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Effects of ultrasonic vibration on plastic deformation of AZ31 during the tensile process

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Abstract: An investigation on the plastic behavior of AZ31 magnesium alloy under ultrasonic vibration (with a frequency of 15 kHz and a maximum output of 2 kW) during the process of tension at room temperature was conducted to reveal the volume effect of the vibrated plastic deformation of AZ31. The characteristics of mechanical properties and microstructures of AZ31 under routine and vibrated tensile processes with different amplitudes were compared. It is found that ultrasonic vibration has a remarkable influence on the plastic behavior of AZ31 which can be summarized into two opposite aspects: the softening effect which reduces the flow resistance and improves the plasticity, and the hardening effect which decreases the formability. When a lower amplitude or vibration energy is applied to the tensile sample, the softening effect dominates, leading to a decrease of AZ31 deformation resistance with an increase of formability. Under the application of a high-vibrating amplitude, the hardening effect dominates, resulting in the decline of plasticity and brittle fracture of the samples.

Keywords: ultrasonic effects; tensile testing; magnesium alloys; plastic deformation

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1. Introduction

Magnesium alloys possess a number of advantageous properties, such as low density and high relative strength and stiffness, which are not shared by similar materials, and have many great prospects in the fields of transport and 3C (computer, communication, and consumer electronics). At present, most Mg alloy products are made by casting, and the application of plastic-working is less frequent even though it has the advantages of high efficiency utilization and better mechanical properties. For the hexagonal close-packed (HCP) crystal structure, Mg alloys have few slip systems, and the plasticity is poor at room temperature (RT). The formability of Mg alloys can be improved by heating; however, the requirements of productivity, cost, and forming quality are hard to fulfill. Thus, the development of newly-wrought Mg alloys and relevant plastic-forming technologies have been focused on in recent years [1-2].

In 1955, Blaha and Langenecker discovered the phenomenon of declining flow stress from the superimposition of ultrasonic vibration on single crystal zinc during the tension process [3], which is known as the Blaha Effect. Further studies regarding the effect and its application have been conducted by many researchers [4-9]. It is known that if vibration is superimposed on the mould or workpiece during the plastic forming process, the friction between the mould and workpiece together with the total forming load would decrease, and the deformability and formation uniformity would increase, resulting in the improvement of product quality. Vibrated plastic forming has been studied experimentally in many forming processes, such as drawing of wire and pipe, punching, shearing, precision forming, rolling, extrusion, and rotary forging. Some vibrated form-

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ing methods, like vibrated wire and pipe drawing, have been utilized in practice [10-14].

Because of the complexity of oscillation transmission within the workpiece and the effects of vibration both on the surface and interior of the deforming material, there are many disagreements of the fundamental mechanisms of vibrated plastic forming. Quantitative analysis of the process is still unrealizable. However, the volume effect and surface effect are two generally accepted explanations of this mechanism, as the authors discussed in a review [9]. The volume effect mainly describes the influence of vibration on plastic-deforming resistance and the formability of metal, while the surface effect mainly reflects the reduction of friction between metal and tool, the quality increase of the workpiece surface, or the decrease of abrasion and subsequent consumption of tools.

Research on the vibrated-plastic deformation of light alloys has intensively focused on aluminum and its alloys, and most of the research uses ultrasonic vibration. The superimposition of ultrasonic vibration is proposed on the forming process of Mg alloy at RT to improve the formability and quality of production and to obtain a higher pass-rate [9]. However, little research that focuses on the use of vibration in the formation of Mg alloys has been reported in literatures. Thus, the effectiveness of ultrasonic excitation on forming Mg at RT is still unknown. In the compression test of pure Mg and 6063 Al using 20 kHz ultrasonic excitation, Culp and Gencsoy [5] observed the load reductions for all materials, but Mg in the test showed a very poor plasticity, and the influence of friction between die and specimen was not eliminated.

To discover the underlying effects of ultrasonic vibration on the plastic deformation of Mg alloys, especially the volume effect in the forming process, tensile tests of AZ31 bars were performed under the conditions of routine and ultrasonic-vibration with different amplitudes, and the influence of the surface effect can be ignored in the tests. The deformation behavior and mechanical characteristics in various forming conditions were compared, and the microstructures of deformed AZ31 were observed. A preliminary analysis of the mechanism of the vibrated plastic deformation of AZ31 was presented.

