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Influence of ultrasonic vibration on the plasticity of metals during compression process

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ABSTRACT

In this study, the influence of ultrasonic vibration on the plasticity of lightweight metals (aluminium and titanium) was investigated by means of ultrasonic assisted compression (UAC) experiments. The experiments were carried out based on the newly designed ultrasonic horns and transducers which can generate a series of vibration frequencies (20, 30 and 40 kHz) and adjustable vibration amplitudes (4.06–10.37 μm). It is found that, the ultrasonic vibration can reduce flow stress during UAC process for both aluminium and titanium, a phenomenon referred as ultrasonic softening effect. Different vibration amplitude and frequencies were specifically altered for observing the ultrasonic softening effect. The result is: in the range from 20 to 40 kHz the ultrasonic softening effect can be enhanced by increasing the vibration amplitude; however, increasing vibration frequency will decrease the ultrasonic softening effect, which is different from the previous acceptance stating that the vibration frequency (from 18 kHz to 80 kHz) has no influence on the ultrasonic softening effect. Apart from the ultrasonic softening effect, it is also found that the ultrasonic vibration can lead to residual hardening effect to aluminium and residual softening effect to the titanium. The influence of experiment parameters to the ultrasonic softening and residual effect during the UAC were assessed quantitatively and individually. These parameters include vibration frequency and amplitude, vibration duration as well as the sample size. Based on the UAC test within the elastic deformation stage, the mechanism of ultrasonic softening effect was explained from the occurrence of the unload phenomenon caused by ultrasonic vibration induced localized deformation. To validate the proposed mechanism, nanoindentation and electron backscatter diffraction (EBSD) test were carried out. According to the test result, ultrasonic vibration can induce plastic deformation and refine the grains for both aluminium and titanium sample. And for aluminium sample, comparing with the grains in the sample centre, the grains in the sample up boarder area are more sensitive to the ultrasonic vibration in terms of grain refinement, while for the titanium it is on the contrary.

1. Introduction

The ultrasonic vibration has been widely used as assistance to different metal processing technologies, such as ultrasonic metal welding, ultrasonic wire drawing, and ultrasonic assisted sheet forming. During the ultrasonic vibration assisted manufacturing, several parameters like vibration frequency, amplitude and duration of vibration are adjustable for different forming process and different materials.

In regard to the frequency influence on ultrasonic vibration assisted forming process, the first experimental study could be dated back to 1957, when Nevill and Brotzen (1957) conducted a tensile test of low carbon steel wire under superimposed ultrasonic vibration. By adjusting the length of wire, some longitudinal standing waves with a range of vibration frequencies were generated on the specimen wire. According to their report the stress reduction caused by the ultrasonic vibration is independent to the vibration frequency in the range from 15 kHz to 80 kHz. However, a concern is raised with the experiment setup used in this research. Although the frequency of input current can vary from 15 kHz to 80 kHz, the crystal and the exponential stub (also called as ultrasonic horn) were unchanged during the experiments. In this case a stable vibration mode of resonance could not be reached when the input frequency varies. Ideally with the change of input current, the crystal and exponential stub should be adapted according to the input frequency, so that the output vibration from the exponential stub to the specimen is controllable in the aspects of vibration amplitude and mode. Moreover, for studying the influence of vibration frequency on the plasticity of the sample, the length of the sample wire was adjusted to make it resonate to the exponential stub. This change however may

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affect the plastic behaviour of the samples in vibration due to the size effect. Furthermore, during the tensile test, deformation of the sample may shift its natural frequency and even make it no longer resonates when the exponential stub keeps a same vibration mode as before. Blaha and Langenecker (1959) also reported that the reduced stress is independent to the vibration frequency when the frequency is from 15 Hz to 10^6 Hz. Their explanation was based on the fact that the vibration frequency in this range is much smaller than the natural resonant frequency of dislocation loops, which is normally 10^9 Hz. But no direct evidence was given to prove that without resonating with the dislocation loops the vibration frequency cannot influence the ultrasonic softening. These two reports have been cited by some studies to support the finite element modelling of the ultrasonic softening effect. Siddiq and El Sayed (2011) developed a crystal plasticity finite element model for the ultrasonic vibration assisted manufacturing process with considering the acoustic softening effect and they mentioned that the ultrasonic softening is independent to the vibration frequency in the range of 15–80 kHz. However during the calculation of the ultrasonic softening parameters, the velocity of the material point which is influenced by the vibration frequency was used. Djavanroodi et al. (2013) found that the forming force will be reduced by increasing ultrasonic vibration amplitude and frequency during equal channel angular pressing, and amplitude has more effective influence than frequency. Nevertheless, their conclusion was based on the finite element analysis and no experimental study about the influence of vibration frequency was conducted.

In the application of ultrasonic vibration, such as ultrasonic metal welding and ultrasonic assisted wire drawing, changing the height of a sample to make it resonate with the ultrasonic horn is not practicable. An alteration is to design the ultrasonic horn to let it match its resonance frequency to that of the ultrasonic transducer's, so as to achieve efficient input of the ultrasonic vibration power. For exploring the influence of ultrasonic vibration frequency to the plasticity of metals, in present study with changing the frequency of the input current (20, 30 and 40 kHz), three sets of experiment apparatuses featured with transducers and ultrasonic horns in different sizes are designed. These apparatuses can resonate with the input current at the frequency of 20 kHz, 30 kHz and 40 kHz, thus guarantee a stable and controllable vibration output. Details are illustrated in Section 2.

