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Review

Research Progress of Magnetic Field Regulated Mechanical Property of Solid Metal Materials

Yujun Hu [1,2,*], Hongjin Zhao [1,*], Xuede Yu [3], Junwei Li [2], Bing Zhang [1,2] and Taotao Li [4]

1 Faculty of Materials Metallurgy and Chemistry, Jiangxi University of Science and Technology, Ganzhou 341000, China
2 School of Aeronautical Engineering, Jiangxi Teachers College, Yingtan 335000, China
3 China Nerin Engineering Co., Ltd., Nanchang 330031, China
4 School of Materials and Engineering, Jiangsu University of Science and Technology, Zhenjiang 212000, China
* Correspondence: 7120200017@mail.jxust.edu.cn (Y.H.); 9119960101@jxust.edu.cn (H.Z.)

Abstract: During the material preparation process, the magnetic field can act with high intensity energy on the material without contact and affect its microstructure and properties. This non-contact processing method, which can change the microstructure and properties of material without affecting the shape and size of products, has become an important technical means to develop new materials and optimize the properties of materials. It has been widely used in scientific research and industrial production. In recent years, the magnetic field assisted processing of difficult-to-deform materials or improving the performance of complex and precision parts has been rapidly and widely concerned by scholars at home and abroad. This paper reviews the research progress of magnetic field regulating the microstructure, and properties of solid metal materials. The effects of magnetic field-assisted heat treatment, magnetic field assisted stretching, and magnetic field independent treatment on the microstructure and properties of solid metal materials are introduced. The mechanism of the magnetic field effect on the properties of metal materials is summarized, and future research on the magnetic field effect on solid metal has been prospected.

Keywords: magnetic field treatments; solid metal; mechanical properties; microstructure

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1. Introduction

The magnetic field is a kind of non-contact, green, high-energy, multi-effect physical field, which can change the material preparation process conditions of thermodynamics and kinetics and transfer high intensity energy to the atomic scale of matter without contact. Moreover, it directly affects the material's migration, matching, and arrangement of atoms, molecules, ions, or grain. The magnetic field has a great and profound effect on the microstructure and properties of materials [1,2].

Since the 1960s, when scholars found that magnetic field can affect the microstructure and mechanical properties of ferromagnetic materials [3,4], they tried to use the magnetic field to treat non-ferromagnetic materials and also found that it can affect material structure and properties [5,6]. Therefore, magnetic field treatment in material modification has been rapidly and widely concerned and has become an important technical means to develop new materials and optimize material properties.

In recent years, researchers have been using the magnetic field to regulate the structure and properties of different magnetic materials. With the deepening of research, many new magnetic phenomena have been discovered. Utilizing electromagnetic stirring technology, the magnetic field achieved significant advancements that improved the microstructure and characteristics of the metal solidification process. It gradually regulates the direction of the microstructure and properties of the solid metal material development, mainly reflected in magnetic field-assisted metal material heat treatment, assisted plastic deformation, and independently treated metal materials to improve material structure and properties [7–10], which have achieved good results.

2. Magnetic Field Assisted Heat Treatment of Metallic Materials

To eliminate the residual internal stress generated by the high temperature gradient and quick solidification of Ti-6.0Al-4.4V alloy during selective laser melting (SLM) process, as well as to optimize the microstructure and properties, the magnetic field-assisted annealing treatment was performed under a magnetic field induction intensity of 2–10 T magnetic field induction intensity [11,12]. The annealing temperature was 400 °C, and the annealing time was 30 min.

Under the coupling effect of temperature and magnetic field, the α′ phase of martensite was promoted to transform into α + β phase, and the width of α′/α phase was reduced and more refined. Meanwhile, when the magnetic induction intensity is 8 T, the alloy elongation reaches 15.1%, which was increased by 62.4% compared with 9.3% without the magnetic field. The tensile strength of the alloy was slightly increased by 2.8%, as shown in Figure 1. The strength and plasticity of Ti-6.0Al-4.4V alloy are improved synchronously by the magnetic field.

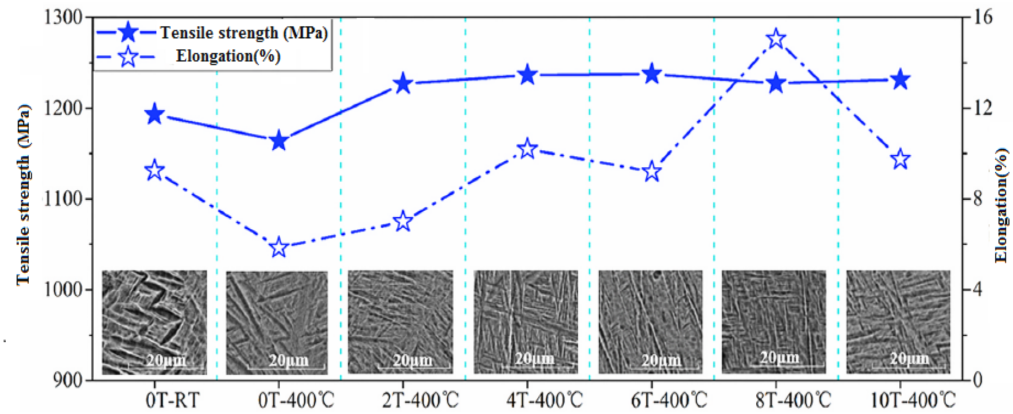

Figure 1. The properties and microstructure of Ti–6Al–4V by heat treatment under the magnetic field. Reprinted with permission from Ref. [11]. Copyright 2021 Elsevier.

To study the influence of magnetic field on the properties of different magnetic metals, high-purity Al, Ni, and Cu samples were firstly stressed, relieving annealing, then subjected to 30% compression deformation, and finally subjected to heat preservation and alternating magnetic field [13]. With the increase of magnetic induction intensity, the microhardness of paramagnetic pure Al and Ni (temperature above Curie point) gradually increased, while the microhardness of ferromagnetic pure Ni (temperature below Curie point) and diamagnetic pure Cu steadily declined. The microhardness of alloys increased by 8.6%, increased by 5.9%, decreased by 6.2%, and decreased by 12.3%, respectively, compared with that without a magnetic field. It found that the microhardness of different magnetic metals is not consistent when the magnetic field assisted heat treatment.

After solid solution, the sample of paramagnetic Al-5%Cu alloy aged at 130 °C, and a pulsed magnetic field was applied [14]. Compared with that without magnetic field after three hours of aging, more Al_2Cu phase was dispersed and precipitated inside the alloy, and the hardness value increased by 30.0% to 115.2 HV.

The paramagnetic AA2219 aluminum alloy was solid solution after forging, and an alternating magnetic field was applied during the subsequent aging process [15]. It was found that the microhardness of the alloy with magnetic field was higher than that without magnetic field at the same aging time. After 8 h of aging, the alloy′s microhardness with magnetic field increased by 10.7% compared with that without magnetic field. The changes of microhardness of the alloy was mainly due to the magnetic field affecting the number and distribution of θ′ phase precipitation.