2. Tensile test of AZ31 under ultrasonic vibration

The experiment was performed on a SANS CMT 5105 microcomputer-controlled electronic universal testing machine. As shown in Fig. 1, the ultrasonic-vibration apparatus includes an ultrasonic frequency generator, operating at a frequency of 15 kHz±200 Hz with a maximum output of 2 kW, a piezoceramic vibration transducer, a tapered horn resonator, and a frame which consists of four pillars and two mounting blocks, using as a fixture for all parts.

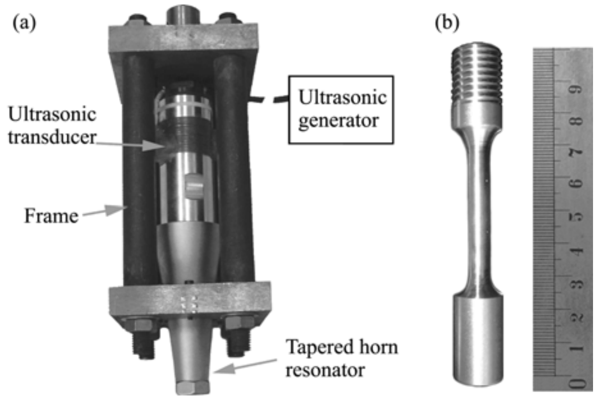

Fig. 1. Ultrasonic-vibration apparatus (a) and AZ31 sample for tensile testing (b).

According to the theory of wave energy [15], the wave energy-flux density (I) is proportional to the square of the amplitude (A) at a constant frequency (f):

$$I = \frac{\overline{P}}{S} = \frac{1}{2}\rho A^2 \omega^2 u \tag{1}$$

where $\overline{P}$ is the average energy flow (output power) through area S during a period of time, ρ the density of the material in which the ultrasonic can travel (ρ=7.8×10^3 kg/m^3 in steel), ω the palstance (ω=2πf), and u the wave velocity in the media (u=5200 m/s in steel). When $\overline{P}$ reaches the maximum power output of 2 kW and the energy loss is neglected, the estimated maximum amplitude (A) along the vertical direction (or the tensile direction) is about 0.003 mm at the end of the tapered horn resonator of 35 mm in diameter as shown in Fig. 1. It is in conformity with the measured peak of vibration displacement at the end surface of the tapered horn resonator under idle load by Keyence LK-G80 CCD laser displacement sensors. Adjusting the position of the amplitude knob on the ultrasonic generator can modify the energy (or amplitude) of the ultrasonic vibration output. In the test, the samples were given ultrasonic excitation at the knob positions of 20%A, 50%A, 60%A, and 90%A in order, respectively.

The chemical composition of the extruded AZ31 bar used in the tests is shown in Table 1. The sample was 5 mm in diameter (d_0) and 25 mm in scale distance (L_0) with one side connecting to the tapered horn resonator by a M16 screw thread and another side holding in the collet of the universal testing machine. All tests were performed at about 20°C. Because of the speed sensibility of Mg alloys, the tensing velocity was uniform at 2 mm/min.

Table 1. Chemical composition of AZ31 wt%

Al	Zn	Mn	Fe	Si	Cu	Mg
3.1225	0.9285	0.385	0.0017	0.0059	0.0017	Bal.

3. Results and discussion

3.1. Ultrasonic vibrated tension results of AZ31

Fig. 2 shows the stress-strain curves obtained from the tensile tests of AZ31 under static tension and vibrated tension with different amplitudes. More than three species were tested for each vibration condition, *i.e.*, at the knob positions of 20%*A*, 50%*A*, 60%*A*, or 90%*A*. It was found that vibration had a large impact on the tensile process of AZ31, and there existed so-called "softening" and "hardening" phenomena of AZ31 after the superimposition of vibration, just like being observed by Langenecker [4] in other materials in previous experiments. But in our test, the hardening was not only observed after ultrasonic irradiation as Langenecker did, but also during the application of ultrasonic vibration.

