving as an untreated control. All TEM specimens were finally thinned using a GATAN-691 ion miller.

Magnetic treatment experiments were conducted on a self-designed pulsed magnetic treatment platform, schematically illustrated in [Figure 1: see original paper]. The platform primarily comprises a pulsed power supply, magnetic field generation system, and cooling circulation system. The pulsed power supply can generate three current waveforms: sinusoidal, unidirectional square, and alternating square waves, with continuously adjustable frequency from 5 to 200 Hz. The magnetic field generation system consists of 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 to 1.7 T. The cooling circulation system comprises a cooling water tank and pump. Calibration measurements using a gaussmeter revealed that the system generates stable, continuous, high-intensity pulsed magnetic fields when using unidirectional square wave current at low frequencies. The pulsed magnetic treatment parameters employed in this study were: unidirectional square wave current at 10 Hz frequency, fixed air gap spacing of 3 mm, treatment duration of 2 min, and magnetic field intensity ranging from 20 to 1500 mT.

A Tecnai G F20 field-emission transmission electron microscope was used to observe changes in dislocation configuration before and after magnetic treatment. Metallographic etching of pre-ground and polished specimens was accomplished 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. After blow-drying, a KEYENCE VK-X100 laser scanning confocal microscope was employed to observe microstructural features including carbide distribution, morphology, and metallographic structure. The pulsed magnetic treatment parameters for these observations were 10 Hz frequency, 2 min duration, and 1500 mT field intensity.

Rockwell hardness of specimens before and after pulsed magnetic treatment at various field intensities was measured using a Rockwell hardness tester. For each treatment parameter, three specimens were tested, with five measurements taken per specimen before and after treatment, and results averaged. Microhardness was measured using an FM-300 microhardness tester under a load of 0.98 N with a dwell time of 15 s.

Results and Discussion

2.1 Influence of Pulsed Magnetic Field on Dislocation Configuration

[Figure 2: see original paper] presents TEM images of dislocation configurations in M42 high-speed steel before and after pulsed magnetic field impact. Compared with the untreated specimen, the magnetically treated sample exhibits significantly increased dislocation density, with the formation of dislocation tangles and dislocation cell structures. M42 high-speed steel is a ferromagnetic material characterized by spontaneous magnetization and domain structure. The material interior is divided into numerous spontaneous magnetization regions (magnetic domains) of relatively uniform size and orientation, as schematically shown in [Figure 3a: see original paper]. Different domains possess different spontaneous magnetization directions. When a ferromagnetic material is placed in a magnetic field, magnetic domains undergo rotation or domain wall displacement to align with the external field direction, as illustrated in [Figure 3b: see original paper]. This process alters the equilibrium distance between atoms. However, due to magnetocrystalline anisotropy in ferromagnetic materials, magnetization intensity varies with field direction—certain directions are easily magnetized (easy axes), while others are difficult to magnetize (hard axes). For example, the easy magnetization direction for Fe single crystal is <100>, while the hard direction is <111> [**?**]. Consequently, the change in interatomic distance induced by the external magnetic field depends on crystallographic orientation; the distance change along easy axes differs from that along hard axes, resulting in lattice distortion, as depicted in [Figure 4: see original paper]. In this process, the magnetic field primarily provides 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—namely, dislocations. From an energy perspective, magnetic fields can reduce dislocation nucleation energy, increase dislocation mobility, and accelerate residual stress release within the material through enhanced dislocation motion [**?**]. Therefore, under pulsed magnetic field action, dislocations continuously multiply, slip, and climb within the crystal, forming high-density dislocation cells and thereby increasing the material’ s dislocation density.