Diamagnetic beryllium bronze alloy, which had been solid solution treatment, was aged in the constant magnetic field of 0.7 T [16–19], and its microhardness changes are shown in Figure 2. It can be found that the microhardness of beryllium bronze alloy decreases basically (in Figure 2a–c), and the microhardness of Cu-1.6Be alloy decreases by 25.0% at most after magnetic field treatment. However, the microhardness of Cu-1.9Be-0.33Ni alloy increased by 38.0% after the addition of the Ni element (in Figure 2d).

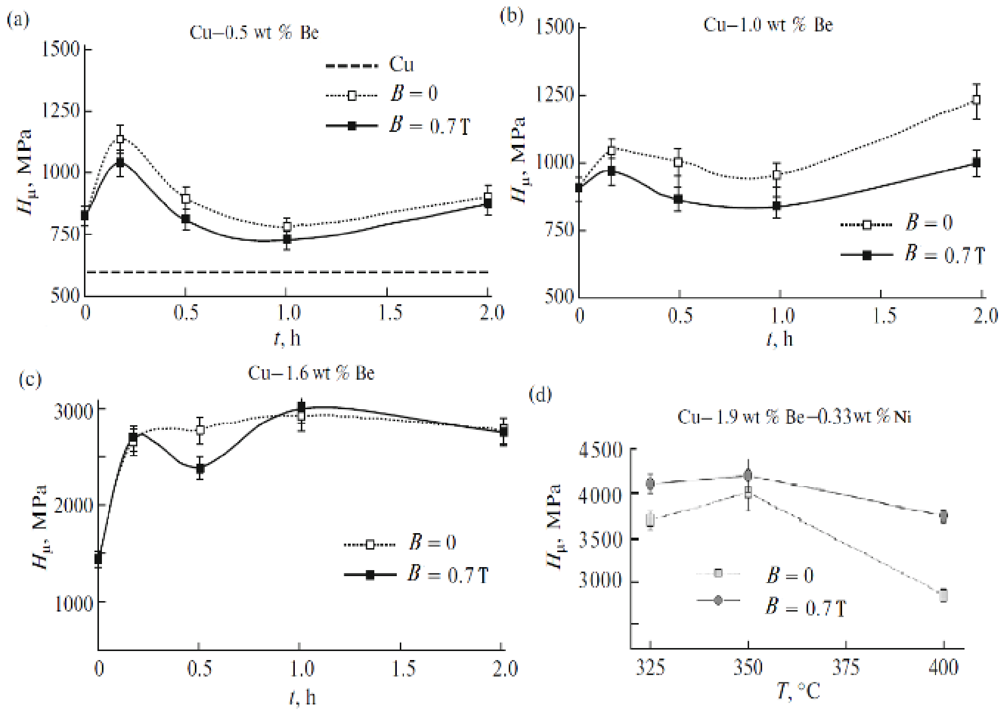

Figure 2. The microhardness of beryllium bronze alloys by aging under magnetic field: (**a**) Cu–0.5 wt % Be; (**b**) Cu–1.0 wt % Be; (**c**) Cu–1.6 wt % Be; (**d**) Cu–1.9 wt % Be-0.33 wt % Ni. Reprinted with permission from Refs. [16,19]. Copyright 2020 Springer Nature.

For this phenomenon, there was a similar situation in magnetic field-assisted aging aluminum alloy. Figure 3 shows the microhardness changes of aluminum alloys with different components under magnetic field-assisted aging [20,21]. It can be seen in Figure 3a that the microhardness of the alloy with magnetic field at the same aging time was higher than that without magnetic field. Meanwhile, Figure 3c,d shows a similar rule to Figure 3a. On the contrary, the hardness of the alloy decreases when the magnetic field assistance applied at the same aging time in Figure 3b.

According to the above research contents [11–21], the changes in microhardness of magnetic field-assisted heat treatment of aluminum and aluminum alloy, beryllium-bronze alloy, and titanium alloy compared with that without magnetic field are sorted into Table 1. It can be seen from Table 1 that the magnetic field can significantly change the hardness of the alloy during metal heat treatment assisted by a magnetic field. In particular, magnetic field-assisted annealing can significantly improve the plasticity of Ti-6.0Al-4.4V alloy prepared by selective laser melting process.

Analyzing the microhardness changes of beryllium bronze alloys No. 7–14 in Table 1 found that the microhardness of beryllium bronze alloys without the addition of Ni element (No. 10 except) decreased with magnetic field-assisted aging. In contrast, the microhardness of alloys containing the Ni element added increases. Analyzing the microhardness changes of aluminum alloys No. 15–18 in Table 1 found that the microhardness of aluminum alloys increased with magnetic field-assisted aging as compared to that without a magnetic field. However, only the microhardness of No. 7 aluminum alloy containing the Fe element decreased. After applying the magnetic field, the microhardness of beryllium bronze alloy containing Ni and aluminum alloy containing Fe showed a different trend from that of other alloys without adding Ni or Fe whether this phenomenon is related to the ferromagnetic Fe and Ni element, and the influence of ferromagnetic elements on the properties of alloys with paramagnetic or diamagnetic base, which is worth further study.

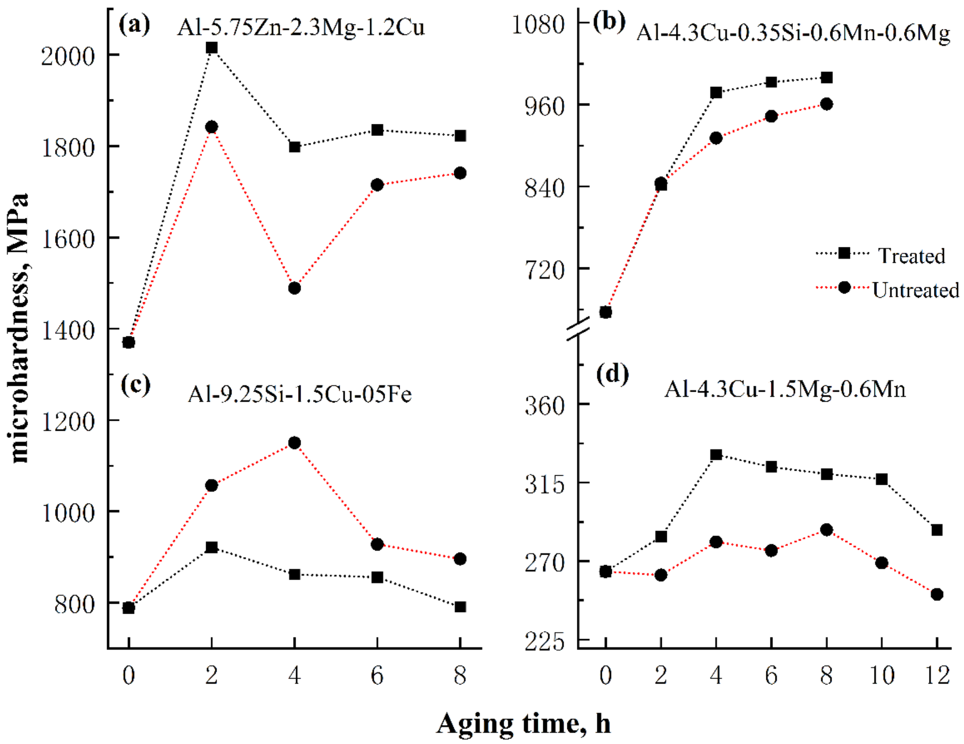

Figure 3. The microhardness of aluminum alloys by aging under magnetic field: (**a**) Al-based alloys with Zn, Mg, and Cu dopants; (**b**) Al-based alloys with Cu, Si, Mn, and Mg dopants; (**c**) Al-based alloys with Si, Cu, and Fe dopants; (**d**) Al-based alloys with Cu, Mg, and Mn dopants. Data from Ref. [20].