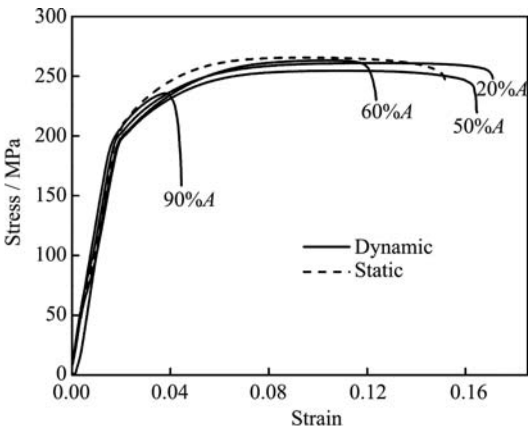

Fig. 2. Stress-strain curves of AZ31 under static tension and vibrated tension with different amplitudes.

As soon as ultrasonic vibration was superimposed, the resistance to the deformation of all AZ31 samples in the plastic stage decreased, implying the occurrence of a softening effect in accord with the experimental results of other kinds of metals. When the vibration energy increased, the deforming resistance did not completely reduce. In the tests, the reduction of deforming resistance was at its maximum near 50%*A*, in other words, the softening effect of AZ31 was most obvious under this range of vibration amplitude. In Fig. 3, the flow stress instantly declines as soon as the ultrasonic excitation of 20%*A* is added to the sample, which can be interpreted by the published theories on the stress superimposition effect [7]. Because of the small reduction of stress, it can be deduced that the stress superimposition effect is not the main mechanism of softening in the study.

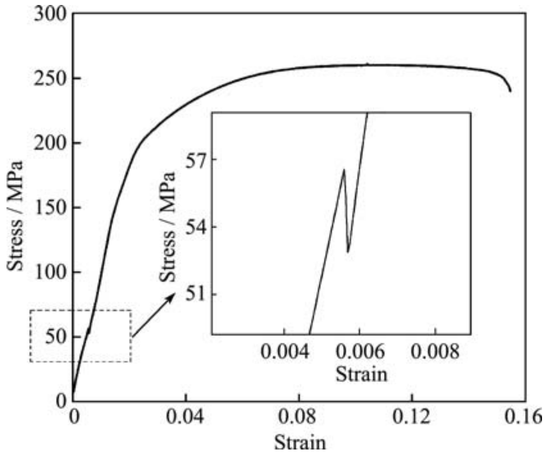

Fig. 3. Decrease of flow stress at the ultrasonic vibration amplitude of 20%*A*.

Elongation represents the formability of metal. As shown in Fig. 2, not only the deformation resistance of AZ31 reduces, but also the elongation increases at lower levels of vibration energy, which means that proper vibration can improve the plasticity of AZ31. The deformation resistance of AZ31 rebounds to that of static tension when the excitation energy is in a range of 50%*A*-60%*A*, and the elongation reduces significantly when the vibrating amplitude is close to 90%*A*. With the increase of vibration energy, the elongation decreases, and the hardening effect becomes apparent.

Fig. 4 illustrates the fracture shapes of the tensile sample under various conditions of stretch. The fracture surfaces of the samples under static tension and 20%*A* vibrated tension show a typical ductile character, as evidenced by a cone cup-type fracture and an apparent necking effect. The fracture faces of the samples at 60%*A* and 90%*A* are in 45° with the tension axis and display no obvious necking, while the fracture face at 90%*A* has a remarkable shape of brittle fracture.

Fig. 5 shows the tensile fractography of AZ31 under different conditions. The fracture under static tension in Fig. 5(a) has a certain character of plasticity with a few dimples, which are indicative of a typical cleavage fracture. Because of the large and deep dimples, the fracture of 20%*A* is likely to be ductile fracture. When the vibrating amplitude increases to 60%*A*, the fracture surface shows a mixed mode of dimple fracture and cleavage patterns. Finally, the fracture of 90%*A* is an apparent transgranular brittle fracture.

