

Improvement in plasticity of Al-Cu-Mg alloy by electromagnetic coupling treatment

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Abstract. Electromagnetic coupling treatment (EMCT) is a new method to regulate material properties. To investigate the effect of EMCT on the plasticity of the Al-Cu-Mg alloy, a software simulation calculation was carried out, and then the alloy was treated with an electromagnetic field, and its mechanical properties were tested at room temperature. The simulation results reveal that the sample generates a plastic strain of 6.88×10^3 ppm, potentially enhancing its tensile properties. The experimental findings indicate that EMCT did not have a substantial impact on the strength and hardness of the aluminum alloy. However, it did result in a 16.9% increase in the sample's plasticity and a 5.6% drop in the elastic modulus

Keywords. Electromagnetic coupling treatment (EMCT), Plasticity, Simulation, Tensile.

1 Introduction

Electromagnetic field treatment is an innovative technique for modifying materials. This method uses electric or magnetic fields to modify the microstructure of materials, resulting in changes to their properties. The electroshock treatment can optimize the microstructure and mechanical properties of titanium alloy [1] and may also modify the residual stress of M50 steel [2]. Pulsed magnetic treatment can prolong the fatigue life of alloy steel [3], enhance the anti-friction effect of cemented carbide [4], and reduce the residual stress of magnesium alloy [5].

Studies have focused not just on a single electric or magnetic field but also on the combination of two. Literatures [6-9] have demonstrated that the application of electromagnetic field treatment has a notable effect on improving the cutting performance and longevity of cemented carbide tools. Liu [10] utilized pulsed electromagnetic treatment on the WC-6Co end mills, resulting in a substantial decrease in the milling force and a reduction in wear amount by about 35%. According to Zhou's research [11], the application

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of electromagnetic treatment can enhance the lifespan of cemented carbide tools by 133%. Sun [12] has shown that electromagnetic coupling treatment may promote element diffusion, increase coating binding force, and so improve coating tool performance.

Furthermore, reports indicate that electromagnetic field treatment technology is being used to regulate the performance of other materials or parts [13]. Electromagnetic impact can slow down fatigue fracture propagation and increase the fatigue life of titanium alloy bolts [14]. Sun [15] proposed that the electromagnetic shock technique could improve the corrosion resistance of the T73-Al7075 alloy. Zhang [16] found that applying electromagnetic coupling treatment (EMCT) resulted in a 17.5% improvement in the thermal conductivity of the 690 alloy. Ashi [17] pointed out that electromagnetic coupling treatment can eliminate the residual stress of 7050 aluminum alloy.

Current studies primarily focus on the electromagnetic field's influence on the practical performance of materials, whereas there is a lack of research on the impact of plasticity. In this study, the effects of EMCT on the mechanical properties of the Al-Cu-Mg alloy were studied by combining simulation and experiment, hoping to provide a reference for further application of EMCT.

2 Design of Experiments

2.1 Simulation setup

COMSOL Multiphysics software was used to construct the simulation calculation model of the EMCT process, as shown in Fig. 1. The excitation coil is used to generate a pulsed magnetic field, which is simplified to a cylindrical, thin-walled shell when modeling, and the cavity is regarded as ideal air. The coil and electrode are made of pure copper. The sample is placed in the center of the electrode and is in direct contact with the electrode. Tetrahedral mesh is used for aluminum alloy specimen and electrodes, and swept mesh is used for coil to reduce calculation.

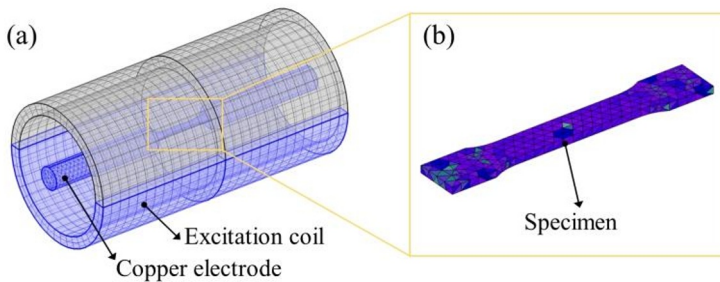


Fig. 1. Meshing of EMCT model: (a) whole area; (b) aluminum specimen

2.2 Experimentation

The experimental material employed is an Al-Cu-Mg alloy that has undergone solid solution and aging treatment. The composition of this alloy is presented in Table 1. According to the results of the simulation calculation, the EMCT parameters for this experiment were determined. In addition, a single electric treatment (ET) and a magnetic treatment (MT) were designed to compare the experimental effects, as shown in Table 2. The original sample was labeled UT. The tensile specimens were produced in accordance with the International Standard (ISO 6892-1:2019). At room temperature, the ETM305D universal testing machine was employed to conduct the tensile test with a loading rate of 2 mm/min. The HV-1000

digital microhardness tester was employed to conduct a hardness test. A test force of $F = 0.98$ N was chosen, and the loading duration was 15 s. Every sample underwent 5 tests, and the final result was determined by taking the mean.