Table 1. The properties of metal materials by heat treating under magnetic field.

No.	Alloy Types	Solid Solution Process	Aging Process	Magnetic Field Types or Strength	Microhardness Change	Reference
1	Ti-6.0Al-4.4V	SLM process	400 °C, 30 min	2–10 T	+62.4% (Elongation)	[11,12]
2	High purity Al	Stress relieving + 30% compression deformation	200 °C, 1 h	Alternating magnetic field 0.05, 0.1 T	+8.6%	[13]
3	High purity Ni		500 °C, 1 h		+5.9%	
			300 °C, 1 h		−6.2%	
4	High purity Cu		200 °C, 1 h		−12.3%	
5	Al-5%Cu	515 °C, 10 h, Water cooling	130 °C, 2–3 h	Pulsed magnetic fields Pulsed voltage 180 V Pulse frequency 15 Hz	+30.0%	[14]
6	AA2219 Aluminum alloy	535 °C, 35 min, Water cooling	175 °C, 8 h	Alternating magnetic field 0.5 T	+10.7%	[15]

Table 1. *Cont.*

No.	Alloy Types	Solid Solution Process	Aging Process	Magnetic Field Types or Strength	Microhardness Change	Reference
7	Cu-0.5Be	800 °C, 20 min, Water cooling	300 °C, 10–120 min	Constant magnetic field 0.7 T	−13.0%	[16]
8	Cu-1.0Be				−23.5%	
9	Cu-1.6Be				−25.0%	
10	Cu-2.0Be		350 °C, 10–120 min		+10.0%	[17]
11	Cu-2.0Be-0.4Ni				+25.0%	
12	Cu-2.0Be-1.0Ni				+35.0%	
13	Cu57Be43		350 °C, 1 h		−6.0%	[18]
14	Cu-1.9Be-0.33Ni	800 °C, 30 min, Water cooling	400 °C, 1 h		+38.0%	[19]
15	Al-5.75Zn-2.3Mg-1.2Cu	470 °C, 1 h, Water cooling	140 °C, 2–8h		+21.0%	[20,21]
16	Al-9.25Si-1.5Cu-0.5Fe	535 °C, 2 h, Water cooling	175 °C, 2–8 h		−25.0%	
17	Al-4.3Cu-0.35Si-0.6Mn-0.6Mg	450 °C, 30 min, Water cooling	190 °C, 2–8 h		+8.0%	
18	Al-4.3Cu-1.5Mg-0.6Mn	500 °C, 20 min, Water cooling	190 °C, 2–12 h		+18.0%	
19	Al-4.0Mg-1.2Li	500 °C, 1 h, Water cooling	120 °C, 2–8 h		+11.0%	

3. Magnetic Field Assisted Stretching of Metallic Materials

Cold-rolled state 2024 aluminum alloy in the pulse magnetic field assisted tension [22–24], and the magnetic field accelerated the free radical pair transition from the singlet to triplet state between the dislocation and the obstacle. This reduced the bond energy between the dislocation and the obstacle, improved the dislocation mobility, and increased the dislocation density and refined grains. Thus, the plasticity and strength of the alloy are improved simultaneously. As shown in Figure 4, when the magnetic induction intensity was 1 T, the alloy had better comprehensive mechanical properties. At this time, the elongation was 17%, and the tensile strength was 410 MPa, which was 30.8% and 9.3% higher than those without magnetic fields.

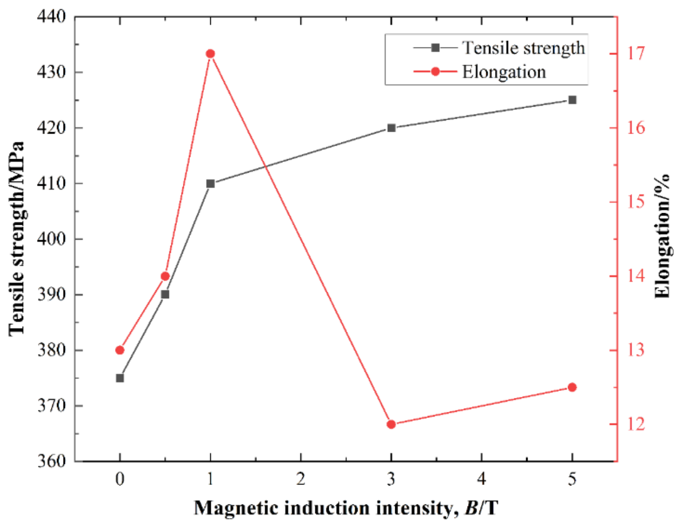

Figure 4. The tensile properties of 2024 aluminum alloy under magnetic field. Data from Ref. [23].

The pulse magnetic field-assisted stretched cold-rolled state 7075 aluminum alloy [c] significantly promoted the dissolution of the minor second phase inside the alloy, weakened the continuity of the precipitated phase at the grain boundary, widened the precipitated zone at the grain boundary, and improved the alloy elongation. As shown in Figure 5, when the magnetic induction intensity was 1 T, the alloy elongation reached the maximum value of 17.3%, which was increased by 3.9% compared to that without the magnetic field, and the tensile strength of the alloy did not decrease at this time.

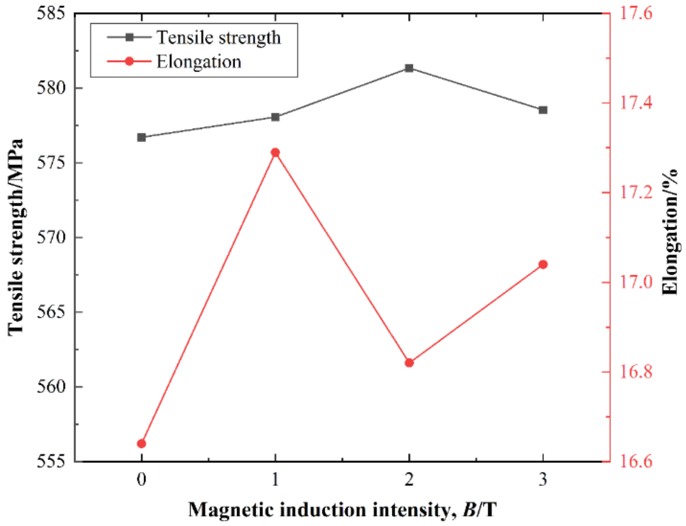

Figure 5. The tensile properties of 7075 aluminum alloy under magnetic field. Data from Ref. [25].

For the pulse magnetic field-assisted stretched cold-rolled state 7075 aluminum alloy [26], the magnetic field promotes dislocation de-pinning, reduces dislocation pile-up, reduces internal residual stress, improves internal stress concentration, and improves the plastic deformation ability of the material. When the magnetic induction strength was 3 T, the alloy's optimal tensile strength and elongation were 587 MPa and 8.3%, which were increased by 3.9% and 10.7%, respectively, compared with those without magnetic field, as shown in Figure 6.