Therefore, the study illustrated that with the increase of vibrating energy, the plasticity of metal first increased, then decreased, and finally became brittle. In the experiment, the maximal plasticity occurred within the energy range of

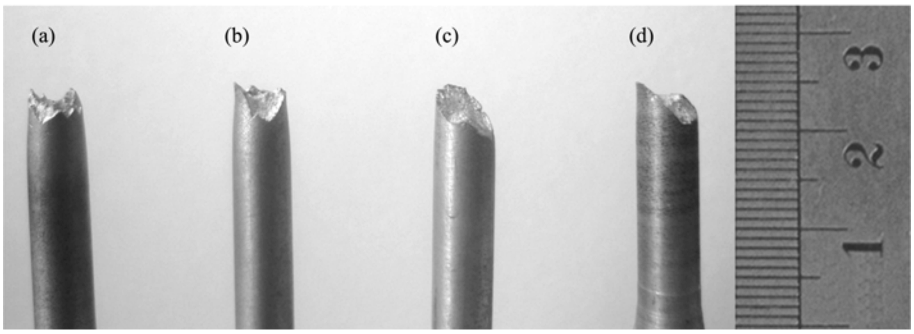

Fig. 4. Appearance of fracture under different tensile conditions: (a) static tension; (b) 20%*A*; (c) 60%*A*; (d) 90%*A*.

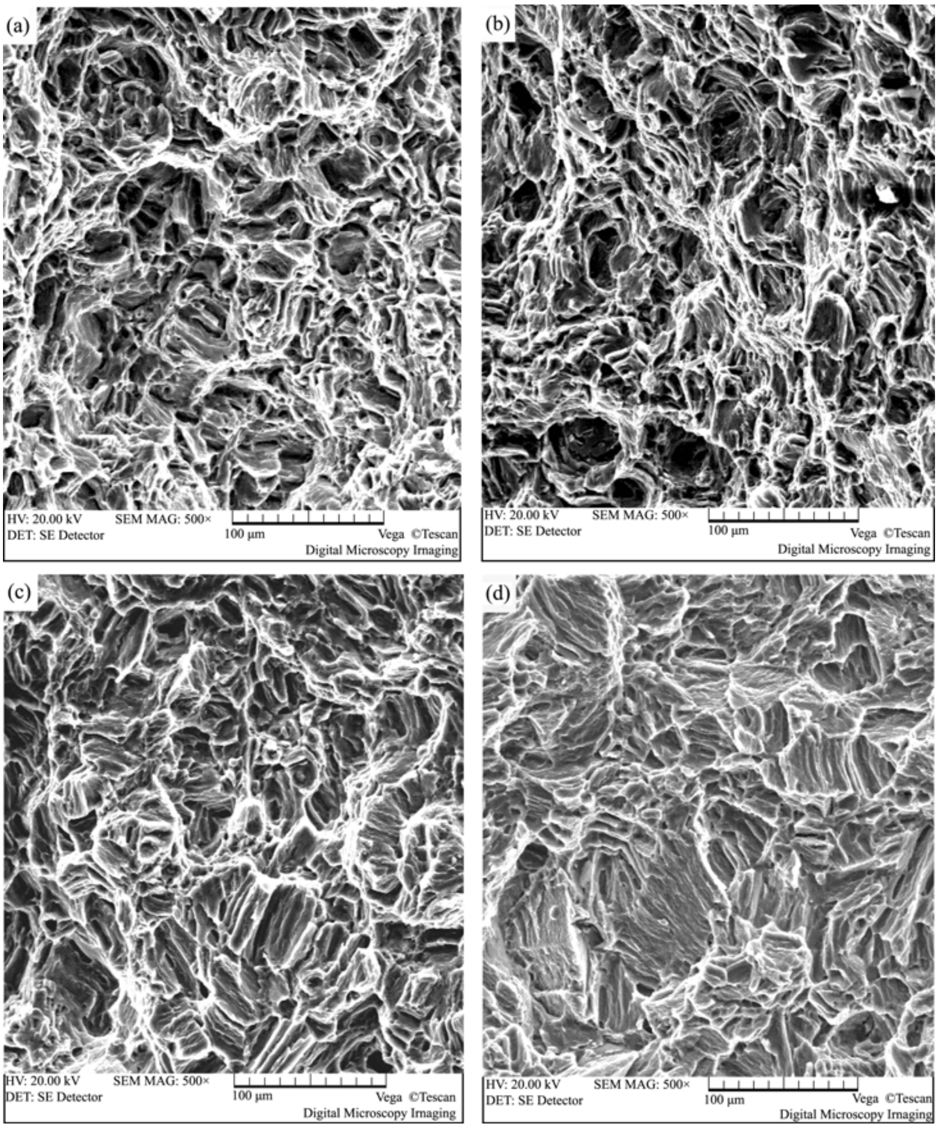

Fig. 5. Tensile fractographies of AZ31 under different tensile conditions: (a) static tension; (b) 20%*A*; (c) 60%*A*; (d) 90%*A*.

