

Compressive Behaviour and Energy Absorption of Copper Tube under Quasi-Static and Ultrasonic Compression Test

Nur Amanina Damira Binti Muhalim

Mohd Yusof Bin Md Daud

Mohamad Zaki Bin Hassan

Sa'ardin Bin Abdul Aziz

Norazmein Bin Abdul Raman

Shamsul Bin Sarip

UTM Razak School of Engineering and Advanced Technology,
Universiti Teknologi Malaysia, 54100 Kuala Lumpur, Malaysia

ABSTRACT

The application of ultrasonic vibration in metal forming has significantly reduced the forming force. This force reduction can be explained by the softening effect of material and the reduction of friction between the interfaces. However, studies on metal forming focused on the deformation of bulk metal, but specific study focusing on the application of ultrasonic vibration on tube forming is very limited. Therefore, the present study aims to investigate the compressive behavior and energy absorption of a copper tube under quasi-static and ultrasonic compression. This investigation was carried out for copper tube specimens on a simple compression test set-up using a constant cross head speed of 30 mm/min on dry surface condition. For the quasi-static compression test, specimens were statically compressed without ultrasonic vibration between an upper and lower rigid platen. For the ultrasonic compression test, specimens were compressed with ultrasonic vibration between upper rigid platen and ultrasonic horn. A specifically designed ultrasonic horn was fabricated prior to the test as a medium to transmit the ultrasonic vibration to the specimens. The horn was tuned to a longitudinal mode at 19.89 kHz frequency with a uniform nominal vibration peak amplitude of 6 μm on the horn surface. Load-displacement distributions for quasi-static and ultrasonic compression tests were analysed. A comparison of quasi-static and ultrasonic compression test results has been made. It was found that the compressive stress was remarkably reduced with

the onset of superimposed ultrasonic vibration during plastic deformation and has lowered the energy absorption of the specimens. In addition, better deformation profiles of end products were obtained by the increase of compressibility and formability of the specimens as compared to quasi-static compression.

Keywords: *Ultrasonic Vibration, Ultrasonic Horn, Tube Forming, Compression Test*

Introduction

Metal forming technology plays a crucial role in the manufacturing industry and is evolving over the years. The increase of demand for high quality product in large volume forced the manufacturer to enhance their processing technique including the use of ultrasonic technology in this industry. It has been reported that the application of ultrasonic vibration in metal forming has benefited most metal forming, extrusion, bending, forging and drawing by reducing the forming force, increased processing rates, less tool wear and improved surface finish [1-5].

Conventional metal forming processes offer some limitations in terms of its high forming forces, poor surface finishing, low production rates and shorter tool life. Ultrasonic vibration has been applied to these varied metal forming process to enhance the performances. Blaha and Langenecker [1] had first studied the effect of ultrasonic vibration on the mechanical properties of metals. The study showed that superimposing an alternating stress on a workpiece greatly affected the process rate and the force needed for workpiece deformation decreased. This study triggered continuous developments in the field of ultrasonic metal forming. The effectiveness of applying ultrasonic vibration during deformation processes are related to the process rate, friction condition, ultrasonic frequency and amplitude, vibration mode, type of deformation and material properties [6]. The application of ultrasonic vibration has been widely used to determine fatigue life of material. An ultrasonic fatigue test can provide high cyclic load cycle and therefore shortened the time to complete the test [7]. However, this test can only suggest the time service duration of the component before failure at constant cyclic load. Some application may involve a superimposed cyclic force during applied static stress [8]. The application of ultrasonic vibration has been extended into specific metal forming process. In tube hydroforming process, ultrasonic has assisted to reduce forming force and gained better surface quality of end product. It was proved that this process has increased the corner filling ratio and uniform wall thickness were obtained [9]. Similar

benefit was reported for ultrasonic tube drawing. In this process, ultrasonic vibration was successfully applied to replace lubricant [10].