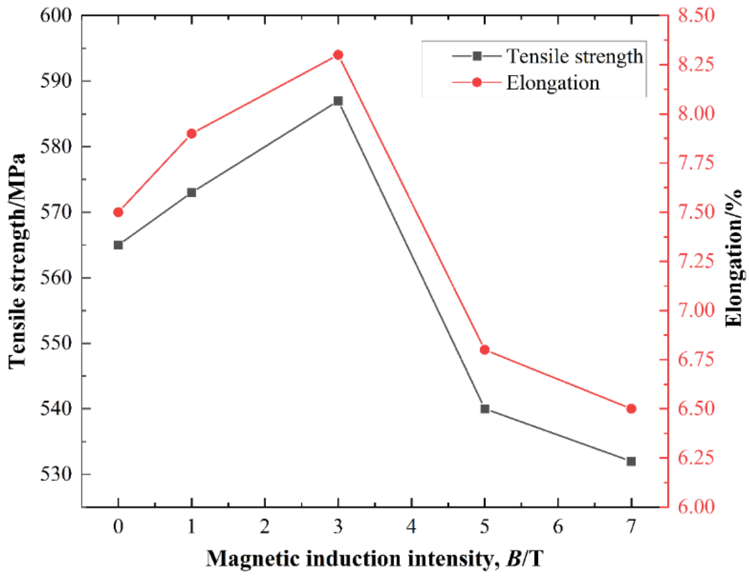

Figure 6. The tensile properties of 7055 aluminum alloy under magnetic field. Data from Ref. [26].

Cold-rolled state Ti-6.2Al-4.1V-2.3Zr titanium alloy assisted stretching in the pulse magnetic field [27,28]. The magnetic field can promote the transformation of β phase to α phase. The preferred orientation of the crystal plane toward the easy slip direction is generated, which improves the plasticity of the alloy, and the dislocation density increases, which increases the strength of the alloy. With the increase of magnetic induction strength, the α phase content and dislocation density of the alloy gradually increase. When the magnetic induction strength is 3 T, the optimal tensile strength is 965 MPa, and the elongation is 12.4%, which are increased by 0.9% and 24%, respectively, compared with those without magnetic field. When the magnetic field induction strength continues to increase to 5 T, the α phase content and dislocation density in the alloy decrease. Thus, the tensile strength and elongation decrease, as shown in Figure 7.

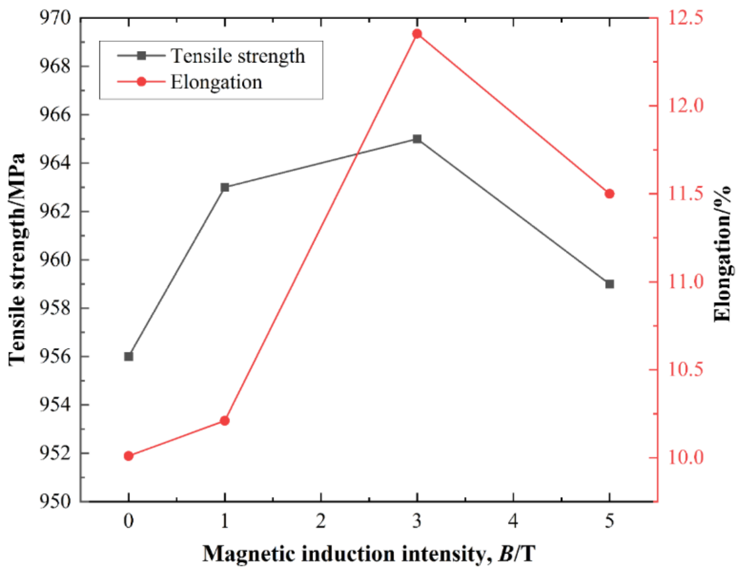

Figure 7. The tensile properties of Ti-6.2Al-4.1V-2.3Zr titanium alloy under magnetic field, Data from Ref. [28].

When extruded AZ31 magnesium alloy was subjected to pulsed-magnetic field assisted tensile after solution aging [29], the magnetic field promoted dislocation movement, and dislocation proliferation, dislocation pile-up, and stress concentration at grain boundaries promoted recrystallization, and grain refinement played a strength and toughness effect. In addition, the grain rotation induced by the magnetic field during plastic deformation leads to the preferred orientation, which enhances the plastic deformation ability of the alloy. When the magnetic induction intensity is 3 T, the tensile strength and elongation of the alloy are 230 MPa and 13%, respectively, which are increased by 2.2% and 28.7% compared with those without magnetic field.

According to the above research content [22–29], the changes in elongation and tensile strength of magnetic field-assisted tensile aluminum and aluminum alloy, titanium alloy, and magnesium alloy compared with that without magnetic field are sorted in Table 2. It can be seen from Table 2 that magnetic field-assisted tensile can significantly change the mechanical properties of 7 series aluminum alloy, titanium alloy, and magnesium alloy with difficult deformation, and two series aluminum alloy with good plasticity. Moreover, it can be found that the elongation and tensile strength of the alloy do not increase with the increase of magnetic induction intensity. However, there is an optimal magnetic induction strength, which can improve elongation and tensile strength or significantly increase the elongation of the alloy without reducing the tensile strength. Therefore, for different grades and processing states of the alloy, the study of obtaining the optimal magnetic field technology and alloy properties is worth the attention of material researchers.

Table 2. The properties of metal materials by tensile under magnetic field.

NO.	Alloy Types	Alloy Original State	Magnetic Field Types or Strength	Tensile Rates	Property Changes	References
1	2024 aluminum alloy	Cold-rolled state Elongation: 13% Tensile strength: 375 MPa	Pulsed magnetic fields 0.5, 1, 3, 5 T Pulsed number: 30 times Pulse interval: 20 s	1 mm/min	Elongation: +30.8% Tensile strength: +9.3%	[22–24]
2	7075 aluminum alloy	Cold-rolled state Elongation: 16.64% Tensile strength: 579 MPa	Pulsed magnetic fields 1, 2, 3 T Pulsed number: 20 times	2 mm/s	Elongation: +3.9% Tensile strength: +0.8%	[25]
3	7055 aluminum alloy	Extrusion state Elongation: 7.5% Tensile strength: 565 MPa	Pulsed magnetic fields 1, 3, 5, 7 T Pulsed number: 30 times Pulse interval: 20 s	0.5 mm/min	Elongation: +10.7% Tensile strength: +3.9%	[26]
4	TC4 titanium alloy	Extrusion state Elongation: 10.01% Tensile strength: 956 MPa	Pulsed magnetic fields 1, 3, 5 T Pulsed number: 30 times Pulse interval: 20 s	0.5 mm/min	Elongation: +24.0% Tensile strength: +0.90%	[27,28]
5	AZ31 magnesium alloy	Solution and aging state Elongation: 10.1% Tensile strength: 225 MPa	Pulsed magnetic fields 3 T Pulse interval: 5 s	1 mm/min	Elongation: +28.7% Tensile strength: +2.2%	[29]

4. Magnetic Field Independent Treated to Metallic Materials

Using magnetic induction intensity of 5–40 T pulse magnetic field treated four kinds of paramagnetic Al, Al-6%Zn, and diamagnetic Zn, Sn foil of thickness 0.02 mm [30]. It was found that the microhardness of paramagnetic Al and Al-6% Zn foil increases by 48% and 44%, respectively, and the microhardness of diamagnetic Zn and Sn foil decreases by 10% and 13%, respectively, compared without magnetic field treatment.