Table 1. Chemical composition of Al-Cu-Mg alloy.

Element	Cu	Mg	Mn	Fe	Si	Ti	Zn	Al
Wt.%	2.93	2.20	0.59	0.35	0.27	0.14	0.09	Balance

Table 2. Parameters of Experiments

Sample	Electric field intensity (V/m)	Magnetic field intensity (T)	Processing time (s)
UT	0	0	0
ET	0	1.5	300
MT	800	0	300
EMCT	800	1.5	300

3 Results and Discussion

3.1 Numerical simulation results

During EMCT, the simulation focuses on the distribution of current and magnetic field on the sample, as well as the microscopic stresses and strains caused by electromagnetic and temperature fields. Since the pulse width of a single pulse current is 20 ms, four instantaneous states of $T = 5, 15, 25,$ and 35 ms were selected in the simulation process to analyze the changes of current and magnetic field on the sample, as shown in Fig. 2.

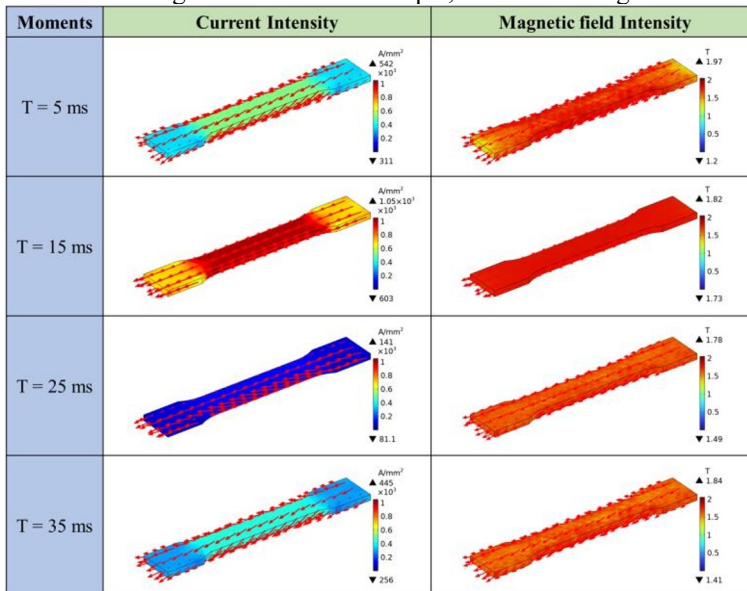


Fig. 2. Intensity and direction of pulsed current and magnetic field at different moments

The legend and vector arrows show that the current density's amplitude and direction change significantly in a short period of time during the processing. This is because the moving charge is acted on by the Lorentz force in the magnetic field, causing the current to

have a component in the width direction of the sample. At $T = 15$ ms, the superposition of input current and electromagnetic induction produces a high-density current with a peak value of 1.05×10^3 A/mm². Under the action of a coil magnetic field with a strength of 1.5 T, the magnetic field intensity of the sample reached a peak value of 1.97 T in a very short time (5 ms) and was basically maintained at a high level, indicating that there was an induced magnetic field of 0.3–0.5 T in the sample. The induced magnetic field is affected by the current density, so the magnetic field direction and the current direction are simultaneously deflected in the sample.

Figure 3 shows the stress and strain distribution characteristics of the sample at different times. With the continuous input of electromagnetic field energy, stress and strain gradually increase. The strain accumulation mainly occurs in a parallel section of the tensile specimen, and the peak value reached 6.88×10^3 ppm. Due to the influence of the Coulomb force, Lorentz force, and thermal stress, the distribution of stress and strain is complicated. According to the electroplastic theory [18], the electromagnetic field generates a large amount of microplastic strain inside the material through energy transfer and accumulation, which improves the sample's tensile properties [19].