2.2 Influence of Pulsed Magnetic Field on Microstructure

[Figure 5: see original paper] shows the morphologies of carbide distribution in M42 high-speed steel before and after pulsed magnetic treatment. Compared with the untreated specimen, the magnetically treated material exhibits significantly increased carbide content. [Figure 6: see original paper] presents high-magnification views of carbide morphologies before and after treatment, revealing two distinct changes: (1) precipitation of new fine carbides in previously carbide-free regions, and (2) fragmentation of some existing blocky carbides into smaller particles. During magnetization, the alignment of atomic magnetic moments within the material alters the equilibrium distance between crystal lattice points, causing lattice distortion and inducing small magnetostrictive deformation in austenite. Under continuous pulsed magnetic field impact, repeated lattice distortion occurs, generating small deformations in austenite. This deformation pressure can significantly reduce carbon solubility in austenite [**?**], resulting in extensive precipitation of dispersed carbides from the austenite matrix. Simultaneously, moving dislocations can shear through carbides when encountered, causing morphological changes or fragmentation. Both newly precipitated and fragmented dispersed carbides can strengthen the martensite matrix and enhance wear resistance, representing one mechanism by which pulsed magnetic treatment can increase tool life.

[Figure 7: see original paper] shows high-magnification microstructures before and after pulsed magnetic treatment. The microstructure becomes noticeably finer and more uniform following magnetic field impact, likely due to transformation of retained austenite to martensite. The external magnetic field causes magnetostrictive isotropic expansion of the metallic material, reducing the activation energy for austenite-to-martensite transformation. Consequently, the energy generated during magnetic domain rotation and domain wall displacement may induce transformation of retained austenite to martensite [**?**, **?**]. As indicated by arrows in [Figure 8: see original paper], original large grains become partially subdivided and refined after magnetic treatment. This occurs because newly precipitated black needle-like bainite can partition original austenite grains, refining both austenite grain size and martensite packet or lath dimensions. Therefore, pulsed magnetic field impact treatment results in grain refinement, further increasing material strength.

2.3 Influence of Pulsed Magnetic Treatment on Hardness

[Figure 8: see original paper] illustrates the effect of pulsed magnetic treatment on Rockwell hardness of M42 high-speed steel. The results demonstrate significant hardness enhancement following treatment, with a maximum increase of 2.9 HRC. Generally, higher magnetic field intensity yields greater hardness increments, as the magnetic field provides the driving force for dislocation motion during pulsed impact. Stronger magnetic driving forces more readily facilitate dislocation multiplication and slip, forming high-density dislocation cells within the material and substantially increasing hardness. [Figure 9: see original paper] shows microhardness measurement results for M42 high-speed steel (annealed state) before and after pulsed magnetic treatment, revealing significant microhardness improvement. All specimens were obtained from the same plate; however, due to inevitable variations in microstructure and heat treatment degree across different plate locations, initial Rockwell hardness values exhibit some differences. Furthermore, different surface microstructures present varying resistance to dislocation motion through lattice points, dislocation network nodes, grain boundaries, and carbides. Consequently, dislocation motion behavior varies among specimens under magnetic driving forces, resulting in different hardness enhancement magnitudes.

2.4 Influence of Pulsed Magnetic Treatment on Surface Temperature

When analyzing the mechanisms underlying microstructural and property changes in high-speed steel during pulsed magnetic treatment, temperature variations during processing must be considered. [Figure 10: see original paper] shows the temperature change of a specimen surface during 1 hour of pulsed magnetic treatment, measured using a temperature sensor attached to the surface. The surface temperature increased by approximately 5 °C during the 1-hour treatment period—an insufficient temperature rise to induce microstructural or mechanical property changes. Heat generation during magnetic treatment originates from two sources: (1) Joule heating in the coil during pulsed current passage, which is largely removed by the platform’ s cooling water circulation system, maintaining constant iron core temperature; and (2) eddy current effects in the specimen during pulsed magnetic treatment, which generate some heat. However, due to the very low frequency of the power supply used in this study, heat generated by eddy current effects is minimal.