Using constant magnetic field treated 7055 aluminum alloy [31], it was found that the magnetic induction intensity increases from 1 to 7 T. Compared with the samples without magnetic field, the tensile strength of the alloy decreases slightly, and the elongation first increases and then decreases. The comprehensive mechanical properties of the samples reached the optimum at 3 T, with the tensile strength, elongation, and residual stress of 555 MPa, 10.5%, and 38 MPa, respectively, which decreased by 1.8%, increased by 40.0%, and decreased by 68.9% compared with the samples without magnetic field. The reason for these properties changes was that the magnetic field could make the dislocation more easily de-pinned and enhance the flexibility of dislocation movement, promote the transformation of cellular dislocation to network dislocation, then migrate and merge to form sub-grain, which has a positive effect on grain refinement. In addition, the magnetic field changes and the electron spin state breaks the covalent bond between Zn and Mg, and promotes the transition of η($MgZn_2$) to η′ phase.

The Al_2O_3 reinforced 7055 Al matrix composites prepared from CeO_2 powder and aluminum liquid by in situ endophytic methods were treated with pulsed magnetic field [32]. The magnetic induction intensity increased from 1 to 5 T, and the tensile strength, elongation, and microhardness increased first and then decreased. When the magnetic induction strength was 3 T, the tensile strength, elongation, and microhardness reached 548.0 MPa, 17.2%, and 1224 MPa, which were 10.3%, 16.2%, and 20.7% higher than those of the samples without magnetic field, respectively. It was found that dislocations proliferate and density increases in response to magnetic field. The magnetic field promoted the precipitate increase and dispersed in the matrix. Dislocation strengthening and second phase strengthening were the main reasons for improving mechanical properties.

Cold-rolled nickel-aluminum bronze (NAB) and extruded aluminum alloy were placed in 1.24 T alternating magnetic field for 30 min, and then the pin-disc wear test was carried out [33]. Compared to those without magnetic field, the wear rate was reduced by 61.0% and 56.0%, and the wear width was reduced by 18% and 15%, respectively. The main reasons for the improvement of the alloy wear property were as follows: For NAB alloy, the magnetic field accelerates the diffusion of Fe atoms or $AlFe_3$ particles, promotes the precipitation of more κ_{IV} phase, and decreases the residual tensile stress by 40%. The magnetic field accelerates the diffusion of free Cu atoms for aluminum alloys. It precipitates them from the solid solution, forming the GP region and precipitating the evenly distributed and fine needle-like θ″ phase, which changes the residual tensile stress to the residual compressive stress.

When cold-rolled EN8 steel and extruded AA2014-T6 aluminum alloy were placed in 0.54 T alternating magnetic field for 30 min [34], it was found that the fatigue life of steel was increased from 791,990 times to 5,364,498 times, and the fatigue life of aluminum alloy was increased from 512,979 times to 3619,824 times compared with that without magnetic field. The fatigue life of the two alloys was increased by 577.3% and 605.6%, the residual compressive stress was increased by 19% and 30%, and the microhardness and tensile strength were slightly increased. The increase and uniform distribution of residual compressive stress were the main reasons for improving fatigue life. The magnetic field promoted the diffusion of copper atoms to form the GP region, which resulted in precipitation strengthening and increased aluminum alloy's tensile strength and fracture toughness. Moreover, the fatigue life of 20Cr2Ni4A alloy was also increased by 42.11% after pulsed magnetic field treatment [35].

Solution-aging TC4 titanium alloy was treated by pulsed magnetic field [36]. Compared with that without magnetic field, the maximum tensile strength of the alloy was 1330 MPa when the magnetic induction intensity was 3 T, but the elongation decreased seriously. When the magnetic induction intensity was 4 T, the maximum elongation of the alloy was 15.6%, an increase of 4.8%, and the tensile strength of the alloy was 1265 MPa, an increase of 2.3%. The results showed that the magnetic field could promote the transition from β to α phase in the alloy. The distribution of the strip secondary α phase was relatively independent and rarely interleaved, which reduced the slip resistance and contributed to the improvement of plasticity. On the other hand, it drove the Frank –Read dislocation source to cause dislocation proliferation and play a role in dislocation strengthening. Subsequently, the scholar treated hot-rolled TC4 titanium alloy with a constant magnetic field [37]. With the increase of magnetic induction intensity, the alloy's elongation reached the maximum of 14.7% at 7 T, and the hardness reached the maximum of 335.9 HV at 2 T, which were increased by 47.5% and 8.1%, respectively, compared with that without magnetic field. Further analysis showed that these properties change mainly due to dynamic recrystallization promoted by magnetic field, which refined the grains. Dislocation proliferation led to dislocation strengthening, and the crystal plane was deflected along the slip direction, which improved plasticity.

When the pulse magnetic field, pulse current, and electromagnetic composite field were applied to TC11 titanium alloy [38], it was found that the α phase increased to different degrees, and the microhardness of the alloy decreased slightly. After only application of pulsed magnetic field, the macroscopic residual tensile stress of TC4 titanium alloy decreases by 24.0% on average. In situ observation showed that the distribution of in-grain dislocation was more uniform, the local high dislocation density area disappeared, the low angle grain boundaries decreased, and the heavy lattice grain boundary increased.

The above studies [30–39] showed that the magnetic field had a significant effect on the mechanical properties of the alloy and also played a non-negligible role in the friction and wear properties of the alloy. After pulsed magnetic field treatment, the milling performance of WC–12Co cemented carbide milling tool was improved. The feed force Fx decreased by 15.90%, the main cutting force Fy decreased by 13.29%, and the resistance to cutting depth Fz decreased by 47.6%, respectively. The surface roughness of workpiece was decreased by 63.7% [40]. The dislocation distribution of P10 cemented carbide tool became more uniform, and the residual stress in different directions at the tool edge decreased by 31.95% on average [41] The lateral fracture strength of YG8 cemented carbide was increased by 9.5%, the microhardness was increased by 5.7%, and the cutting distance was increased by 13.9% [42]. The friction behavior between nickel-based alloy die and workpiece changed from severe adhesive wear to mild abrasive wear. The average service life of die was increased by 34.9%, and the tensile strength and elongation of the alloy were increased by 7.3% and 34.6%, respectively [43]. The friction coefficient of AISI 52100 high carbon steel decreased by 12.5% from 0.08 to 0.07, and the wear scar width decreased by 23.9% from 180 to 137 um [44].

According to the above research contents [30–44], the properties changes of aluminum and aluminum alloy, nickel-aluminum bronze, titanium alloy, hard alloy, and high carbon steel independent treated by magnetic field are summarized in Table 3. It can be seen from Table 3 that after the magnetic field was applied for a certain time, the related properties of the alloy can be changed, especially the fatigue life of AA2014-T6 aluminum alloy and EN8 steel, the wear resistance of AA2014-T6 aluminum alloy and nickel-aluminum bronze alloy, and the residual stress of the alloy can be significantly affected.

Table 3. The properties change of metal materials independent treated by magnetic field.