In addition to the vibration frequency, vibration amplitude is another key factor affecting plasticity of metal in ultrasonic vibration assisted manufacturing. Numerous studies have confirmed that the magnitude of stress reduction depends on the vibration amplitude. But for exact quantitative relationship between ultrasonic vibration amplitude and stress reduction, the answers were inconsistent. Siddiq and El Sayed (2012a) proposed a phenomenological crystal plasticity model of aluminium for the ultrasonic consolidation process. In this model the ultrasonic softening effect was suggested to be proportional to the acoustic intensity which is in turn proportional to the square of the amplitude accordingly. And in their following work, Siddiq and El Sayed (2012b) used the same equation to calculate the ultrasonic vibration induced softening effect, however with the use of different parameters the ultrasonic softening effect of aluminium was defined to have a quadratic relation with ultrasonic intensity. Although, both of these two works took aluminium as the subject, by using different sources of experimental data to do the equation fitting, different relationship between the ultrasonic softening and vibration amplitude were achieved. Huang et al. (2009) studied the ultrasonic wire bonding of copper, it showed that the reduction of stress of copper was proportional to the vibration amplitude. And by comparing the results of cooper and gold, they suggested that the ultrasonic softening may be largely influenced by the crystal structure rather than the materials type. Since titanium has a different crystal structure to aluminium and there is little quantitative research about the ultrasonic softening of titanium, so in this study through using of titanium samples which have a relatively high strength, the influence of vibration amplitude to the stress reduction during UAC has been studied over a wide range of amplitudes.

On the other hand, there have been some reports on the mechanism of the ultrasonic softening effect. Malygin (2000) proposed a stress superimposition mechanism for the acoustic plastic effect based on the computer simulation. However Daud et al. (2007) found that the oscillatory stress induced by the ultrasonic vibration was smaller than reduction of mean stress during the ultrasonic vibration assisted compression and tension test of aluminium. To better understand the underlying mechanism of acoustic plasticity from the microstructure aspect, Siu and Ngan (2011) conducted the dislocation dynamic simulation on the interaction of dislocations with the superimposing of quasi-static and oscillatory stress. They found that the dislocation annihilation was enhanced in this combined stress state and it led to larger strain at the same loading history. Furthermore, since ultrasonic vibration just works like an ultra-high frequency impacting in the UAC test, it is necessary to investigate if the strain induced by the ultrasonic vibration is localized or evenly distributed to have a better understanding of the ultrasonic softening effect.

Besides ultrasonic softening effect, the high frequency vibration could also cause the residual effect to the metal materials during plastic deformation. Yao et al. (2012) conducted the ultrasonic assisted compression test of aluminium and built a crystal plasticity based model for this process. In their research the acoustic residual hardening effect was interpreted by the multiplication of dislocation density which was time dependent, and the ultrasonic residual softening effect were also mentioned as the possible result of dislocation annihilation. Lum et al. (2009) found that during the ultrasonic wire bonding of gold there existed a residual softening effect. They explained that the ultrasonic vibration could induce sufficient heat input to the sample to make it annealed and reduce the dislocation; hence there was a residual softening effect. The same theory was also applied to the cooper, when Huang et al. (2009) studied the residual softening effect during the ultrasonic wire bonding of it. Zhou et al. (2017) conducted EBSD test to investigate the ultrasonic vibration induced residual effect of aluminium and titanium. They found that for aluminium the ultrasonic vibration reduced the grain size and changed the orientation of the grains, and both of which contribute to the residual hardening effect. However, for the titanium, the grain refinement induced by ultrasonic vibration is limited. And the ultrasonic vibration can promote the saturation of twinning and reduce the fraction of twinning boundaries. Since the twinning boundary works as a hardening factor to titanium, the UAC titanium sample exhibits a residual softening effect with less twinning boundaries. Although there have been some discussions about the mechanisms of the ultrasonic vibration induced residual effects, the quantitative relationship between the ultrasonic vibration parameters and the residual effects still needs to be investigated.

Although there have been many discussions regarding the influence of ultrasonic vibration parameters to the plasticity of metal, different conclusions have been drawn due to the differences in experiment apparatus applied among these studies. As shown in Table 1 in present study three ultrasonic vibration experiment setups with different vibration frequencies and adjustable amplitude were built to provide stable, adjustable and comparative parameters for the ultrasonic assisted compression test. Lightweight materials pure aluminium and titanium were chosen as samples due to their widely industrial usage and quite different crystal structures which may respond variously to the ultrasonic vibration. Comparing to previous studies, current work investigated the influence of ultrasonic vibration frequency and conducted microstructure analysis for the samples that subjected to transient ultrasonic vibration to study the mechanism of ultrasonic softening. What is more, the study of ultrasonic residual effects can give some hint in evaluating the service performance of the products manufactured with the assistance of ultrasonic vibration.