Most researchers had focused on the ultrasonic forming of solid specimens. However, hollow part such as metal tube and pipe are also commonly deformed and fabricated for competitive design and manufacturing. Therefore, further studies are required to improve the process and quality of deformed metal tube. In line with that, the present study had investigated the influence of ultrasonic vibration in compression test of copper tube. The criticality of full understanding of the compressive behavior and energy absorption of copper tube under quasi-static and ultrasonic compression test has been carried out to justify the deformation process of a metal tube specimen. A characteristics of load-displacement curves and specific energy absorption were analysed. In addition, further deformation profile of the compressed copper tube was observed. It is expected that through in-depth understanding of material response under high cyclic stress provides useful information for metal tube design, process, quality, fabrication and applications.

Methodology

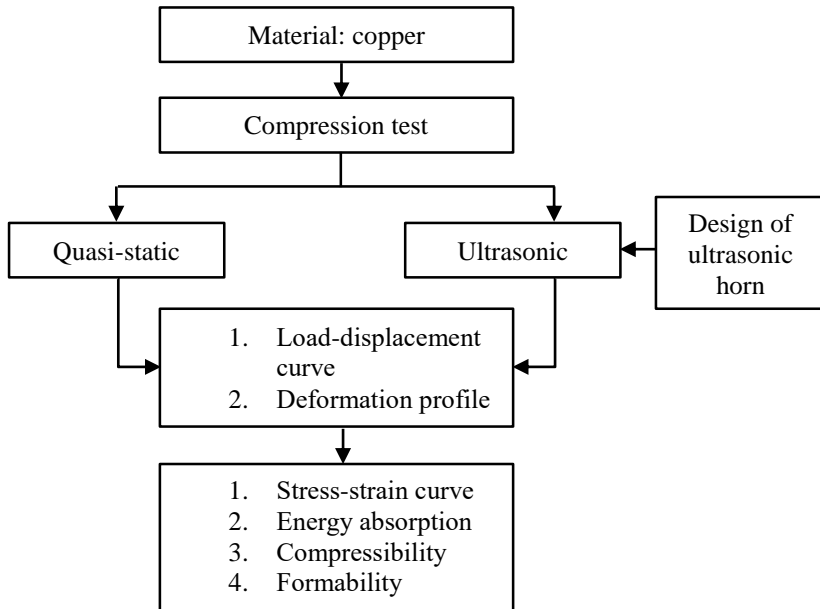


Figure 1: Research framework

A detailed methodology was formulated to design and fabricate the ultrasonic horn and exhibit direct experimental determination of mechanical and physical response of copper tube. This method was carried out to establish characteristics of load-displacement curve and deformation profile of copper tube from the quasi-static and ultrasonic compression test as shown in the framework in Figure 1.

Design of Ultrasonic Horn

A double-slotted block horn design was adapted in this study [11]. The horn was able to excite ultrasonic vibration at a frequency of 19.89 kHz and giving longitudinal mode vibration on the working surface. A three dimensional model was developed to calculate the longitudinal natural frequency and mode shape of the horn using a commercial finite element (FE) simulation code, Abaqus 6.14. The horn was derived using high grade aluminium properties and was assumed to be homogeneous. Details of the material properties used in the model are tabulated in Table 1.

Table 1: Material properties of aluminium

Material properties	Aluminium
Young's Modulus (GPa)	69
Poisson's ratio	0.33
Density (kg/m ³)	2712

Standard slotting configurations were included in this design to maximize vibration amplitude uniformity at the working surface. A static and dynamic responses of loaded structures was analyzed using a frequency analysis to define the mode shape and natural frequencies with free boundary condition. A vibrational analysis consists of two prescribed step which are frequency step and steady-state dynamics direct step. The frequency step using Lanczos to obtain natural frequencies within the specified frequency range. This step can predicts natural frequencies and mode shapes of the system. The steady-state dynamics direct step predicts the stress and displacement amplitude for the applied loading condition. The modelling process was iteratively conducted by adjusting the horn dimensions until the final dimension is able to excite 19.89 kHz frequency in a longitudinal mode. Figure 2 depicts the undeformed and deformed mesh in longitudinal mode of the horn derived from the FE modelling.