NO.	Alloy Types	Magnetic Field Types or Strength,	Property Changes	References
1	Al	Pulsed magnetic fields 5–40 T	Microhardness: +48.0%	[30]
2	Al-6%Zn		Microhardness: +44.0%	
3	Zn		Microhardness: −10.0%	
4	Sn		Microhardness: −13.0%	
5	7055 aluminum alloy	Pulsed magnetic fields 1, 3, 5, 7 T Treatment time: 200 s	Elongation: +40.0% Tensile strength: −1.8% Residual stress: −68.9%	[21,31]
6	7055 aluminum alloy	Pulsed magnetic fields 1, 3, 5 T Pulsed number: 30 times	Elongation: +16.2% Tensile strength: +10.3% Microhardness: +20.7%	[32]
7	NAB Al, 8.5–10; Ni, 4–5; Fe, 4–5; Mn, 0.5;	Alternating magnetic field 1.24 T Treatment time: 30 min	Wear rate: −61.0% Wear scar width: −18.2% Residual tensile stress: −40.2% Microhardness: +6.2%	[33]
8	AA2014-T6 aluminum alloy		Wear rate: −56.0% Wear scar width: −15.0%, Residual tensile stress: becomes compressive stress Microhardness: +4.5%	

Table 3. *Cont.*

NO.	Alloy Types	Magnetic Field Types or Strength,	Property Changes	References
9	AA2014-T6 aluminum alloy	Alternating magnetic field 0.54 T Pulsed number: 360 times. Treatment time: 30 min	Fatigue life: +605.6% Residual compressive stress: +31.3% Microhardness: +3.2% Tensile strength: slightly increase	[34]
10	EN8 steel		Fatigue life: +577.3% Residual compressive stress: +19.4% Microhardness: +2.2% Tensile strength: +3.1%	
11	20Cr2Ni4A steel	Pulsed magnetic fields 1, 4, 9 T	Fatigue life: +42.1%	[35]
12	TC4 titanium alloy	Pulsed magnetic fields 2, 3, 4 T Pulsed number: 30 times Pulse interval: 20 s	Elongation: +4.8% Tensile strength: +2.3%	[36]
13	TC4 titanium alloy	Constant magnetic field1-7T Treatment time: 200 s	Elongation: +47. 5% Microhardness: +8.1%	[37]
14	TC11 titanium alloy	Pulsed magnetic fields 3 T Treatment time: 40 s	Microhardness: slightly decrease	[38]
15	TC4 titanium alloy	Pulsed magnetic fields 2 T Pulsed number: 100 times	Residual tensile stress: −24.0%	[39]
16	WC–12Co cemented carbide	Pulsed magnetic fields 1.5 T Pulsed number: 30 times Pulse interval: 10 s	The feed force Fx: −15.90% The main cutting force Fy: −13.29% The resistance to cutting depth Fz: −47.6% The surface roughness of workpiece: −63.7% The microhardness of milling tool: +10.6%	[40]
17	P10 cemented carbide	Pulsed magnetic fields 1 T Pulsed number: 25 times Pulse interval: 1 s	Residual stress: −31.9%	[41]
18	YG8 cemented carbide	Pulsed magnetic fields 0.5, 1, 1.5 T Pulsed number: 20 times	Transverse rupture strength: +9.6% Microhardness: +5.7% Cutting distance: +13.9%	[42]
19	Nickel-based alloy Ni-16Cr-12Co-4W-4Mo-3Al-3Ti	Pulsed magnetic fields 1 T Pulsed number: 120 times Pulse interval: 10 s	Severe adhesive wear becomes mild abrasive wear Tensile strength: +7.3% Elongation: +34.6%,	[43]
20	AISI 52100 high-carbon steel	Pulsed magnetic fields 8.75 T	Friction coefficient: −12.5% Wear scar width: –23.9%	[44]

5. Mechanism Analysis of Magnetic Field Regulate Metal Material Properties

It has become an indisputable fact that magnetic field affects the properties of metal materials, according to the above research on the magnetic field-assisted heat treatment, assisted stretching, and independent treatment of metal materials. However, so far, there is no unified conclusion on the mechanism of magnetic field affecting material properties [45,46]. At present, scholars generally agree that the essence of magnetic field improving the macroscopic plastic deformation ability of materials mainly lies in the effect of magnetic field on the characteristics of the internal microstructure dislocation of materials. When exploring the influence of magnetic field on dislocations, scholars found that the thermal effect and magnetization force effect of magnetic field were not sufficient to have a substantial impact on the microstructure and properties of the alloy, and these were not the main reasons for the change of alloy hardness or plasticity. When magnetic field assisted pure Ni, Al heat treatment and magnetic field-independent treated solid 7075 aluminum alloy and AZ31 magnesium alloy, the specimen temperature did not exceed 40 °C. The magnetization force produced by the magnetic field to the alloy was much lower than the yield strength of the material, which could not reach the degree of plastic deformation of the material.

5.1. Magnetic Field Promotes Dislocation Motion

Dislocation morphology directly affects the mechanical properties of metal materials. When sorting out the magnetic field assisted treatment and independent treatment, it was found that the essence of the alloy properties changes is that magnetic field affects the movement of dislocation, mainly reflected in: (1) Dislocation de-pinning effect: magnetic field weakens the bonding force between atoms, and enhances the atomic mobility. It causes dislocation loosening at the pinning place [47–49]. (2) Dislocation core expansion: the expansion of dislocation core is caused by magnetic field in the process of dislocation de-pinning, which reduces the pinning resistance of dislocation movement and improves the effective stress driving dislocation movement [48]. (3) The change of electron pair between dislocation and obstacle: the magnetic field stimulates the free radical electron pair between dislocation and paramagnetic obstacle. It promotes the transformation of the electron spin state from S to T state. As a result, the binding energy between dislocation and obstacle is reduced, the potential barrier to be overcome by dislocation is reduced, and the dislocation motility is increased [49–51]. (4) Dislocation proliferation: magnetic field reduces dislocation of nuclear energy, resulting in increased dislocation nucleation [46].

5.2. Magnetic Field Changes Residual Stress Distribution

When aluminum alloy [21,30], aluminum bronze alloy [33], EN8 steel [34], titanium alloy [37], and magnesium alloy [52,53] were treated with magnetic field, the residual stress of the alloy was obviously reduced. Further analysis showed that the residual tensile stress of alloy decreased gradually to the residual compressive stress under the magnetic field, while the sample initially showed residual compressive stress increased gradually under the magnetic field. Dislocation movement was closely related to the stress inside the material. The location of dislocation pile-up would cause stress concentration, and the existence of a large amount of internal stress was a necessary condition for dislocation nucleation [54]. As a result of the magnetic field treatment, the dislocation nucleated preferentially in the dislocation pile-up place and consumed a part of stress. Thus, new dislocation would de-pin and move to other places, leaving enough space for the next dislocation nucleation, growth, and migration, until the surrounding stress was exhausted to the point where new dislocations were not generated. This way, the stress inside the material was released through the nucleation, proliferation, and movement of dislocations. When the stress concentration disappears, and the stress was uniformly distributed, the dislocation also reached the ideal state of uniform distribution [52].