20%*A*-50%*A*. It can be inferred from the results that there is a critical value of vibrating energy in the vibrated-plastic deformation process of AZ31. The softening effect is the dominant mechanism if the vibrating energy is lower than the critical value, and the hardening effect is dominant if the vibrating energy is higher than the critical value. However, how to identify the critical energy quantitatively and precisely still requires further study.

Variations in the temperature of the sample during the test are not obvious.

3.2. Microstructure of AZ31 after vibrated plastic deformation

Metallographic analyses of the stretched AZ31 samples were also conducted. The specimens were cut from the longitudinal sections near the fracture surfaces and treated with polishing and corrosion. The corrodent was a mixed solution of 5 g trinitrophenol, 10 mL alcohol, and 5 mL acetic acid. The microstructures of specimens were observed under the metalloscope.

Fig. 6 gives the original microstructure of the extruded AZ31 bar, which consists of approximately uniform equiaxed grains. Fig. 7 illustrates the microstructures around the fracturing surface of the samples under static tension and vibrated tension with different vibrating amplitudes. It is found that the microstructures of the samples superimposed with a lower vibrating energy are similar to those of the workpieces under static tensile, as shown in Figs. 7(a)-(c). The grains stretches along the direction of tension, some distortions occur and a few stripped twins appear in deformed grains. Fig. 7(d) shows the microstructure of a sample superimposed with the vibration amplitude of 90%*A*, there are only a few small twins growing from the grain boundary and no stripped twins are observed. Compared with the original structure, only small and uniform deformations appear.

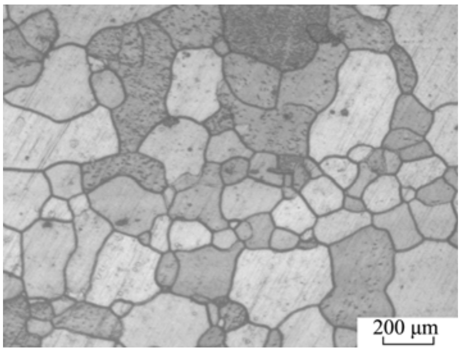

Fig. 6. Original microstructure of AZ31.

3.3. Mechanism of vibrated plastic deformation of AZ31

Slipping and twinning are the dominant mechanisms of metal plastic deformation. For an HCP Mg alloy, it is generally thought that twinning is the main plastic deformation mechanism at RT because of the small amount of basal slip