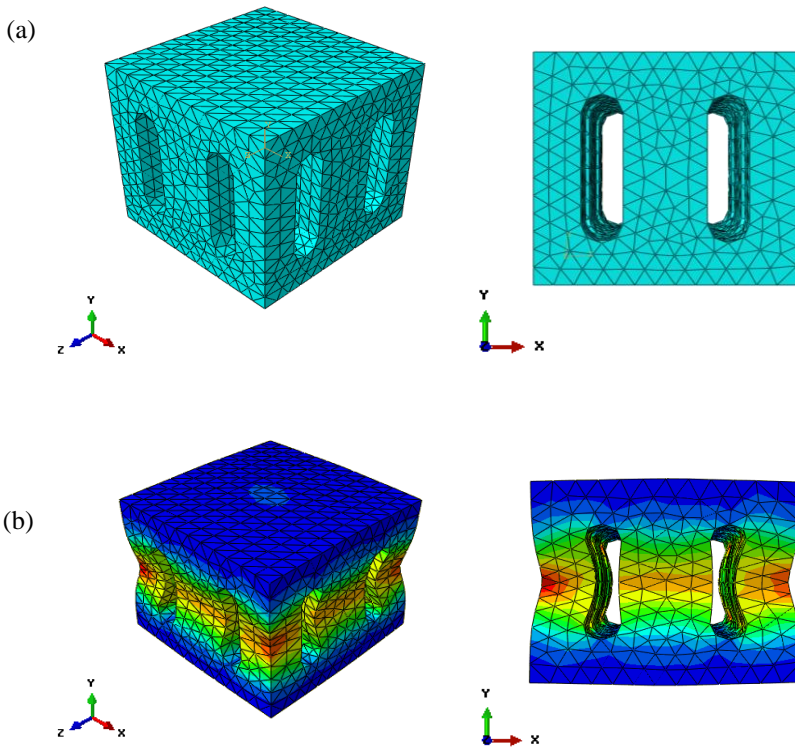


Figure 2: Horn contour for (a) undeformed and (b) deformed mesh of ultrasonic horn

A clear frequency spectrum from the designed double-slotted block horn was predicted by the FE modelling as shown in Figure 3. The measurement took place on a unique nodal at the horn top surface in y-direction which means in longitudinal mode. The fundamental length extensional frequency predicted by the FE modelling was 19.89 kHz with a measured maximum displacement of the top horn at 0.7 mm.

Subsequently, the horn was fabricated using high grade aluminium according to the final dimensions derived from the FE modelling. Figure 4 depicts a complete double-slotted block horn attached to the ultrasonic system. The ultrasonic system consist of ultrasonic horn, transducer and generator. The horn was able to vibrate at a frequency of 19.89 kHz in longitudinal mode. Calibration of the amplitude on the block horn top surface was measured at 6 μm using high precision digital dial indicator.

