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Effects of ultrasonic vibration on SUS304 stainless steel subjected to uniaxial plastic deformation

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ABSTRACT

In this study, a series of experiments was conducted in order to investigate the mechanisms of tensile force reduction and martensitic transformation in SUS304 stainless steel during ultrasonic vibration assisted tensile tests (UAT).

An independent analysis of the impact of the stress superposition effect in the ultrasound assisted tensile tests was done by finite element simulation, and metallographic analysis on the specimens showed that the increase of the amplitude of the ultrasonic vibration has a great influence on the martensite transformation in the material during deformation, reducing the elongation of the specimens. The results also pointed out that the tensile force reduction is caused by a combination of the effects of stress superposition and the energy absorption of dislocations over the hardening of the material due to the increase of dislocation density and induced martensitic transformation.

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Tensile testing; ultrasonic vibration-assisted forming (UAF); strain-induced martensitic transformation; stainless steel

1. Introduction

Ultrasonic vibration has a wide variety of uses in metal processing and many industrial applications use ultrasonic vibration, such as ultrasonic welding, ultrasonic upsetting, and ultrasound-assisted deep drawing. Various studies have demonstrated the beneficial effects of ultrasonic vibration-assisted metal forming, such benefits include reductions of forming forces and surface roughness and enhancement of dimensional accuracy, which might be attributed to the superposition of stress, increased temperatures, varied interface friction, and energy absorption of dislocation.

Blaha and Langenecker (1955) were the first to perform an experimental investigation on the effects of ultrasonic vibration on the plasticity of metals, observing a substantial reduction of the yield stress and flow stress, by superimposing high-frequency vibration on a single-crystal zinc specimen during a tensile test. Subsequent work from other authors with ultrasonic vibration-assisted experiments also observed similar phenomena. Many studies have discussed the softening mechanisms with the addition of ultrasonic vibration. Kempe and Kroner (1956) proposed three mechanisms, namely resonance, relaxation and hysteresis to explain how the dislocations absorb energy from high-frequency vibration, reducing the flow stress. Nevill and Brotzen (1957) proposed a stress superposition mechanism to explain how ultrasonic action can reduce flowing stress in a forming process. Langenecker (1966) applied transmission electron microscopy (TEM) to observe the dislocation density increase in materials under ultrasonic vibration. Huang, Lucas, and Adams (2002) applied ultrasonic vibration to a die and reduced the mean forming force during upsetting, concluding that both stress superposition and interface friction reduction contributed to the aforementioned phenomena. Liu et al. (2012) indicated that ultrasonic vibration can be used in upsetting to refine pure copper grains by dislocation motion. For decades, researches in the field of ultrasonic vibration-assisted metal forming have investigated a wide range of ultrasonic vibration associated effects such as the superposition of stress, increased temperatures, and energy absorption of dislocation (Nevill and Brotzen 1957), (Langenecker 1966). However, these effects are usually coupled and an independent analysis is very hard to accomplish; therefore, the main mechanism that induces these effects is still unclear.

SUS304 stainless steel is a metastable austenitic stainless steel that presents excellent mechanical properties accompanied by corrosion resistance, and has been widely used in various products in the automotive, chemical and food industries, just to name a few. The material has face-centered cubic (FCC) austenite as its primary phase, and it undergoes a deformation-induced martensitic transformation during its plastic deformation behavior (Mcguire 2008). The phenomenon of deformation-induced martensitic transformation depends on the chemical composition (Andrade et al. 2004), temperature (Müller-Bollenhagen, Zimmermann, and Christ 2010), strain rate, and microstructure of the material. Previous researches indicated that cold plastic deformations of austenitic stainless steel considerably increase the density of dislocations (Cigada et al. 1982), (Odnobokova, Belyakov, and Kaibyshev 2015). Iyer (1988) observed the effect of ultrasonic vibration on the transformation of austenite into martensite in 304L stainless steel, attributing the observed effects to the increase of dislocation density and point defects. However, the mechanism of deformation-induced martensitic transformation on the ultrasonic vibration-

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assisted forming of SUS304 stainless steel is still not fully understood.

This study aims to examine the effects of ultrasonic vibration on phase transformation of ultrasound-assisted tensile testing of SUS304 stainless steel, and to correlate the main mechanisms of tensile force and elongation reduction with the phase transformation of the material during deformation and the other effects associated with ultrasonic vibration.

2. Materials and methods

2.1. *Material and experimental apparatus*

Cold-rolled SUS304 stainless steel sheet with thickness of 0.1 mm was used for the experimental work, and the material was annealed before the experiments. Table 1 presents the chemical composition of SUS304. The specimens were cut out from the supplied sheets at 0°, 45° and 90° in respect to the rolling direction using wire-electro discharge machining (WEDM) and to accommodate to the experimental apparatus, the specimens were scaled down from the standard ASTM-E8 (ASTM 2013), and the dimensions of the are shown in Figure 1.