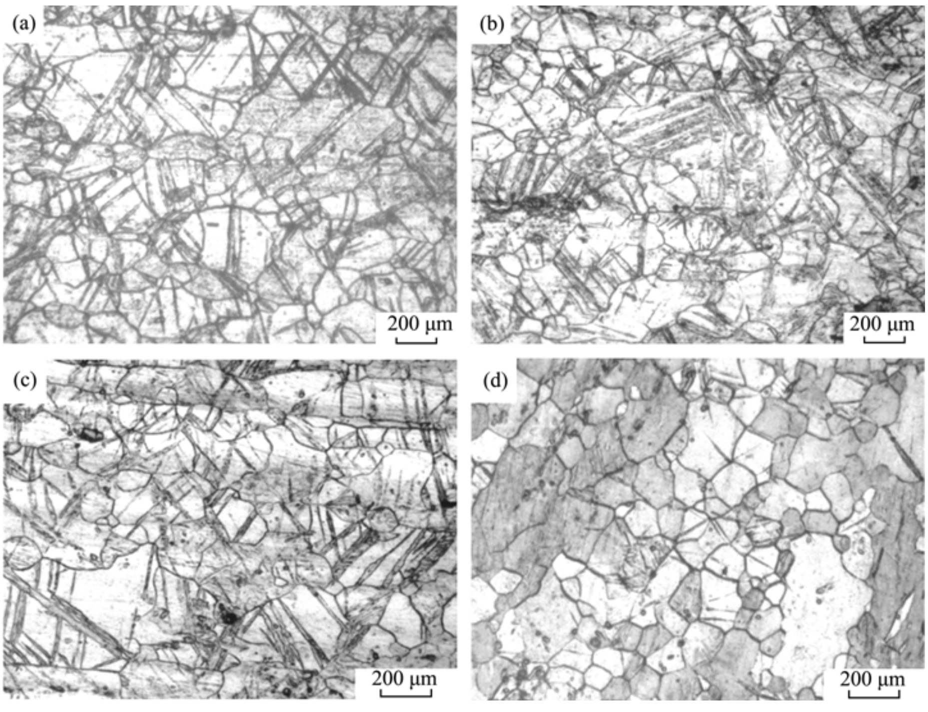

Fig. 7. Microstructures of the samples after tensile testing: (a) static tension; (b) 20%*A*; (c) 50%*A*; (d) 90%*A*.

systems, though the critical shear stress of basal slip is lower than that of the twin at RT.

The experimental results indicate that the effects of softening and hardening exist in the plastic process of AZ31 simultaneously, and convert with the excitation conditions which mainly concern vibration energy in this paper. When the excitation energy is lower, the softening effect is the primary mechanism in the vibrated plastic deformation of AZ31, which leads to a decrease of deformation resistance and an increase of elongation. Twinning of the crystal is plentiful and widely seen in the microstructures (Figs. 7(b)-(c)), and it is still the main plastic-deformation mechanism of AZ31. When the energy is higher, the hardening effect is dominant, the material becomes fragile, and only few twins grow from the grain boundary (Fig. 7(d)). It is shown that high-vibration energy would change the plastic-deformation behavior of AZ31 and promote further hardening.

The influence of vibration on the metal plastic-deformation process contains many aspects, such as mechanical and thermal effects, but the mechanism is not yet well understood. Culp and Gencsoy [5] proposed that the principle of the softening effect was to decrease the stress required for a dislocation movement by supplying energy to dislocation sites and to release the inner stress ultimately. Another viewpoint of Blaha and Langenecker [3] was that the vibrated inner particles became more active and the temperature increased, resulting in the decrease of the material deformation resistance and the hot softening which was involved with dislocation. However, the hot softening theory cannot interpret the hardening phenomenon with brittle fracture by supplying higher energy to the specimen in the test, and there is no great change in the temperature of the specimen. Thus, hot softening can not be the main factor. In addition, the stress superimposition effect is not the main mechanism of softening.

Langenecker [4] also observed hardening while superimposing a higher vibration energy on the tensile test of single-crystal zinc, leading to his consideration that the increase of flow stress was the result of movement and kinking of vibration-supplied zing crystal dislocations. As for the hardening of AZ31 superimposed with a higher vibration energy in the test, the author inferred that some new non-basal slips were probably produced, which increased the intensity and propagation of dislocation movement in a short time. Then, kinking occurred quickly among the dislocations and grain boundaries due to the presence of diverse force directions. All of these phenomena resulted in the blockage of continuous dislocation movement, which ceased the movement, leading to the more intense stress concentration.

4. Conclusions

(1) Ultrasonic vibration has great influence on the tensile force, deformation behavior, and the microstructure of AZ31 during the tensile process. The influence contains two opposite observable aspects, *i.e.*, the softening effect which reduces the flow stress and increases material plasticity, and the hardening effect which lessens the plasticity.

(2) If the excitation energy is low, twinning is still the main plastic-deformation mechanism of AZ31, and the softening effect is the primary mechanism in the vibrated plastic deformation of AZ31, which leads to the decrease of deforming resistance and the increase of formability. If the energy is high, the hardening effect becomes dominant and the material turns fragile.

(3) The preliminary work reveals some phenomena of the vibrated-plastic deformation of AZ31. Further research is still needed for many remaining problems. For example, the deformation process is sensitive to the change of amplitude (maybe frequency) of vibration, so the parameters of vibration superimposed on the forming process must be subtly quantified, then the connection between the vibration and deformation of AZ31 can be setup and understood more accurately. Also, the research on the essence of softening and hardening effects by means of modern electron microscopy observation and analysis techniques is important for the future work.

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