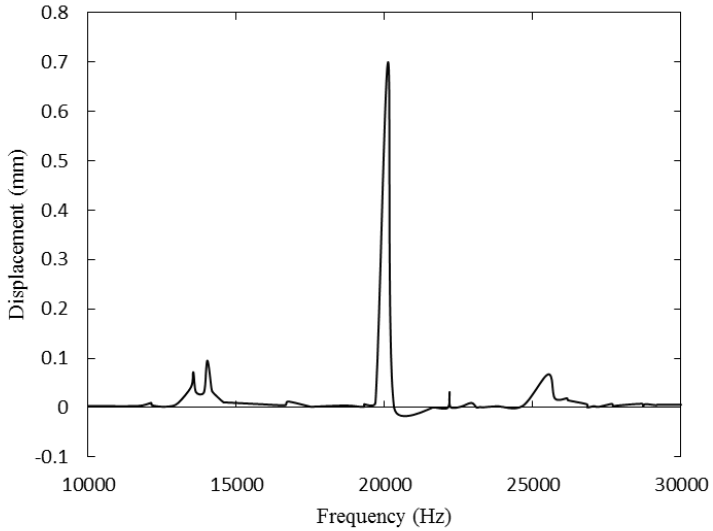


Figure 3: Measured frequency response of ultrasonic horn in y-direction

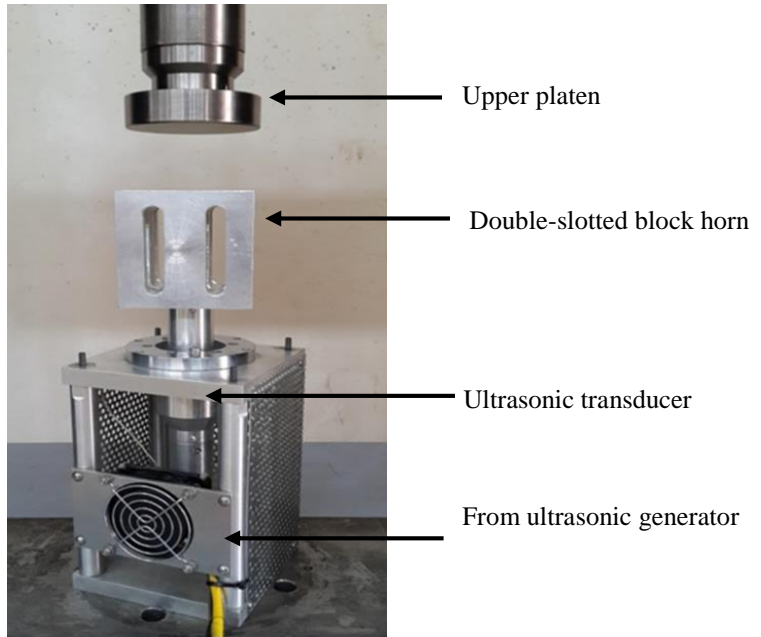


Figure 4. Double-slotted block horn attached to the ultrasonic system

Quasi-static and Ultrasonic Compression Test

A thin copper tube with a Young's Modulus of 55 GPa, Poisson's ratio of 0.35 and a density of 8930 kg/m³ were used. Details of the copper tube dimensions were given in Table 2. A series of quasi-static and ultrasonic compression test was carried out by descending the cross head of universal testing machine at a constant velocity of 30 mm/min. The interface condition of tube specimens between upper and lower rigid platens were remained in dry condition.

For the quasi-static compression test, specimens were statically compressed between two rigid platens. The test procedure was then repeated for the ultrasonic compression test, but the lower platen was replaced with a double slotted block horn as shown in Figure 5. The horn was used as the medium to transfer the ultrasonic vibration from the ultrasonic transducer to the working specimens during the static deformation process.

Two sets of ultrasonic compression test were conducted. For the first set, the ultrasonic vibration was applied during post-yield for three short intervals by switching on the ultrasonic generator for duration of 1 second. Successively, when the ultrasonic vibration was discontinued, static compression was continued between these intervals. For the second set, the ultrasonic excitation was applied continuously from the onset of plastic deformation to the completion of the test. Quasi-static and ultrasonic compression test specimens were compressed until it reduced more than 50% of its original length. Load-displacement data were recorded through hardware and software of the universal testing machine. Furthermore, the deformation profile of compressed tubes were observed and the energy absorption from both quasi-static and ultrasonic compression test were calculated.

Table 2: Dimensions of copper tube

Nominal or standard size (mm)	Outside diameter (mm)	Inside diameter (mm)	Wall thickness (mm)	Length (mm)
9.5	9.53	7.90	0.82	20
12.7	12.70	11.07	0.82	20
15.9	15.88	14.10	0.89	20