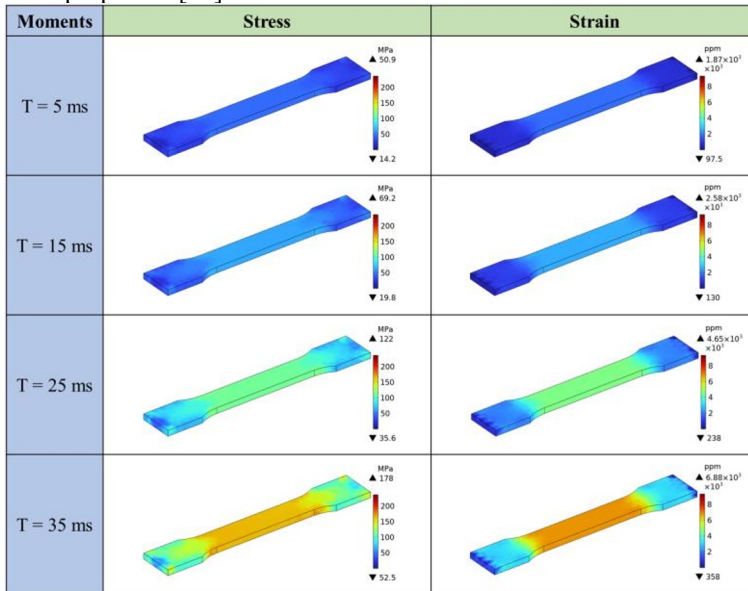


Fig. 3. Microscopic stress and strain at different moments

3.2 Plasticity and strength

The stress-strain curves of specimens are shown in Fig. 4(a). There is no apparent yield phenomenon seen in any of the samples, and the phases of elastic deformation and plastic deformation exhibit a high degree of similarity. All of the samples have close maximum stress values but very different maximum strain values. Fig. 4(b) shows the comparison of tensile strength and elongation. There is a limited influence of different treatment parameters on the tensile strength of the sample, which stays consistent at around 430 MPa. These factors, however, have a significant impact on the sample's elongation. The elongation of the original sample was 10.6%, and this value exceeded 12% after treatment with different parameters. In the EMCT group, the maximum elongation was 12.4%, an increase of 16.9% compared to the original state of the sample. The tensile test's results show that electromagnetic field treatment can improve the plasticity while maintaining the strength of the Al-Cu-Mg alloy.

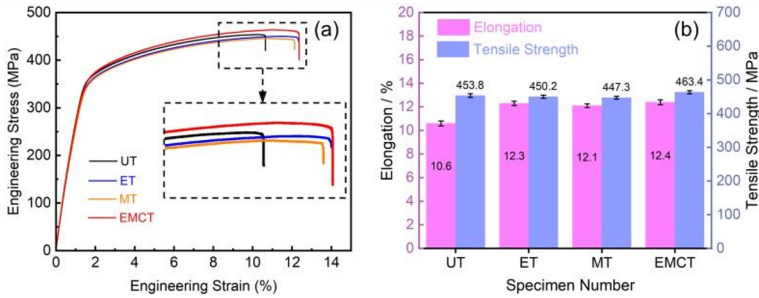


Fig. 4. Stress-strain curves of samples (a), Tensile strength and elongation (b).

3.3 Hardness and elastic modulus

Fig. 5(a) shows the difference in stress-strain curves of different samples. Based on the data obtained from the elastic deformation stage in the stress-strain curve, the determination of the elastic modulus of the specimen is conducted. The stage at which the strain does not exceed 0.01 is chosen in this context. Fig. 5(b) shows the hardness and elastic modulus of the samples. It is evident that the hardness of all samples remains mostly constant, but the elastic modulus undergoes substantial variations. Following the EMCT procedure, the elastic modulus exhibited a reduction from 26.7 GPa to 25.2 GPa, representing a drop of 5.6%. The reduction of elastic modulus helps to disperse stress, delay crack propagation, and better absorb energy when subjected to impact or load [20].

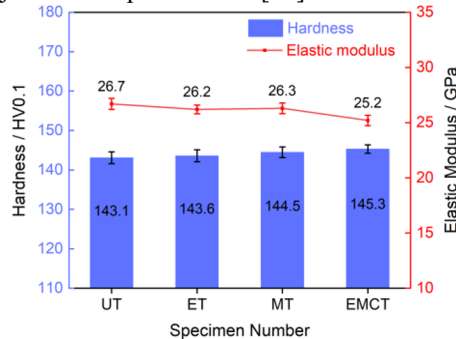


Fig. 5. Hardness and elastic modulus of samples

EMCT transmits energy through an electromagnetic field to the sample being processed. Plastic strain occurs inside the sample due to the collective influence of the Coulomb force, the Lorentz force, and thermal stress. Additionally, the stress state within the sample is regulated. As a result, the use of EMCT improves the specimen's plasticity while simultaneously reducing its elastic modulus.

4 Conclusion

In this study, the combination of computer simulation and a room-temperature tensile test proved that electromagnetic coupling treatment can improve the plasticity of aluminum alloy. Based on the experimental results, the following conclusions have been drawn:

1. There are induced current and induced magnetic fields in EMCT samples, and plastic strain accumulates.
2. The simulation results show that EMCT can improve the tensile properties of the sample, which was confirmed in the experiment.

3. EMCT does not affect the strength and hardness of aluminum alloy, but it increases the plasticity of the material by 16.9% and reduces the elastic modulus by 5.6%.

4. Compared with ET and MT, the effect of EMCT on the elastic modulus of aluminum alloy is more obvious.

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