5.3. Magnetic Field Can Refine Grains

The magnetic field could refine grain inside the material, and grain refinement was also related to the dislocation. According to the variation law of grain and dislocation characteristics of aluminum alloy [19] treated by magnetic field assisted tensile treatment, the grain refinement of materials was affected by dislocation characteristics to a certain extent. As shown in Figure 8, under the magnetic field treatment, the movement activity of dislocations was enhanced, proliferation began, and some dislocations accumulated at grain boundaries. With the proliferation and accumulation of dislocations, networked dislocations would gradually form at the grain boundary, preventing the further migration of dislocations, resulting in more and more dislocation plug accumulation here, which would become more and more reliable and then gradually evolve into a dislocation wall. Under the joint action of magnetic field and tensile stress, the dislocation obtained enough energy to push the dislocation wall to move. The dislocation wall splices with the dislocation wall to form the subgrain. Then, the fine crystal was generated with the connection between the subgrain boundary and the surrounding grain boundary [37].

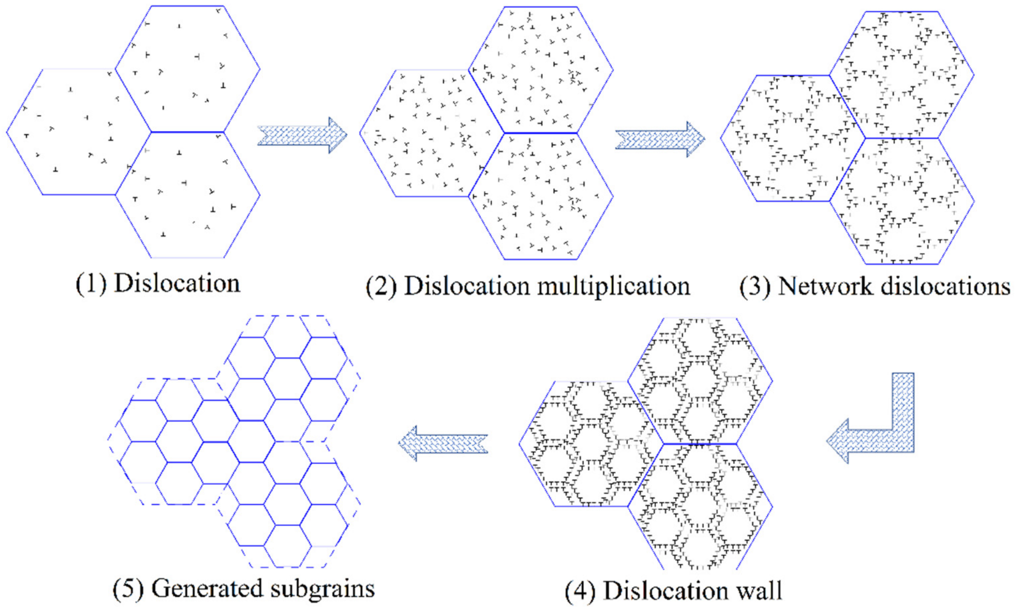

Figure 8. The dynamic recrystallization process of alloy under magnetic field.

5.4. Magnetic Field Affects the Second Phase Precipitation

The pulsed magnetic field assists tensile extruded TC4 titanium alloy [27], and it was found that the magnetic field induced the formation of independent strips of secondary α phase in the β phase matrix with no connection in microstructure, which reduced the slip resistance and increased the plasticity of the alloy. After solution aging treatment, the magnetic field assisted tensile test was conducted on extrusion-state AZ31 magnesium alloy [52]. With the increase of magnetic induction intensity, the precipitated β of magnesium alloy gradually increased. When the magnetic induction intensity reached 3T, the amount of precipitated β phase reached the maximum, while the magnetic induction intensity was 5 T, it was observed that the precipitated phase had a growing trend. The precipitated phase as seen by transmission electron microscopy (TEM) is shown in Figure 9.

When AA2014-T6 aluminum alloy and NAB alloy were independently treated with a 1.24 T alternating magnetic field [33], the fine needle-like phases that had a high density and uniform distribution precipitated in aluminum alloy, as shown in Figure 10. A large amount of fine κ_{IV} phase precipitated in NAB alloy, as shown in Figure 11. For aluminum alloy, the free Cu atoms were accelerated to diffuse, and then precipitated out of the solid solution, forming GP zone and θ'' phase, and aging strengthening occurred. Meanwhile, For NAB alloy, there are two possible explanations. One was that the work done by magnetic field on the material lost in the form of heat, which promoted the diffusion of free Fe and Al atoms in the solid solution, and more κ_{IV} phases formed from the residual β and α phases. The other was the attraction or repulsion between the magnetic dipoles composed of free Fe atoms or small $AlFe_3$ particles, which accelerates the diffusion of Fe atoms or $AlFe_3$ particles and promotes the formation of more κ_{IV} phases.

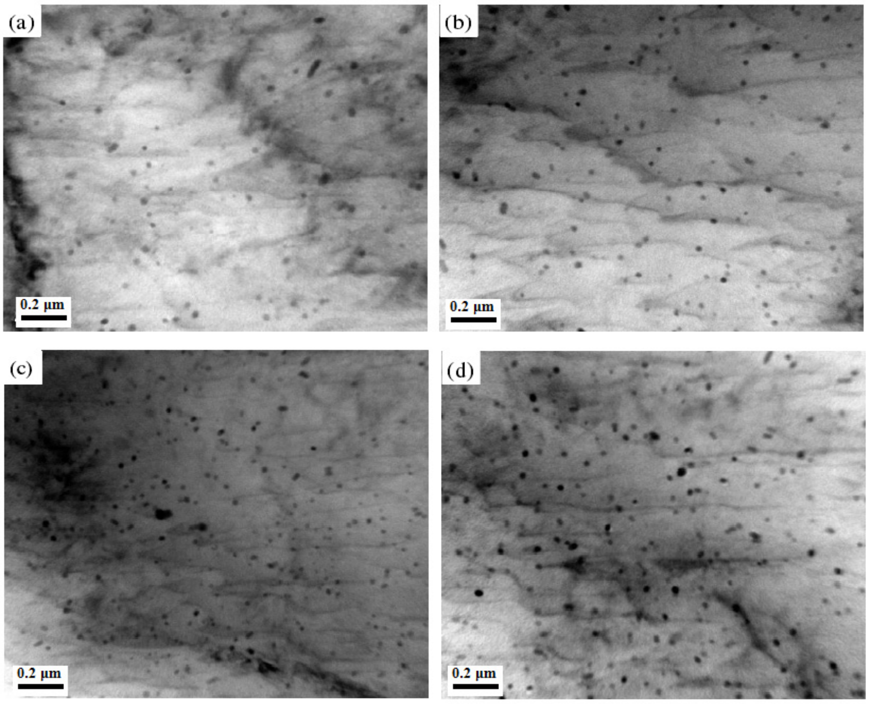

Figure 9. TEM images of AZ31 magnesium alloy's precipitated phase under pulsed magnetic field treatment. (**a**) 0 T; (**b**) B = 1 T; (**c**) B = 3 T; (**d**) B = 5 T. Reprinted with permission from Ref [52].