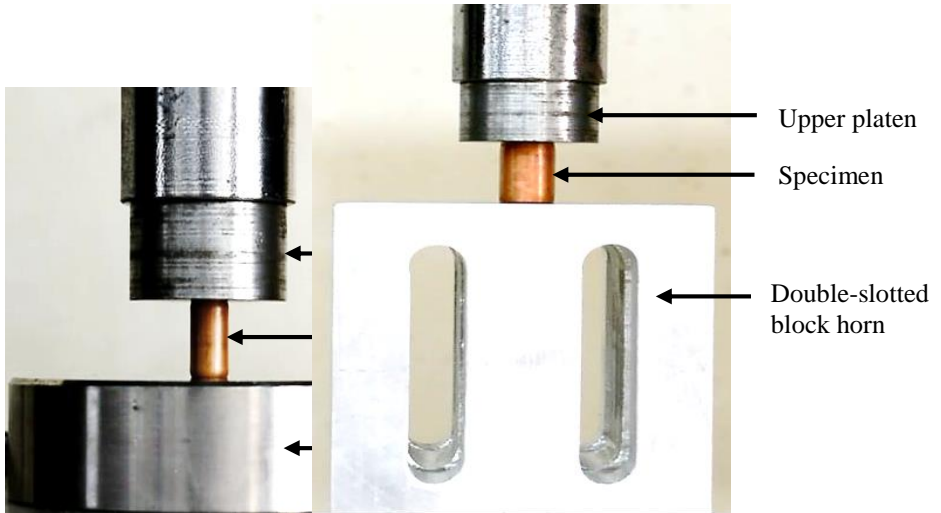


Figure 5: Compression test set-up for quasi-static (left) and ultrasonic (right)

Results and Discussion

To study the effect of ultrasonic vibration during the compression process of the copper tube, set of load-displacement curves has been plotted. Figure 6 and 7 show a comparison of load-displacement curves of both quasi-static and ultrasonic compression test. In the quasi-static compression test, copper tube was initially deformed in elastic behavior until it was displaced nearly at 1.8 mm. The compressive force dropped drastically immediately after yield and the force started to regain lower than the yield point. Subsequently, the force was repetitively dropped and regained at different level before the force continued to increase until the test stop at approximately 50% of tube height reduction. This force fluctuation during post yield could be explained by the repetitive tube swelling before it compressed further and the swelling closely compacted. A significant force reduction has been recorded when continuous and intermittent ultrasonic vibration applied in the plastic region. More than 1.0 kN force was reduced for both ultrasonic compression.

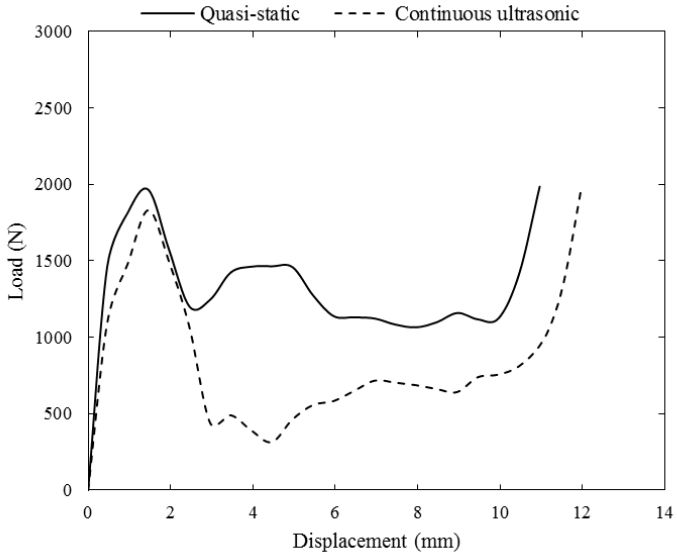


Figure 6: Force-displacement of quasi-static and continuous ultrasonic relationship for 9.5 mm diameter tube