2.5 Analysis of Dislocation Motion Mechanisms

The mechanism by which pulsed magnetic field impact alters material mechanical properties involves continuous lattice distortion under pulsed magnetic field action, leading to increased dislocation density, reduced carbon solubility in austenite, decreased martensite activation energy, and increased martensite nucleation rate. These effects result in extensive precipitation of dispersed carbides within the matrix, significant microstructural refinement, and ultimately, transformation of mechanical properties—specifically, increased Rockwell hardness and microhardness. Thus, pulsed magnetic strengthening of high-speed steel represents the combined effect of multiple strengthening mechanisms, including dislocation strengthening and dispersion strengthening. The root cause of this series of strengthening effects lies in lattice distortion induced by the magnetic field, which generates forces on dislocations, leading to their multiplication, slip, and climb. Therefore, analysis of forces, resistances, and multiplication/slip mechanisms acting on dislocations under magnetic fields is essential.

The force analysis for dislocations in a magnetic field is illustrated in [Figure 11: see original paper]. The force acting on a dislocation of unit length L in a magnetic field can be calculated by [?]:

$$\tau = -\mu_0 M_s H \cos\theta \qquad (1)$$

where is the vacuum permeability (4 ×10 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 a dislocation source, the driving force from the magnetic field must overcome the resistance caused by dislocation line tension. The critical driving force c required to activate a dislocation line of unit length L can be calculated by [?]:

$$\tau_c = Gb/L \qquad (2)$$

where G is the shear modulus and b is 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 c represents the maximum lattice resistance to dislocation motion and can be calculated by [?]:

$$\sigma_c = \frac{2G}{1-\nu} \exp\left(-\frac{2\pi d}{b(1-\nu)}\right) \qquad (3)$$

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

For Fe-C alloys with M = 1.7×10 A/m, G = 7.94×10 MPa, b = 24.8×10^{11} m, = 0.25-0.33, and d = 3.51×10^{1} m, calculations using equations (1)-(3) yield a magnetic force on dislocations of 2.5 MPa at H = 1500 mT. The resistance from dislocation line tension is only 20 Pa, while the maximum lattice resistance (P-N force) is merely 1.5 MPa. These results indicate that the magnetic force acting on dislocations is sufficient to overcome both the resistance from dislocation line tension and the P-N force, establishing the prerequisite condition for activating dislocation sources in high-speed steel during pulsed magnetic treatment. Although dislocation motion in practice is influenced by many factors—including long-range elastic interactions, jog formation from intersection with forest dislocations, and blocking effects from converging dislocations—accurate theoretical estimation of these resistances remains challenging. However, TEM results shown in [Figure 2: see original paper] demonstrate changes in both dislocation density and morphology after pulsed magnetic treatment, consistent with in situ TEM observations reported by Li et al. [?]. This analysis confirms that dislocation sources are activated in M42 high-speed steel after pulsed magnetic treatment, resulting in dislocation multiplication, slip, and other dislocation motions.

[Figure 12: see original paper] illustrates the dislocation motion mechanism under pulsed magnetic field action. During pulsed magnetic treatment, dislocation lines within the material begin moving forward under the combined action of magnetic force , P-N force c, and critical driving force c ([Figure 12a: see original paper]). During forward motion, dislocations encounter newly precipitated carbide particles. When carbide particle strength is sufficient to resist local stress from dislocations without undergoing shear or fracture, dislocation lines can only bypass the particles, become bent, and continue moving forward, leaving a dislocation loop around the carbide particle. Typical ring-shaped dislocation morphologies around carbide particles are visible in [Figure 12b: see original paper] (indicated by arrows). Therefore, dislocation strengthening in high-speed steel under pulsed magnetic field action manifests as Orowan strengthening.

Conclusions

1. After pulsed magnetic treatment of M42 high-speed steel, continuous multiplication, slip, and climb of dislocations within the crystal form high-density dislocation cells, thereby increasing material dislocation density. Extensive precipitation of dispersed carbides occurs within the matrix, and the microstructure becomes significantly finer with refined grains.
2. Pulsed magnetic treatment substantially increases both Rockwell hardness and microhardness of high-speed steel. Under appropriate treatment conditions, Rockwell hardness can be increased by 2.9 HRC.
3. The strengthening of high-speed steel mechanical properties by pulsed magnetic treatment results from the combined effects of multiple strengthening mechanisms, including dislocation strengthening and dispersion strengthening. Under pulsed magnetic field action, 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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