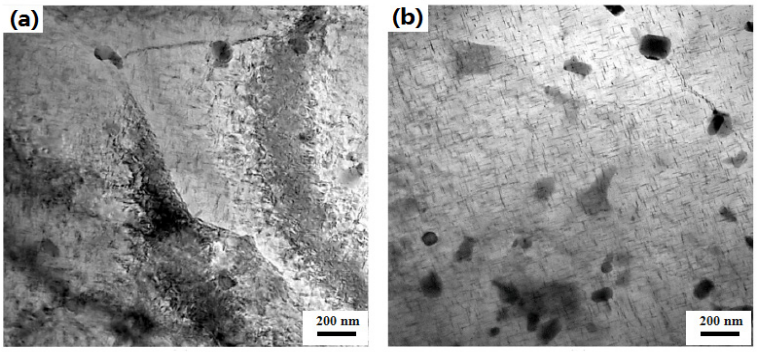

Figure 10. TEM images of aluminum alloy precipitates are treated by alternating magnetic field. (**a**) untreated, (**b**) treated. Reprinted with permission from Ref. [33]. Copyright 2021 Elsevier.

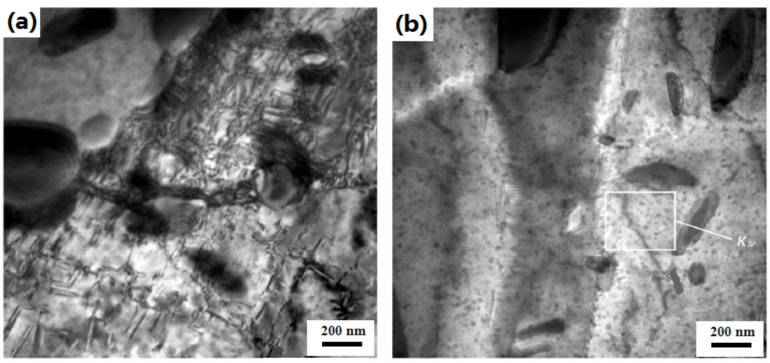

Figure 11. TEM images of NAB alloy precipitates are treated by alternating magnetic field (**a**) untreated, (**b**) treated. Reprinted with permission from Ref. [33]. Copyright 2021 Elsevier.

5.5. Magnetic Field Improves Alloy Texture

In general, the orientation of grains in polycrystals was arbitrary. However, after plastic or microplastic deformation under magnetic field treatment, the grains in polycrystals would be aligned around the direction of plastic deformation in different degrees. Then the grains would produce the preferred orientation.

Under the action of magnetic field, the crystal plane of (111) and (220) of 2024 aluminum alloy were weakened, while the crystal plane of (311) was enhanced [19], resulting in the change of grain orientation, which was conducive to the slip between crystal planes. The plasticity of the sample was greatly improved. At this time, the strong basal texture inside the material was weakened, and the texture tended to be uniform. When the magnetic field was treated with TC4 titanium alloy [28], the grain rotates, and the orientation along the (100), (101), and (110) crystal planes is enhanced, resulting in the preferred orientation, which is conducive to the slip and further improves the plastic deformation ability of the material. For the magnetic field-treated AZ31 magnesium alloy [52], the C axis of some grains deflected parallel to the magnetic field direction, resulting in grain orientation rotation and weakening of the original (0001) basal plane texture. Meanwhile, more new orientations appear while grains are refined, and finally, the coexistence of basal plane texture and non-basal plane texture was presented.

Based on the above research work, the influence of magnetic field on the properties of metal materials can be generally attributed to: (1) Magnetic field can effectively affect dislocation movement, promote dislocation redistribution, and change dislocation density and morphology. (2) The magnetic field can reduce the residual stress and make it tend to a uniform distribution. (3) Magnetic field has the effect of refining grain. (4) The magnetic field can promote the phase transition and change the morphology and distribution of the second phase. (5) The magnetic field can change the strength and direction of the texture inside the alloy. It is precisely because of the increase of dislocation density and uniform distribution, the refinement of grains, and the diffusion and precipitation of the fine second phase, that the simultaneous increase of elongation and tensile strength is realized or the elongation is significantly improved without reducing the tensile strength of the alloy. The contradiction between the strength and plasticity performance indicators in plastic processing is improved. These are very important to enrich the "magneto plastic theory" and expand the application field of magnetic field treatment.

6. Prospect

Based on the current research work on the influence of magnetic field on the microstructure and properties of metal materials, on the one hand, the alloy is taken as a whole, and the influence of different magnetic second phase on alloy's microstructure and properties is ignored, especially the influence of the content and distribution of different magnetic second phase on the alloy's properties and its mechanism. On the other hand, the influence of thermal effect and magnetization force effect caused by magnetic field on the microstructure and properties of alloys is basically ignored. Therefore, the effects of different magnetic second phases and multi-field coupling, such as magnetic field, temperature field, and force field, on the microstructure and properties may become a new research direction for the magnetic field treatment of metal materials.

Furthermore, according to related research on magnetic field-assisted metal material heat treatment, magnetic field-assisted metal material stretching, and magnetic field-independent treated metal material, it can be found that whether as an assisted or independent process, the magnetic field by using the "non-contact" unique processing method, controls the microstructure of the material or affects the strength, plasticity, hardness, toughness, fatigue resistance, wear resistance and other properties of the alloy. In particular, the simultaneous improvement of alloy strength and plasticity can be achieved, which will make the magnetic field treatment favored by the performance improvement of alloy parts with complex shapes and difficult forming.

7. Conclusions

Based on reviewing the influence of magnetic field treatment on the mechanical properties of solid metal materials, this paper briefly introduces the action mechanism of magnetic field affecting the mechanical properties of metal materials. It summarizes that the magnetic field can improve the properties of metal materials mainly because magnetic fields can promote dislocation motion, reduce residual stress of alloys, refine grains, promote second phase precipitation, and affect the texture of alloys. It points out the research direction of the change of alloy microstructure and properties under the magnetic field and the multi-field coupling numerical simulation of metal materials under the action of the magnetic field. It provides new ideas that the magnetic field can regulate the properties of metal materials, especially the performance of complex and difficult to process or deform metal parts.

However, magnetic field treatment also has certain limitations. The intensity of magnetic field decays rapidly with increasing distance, and the superimposed strong magnetic field equipment is relatively expensive. At present, the treatment of metallic materials with strong magnetic field is basically carried out in a relatively small space. Due to space limitations, the test samples are basically very small, which may be one of the reasons why more studies have been carried out on the microstructure, microhardness, and wear resistance of the alloy by magnetic field treatment, while fewer studies have been carried out on the tensile strength and elongation. Just as in recent years magnetic field treatment has focused mainly on improvements in the performance of carbide tools because of their relatively small size. In addition, the effect of magnetic field on the properties of non-ferromagnetic alloys is less obvious than that of ferromagnetic alloys, which may be one of the reasons why relatively few studies have been conducted on non-ferromagnetic alloys alone using magnetic fields at room temperature. This is why researchers often add temperature, external force, or electric fields when treating non-ferromagnetic alloys with magnetic fields to improve the alloy properties even more significantly. However, whether it is the space limitation or the limitation on the degree of performance enhancement of non-ferromagnetic alloy, the magnetic field having a non-negligible influence on many properties of the alloy has become a consensus, plus the magnetic field "contactless processing" and does not affect the appearance and size of the product and other advantages, and it is believed that the research work will be more comprehensive and deeper to enhance the performance of the alloy with the help of magnetic field.

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