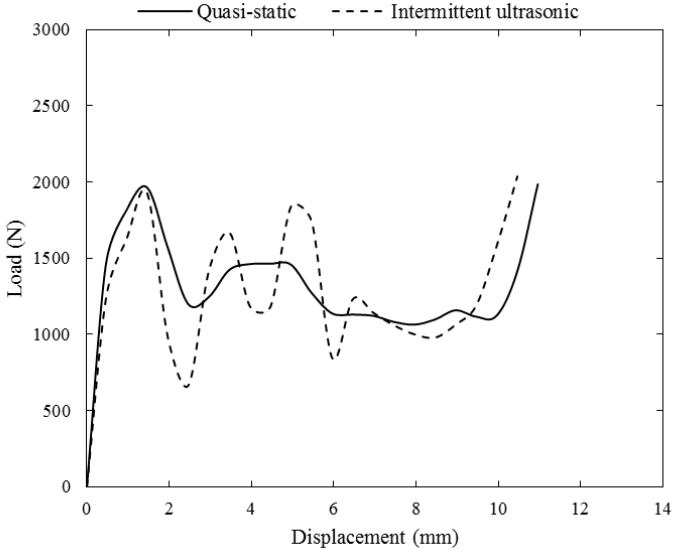


Figure 7: Load-displacement of quasi-static and intermittent ultrasonic relationship for 9.5 mm diameter tube

Stress-strain curves for quasi-static and ultrasonic compression test were plotted as shown in Figure 8 to 10. Figure 8 shows stress-strain curves for quasi-static compression test. There were three distinct deformation regions during the compression process. Initially, the linear-elastic region occurred at 0 to 5% of strain. In the plastic region, slight fluctuation in stress were recorded. This could be explained by the repetitive swelling process of the tube in this region. Finally, the densification process started to occur at a point where the stress has increased rapidly with further small deformation. A comparison of compressive strength with several diameter size of copper tube shows that for increasing diameter size, the compressive strength increased up to 66 MPa.

Figure 9 shows stress-strain curves for intermittent ultrasonic compression test. Based on Figure 9, stress dropped drastically after yield when the ultrasonic vibration was applied and start to regain repetitively at a lower stress than the yield stress. This process continued for three irregular intervals corresponding to the three times application of ultrasonic vibration before the stress risen rapidly until it reached more than half of its height reduction. The stress variation in the plastic deformation regime can be explained by the repetitive ultrasonic vibration application. It was observed that the stress reduced for more than 50% when ultrasonic vibration applied.

Significant stress reduction has been recorded for the continuous ultrasonic compression test as shown in Figure 10. Stress reduced for more than 50% when the ultrasonic vibration was applied after it reached yield stress. However, it was recorded that the process of continuous ultrasonic compression for the largest diameter size of 15.9 mm was interrupted when the specimen shifted from its position after 10% displacement. This interruption could be related to the inappropriate selection of the specimen aspect ratio. The problem was probably due to resonance effect when the excitation frequency reached the natural frequency of the specimen. However, it suggested that the excitation of high frequency at lower platen has remarkably reduced the stress. Another substantial observation that can be deduced from the figure is that the application of ultrasonic vibration on static deformation stress has significantly reduced or eliminated the stress fluctuation as being recorded in quasi-static compression. It was likely able to smoothen the variant stress curve given by the quasi-static compression. Furthermore, the densification has been delayed.

Hence, based on the comparison of quasi-static and ultrasonic compression test described above, it can be assumed that the application of ultrasonic vibration in compression test had assisted the deformation process by reducing the compressive stress. It was believed that the timing when the ultrasonic excitation was imposed could influence the amount of the stress reduction. This was due to ultrasonic vibration that was applied during the weakest point of the compressed foam, definitely further stress drop was

obtained due to these combined effects. The comparison was also supported by the previous researchers who claimed that the stress flow of compressive deformation can be remarkably reduced by superimposing ultrasonic vibration on the static load in compression test [12-14]. It was concluded that the change of elastic-plastic properties and material softening had occurred under the influence of ultrasonic vibration. A possible explanation was also deduced by Winsper and Sansome [15] who suggested that the stress reduction can be associated with the material softening. Few other studies explained that copper material has special characteristic when deformed under ultrasonic excitation. These studies claimed that copper has exhibited special temporary softening in ultrasonic assisted forming [14, 16-18]. Other studies showed that the material flow stress in ultrasonic compression test was under the influence of friction [19-21]. One of the mechanism that contribute to the force reduction is friction vector effect [22]. This occurred when the oscillatory velocity of the lower platen exceeds the specimen velocity. Friction vector is a result from the relative motion between the lower platen and specimen which normally acts in perpendicular direction to the specimen motion. But the friction vector is reversed when the lower platen is vibrated. It is due to the motion of the lower platen is parallel to the specimen motion, such that it assists the motion to the specimen in the working direction and therefore reduced the friction force then stress.

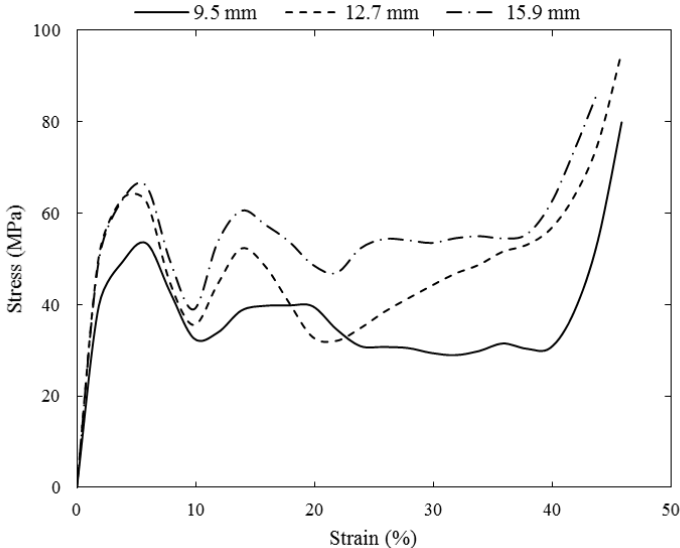


Figure 8 Stress-strain of quasi-static relationship for all diameter tube

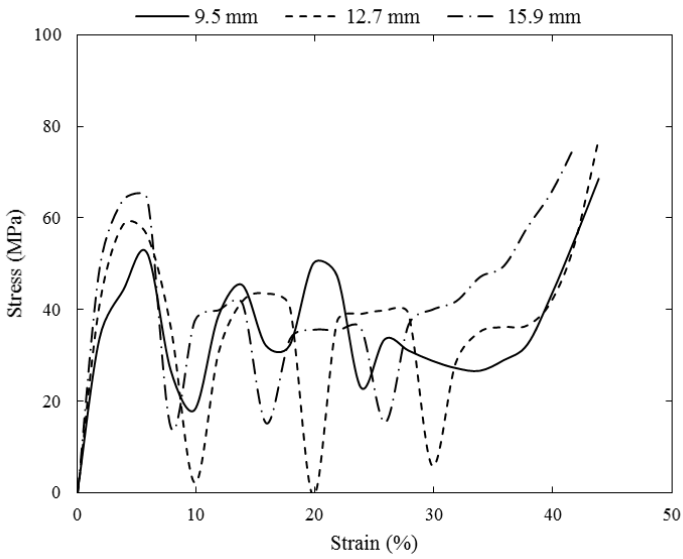


Figure 9 Stress-strain of intermittent ultrasonic relationship for all diameter tube

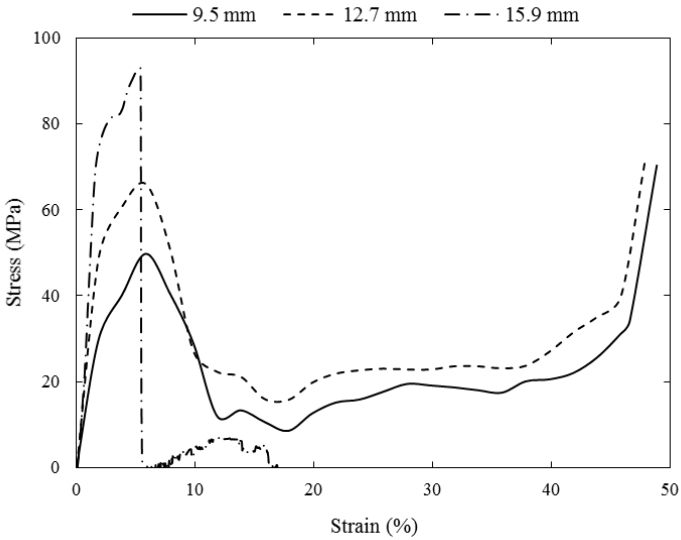


Figure 10 Stress-strain of continuous ultrasonic relationship for all diameter tube

The influence of superimposing ultrasonic vibration during compression test on the energy absorption capability was studied. This can be observed from the bar chart in Figure 11. Figure 11 shows the comparison of energy absorption for all specimens of various diameter size under three types of compression test. To ensure the value of energy absorption are comparable within tests and specimens, the calculation was limited to 38% of strain and below. It was observed that the continuous ultrasonic compression test has the highest reduction of energy absorption compared to intermittent ultrasonic and quasi-static compression test. It means that the ability of the copper tube to absorb energy and plastically deform without fracturing is lowered by the application of ultrasonic vibration in compression test. The material softening effect as described earlier is proven by this lowered energy absorption as it reduced the material toughness. With the presence of ultrasonic vibration during compression test, copper tube withstand low resistance to fracture when stressed.

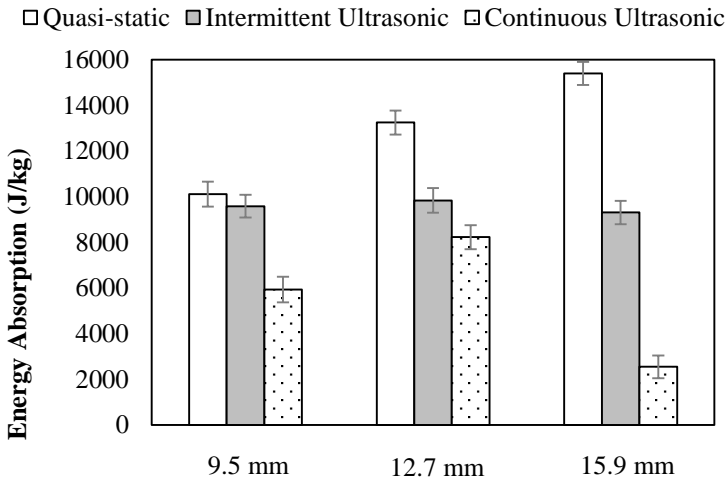


Figure 11 Energy absorption of quasi-static and ultrasonic (intermittent and continuous) for all diameter tube

To support prior explanation, a qualitative investigation has been conducted. The investigation was carried out to study the deformation profile of the compressed tube under quasi-static and ultrasonic compression test as shown in Figure 12. It was observed that the deformed tube under ultrasonic compression test has better swelling effect compared to quasi-static compression. It can be assumed that the material softening in copper tube during ultrasonic compression test has resulted in better deformation profile.

Top view



Front view



(a)

(b)

Figure 12 Comparison of deformed tube – (a) quasi-static compression, irregular swelling and (b) ultrasonic compression, regular swelling

Conclusions

The compressive behavior and energy absorption of copper tube under quasi-static and ultrasonic compression test has been demonstrated. It was found that the compressive stress was remarkably reduced at the onset of superimposed ultrasonic vibration during plastic deformation and has lowered the energy absorption of the specimens. Both effects of stress reduction and lowered energy absorption was related to the material softening. Qualitative investigation on the deformed specimens revealed that the deformation profile of specimens under the application of ultrasonic vibration was uniformly deformed compared to the specimens without ultrasonic vibration. The compressibility and formability of the specimens was remarkably increased with the presence of ultrasonic vibration on the static deformation process. In addition, with the presence of ultrasonic vibration in compression test, copper tube withstand low resistance to fracture when stressed, resulted in lowering the compressive stress and improved the deformation profile.

Acknowledgements

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