The tensile tests were performed with a tensile tester customized by Hung Ta Company from Taiwan. Figure 2(a) illustrates the configuration of the ultrasonic vibration-assisted device. Two miniaturized chucks were especially designed (Figure 2(b)) for holding the specimens and also to allow transmission of ultrasonic vibration to the specimen. The chucks were made from SKD41 tool steel, to avoid the chucks to softening during the ultrasonic vibration. The upper chuck was attached to the ultrasonic horn and the lower chuck was attached to the load cell.

Table 1. Chemical composition of SUS304 steel (%).

C	Si	Mn	P	S	Ni	Cr
0.05	0.39	1.02	0.026	0.002	8.05	18.1

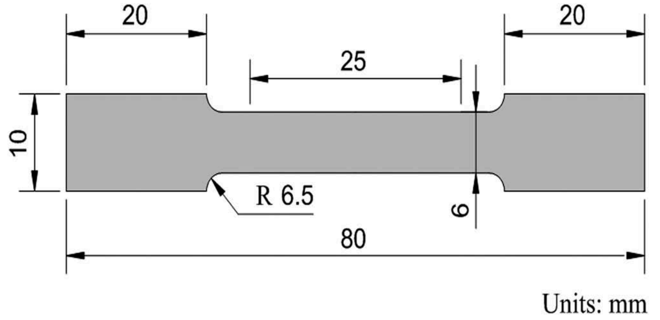

Figure 1. Schematic illustration of the tensile testing specimens.

2.2. *Experimental work plan*

The elongation speed of tensile testing was maintained at 2 mm/min. The test cases were classified as general tensile tests (GTT) and ultrasonic vibration-assisted tensile tests (UAT). The GTTs were conducted until the testing specimen failure without ultrasonic vibration, while the UATs entailed applying an ultrasonic vibration to the specimen 5 s after the test began, to ensure that the stress of the specimen has entered into the elastic regime. The ultrasonic vibration continued until the failure of the specimen.

The UATs used ultrasonic vibration with a frequency of 20 kHz and different amplitudes in the axial direction (Table 2). The amplitude of ultrasonic vibration was measured by an LK-H020

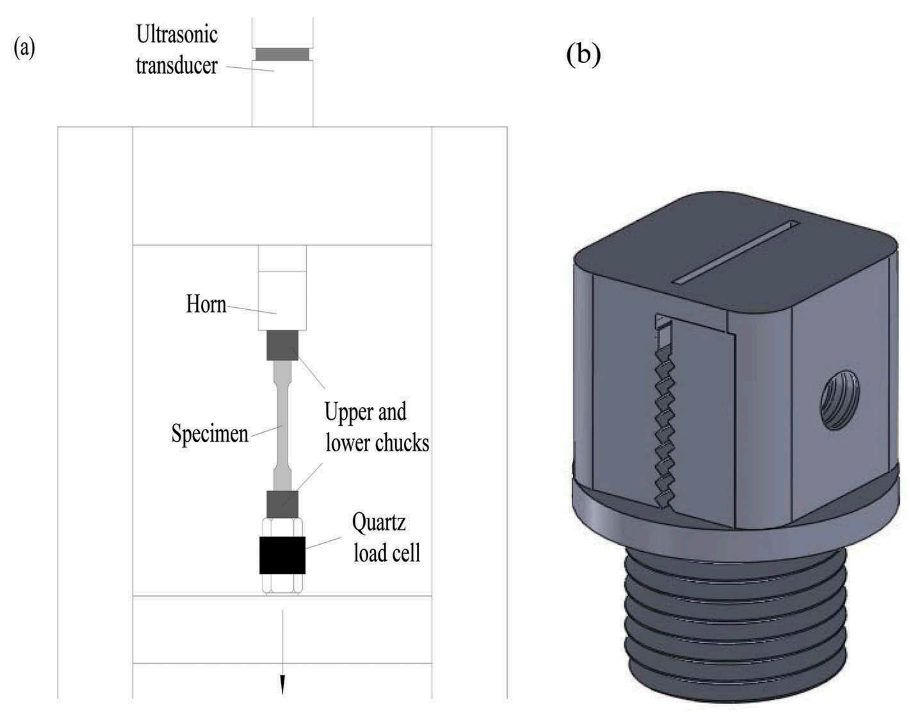

Figure 2. Schematic illustration of (a) the ultrasonic vibration assisted tensile testing apparatus and (b) the miniaturized chucks for ultrasonic vibration assisted tensile testing.

Table 2. Amplitudes of ultrasonic vibrations tested.

Case	Ultrasonic vibration	Amplitude (μm)
1	×	×
2	○	7.5
3	○	11

high-accuracy laser displacement sensor mounted on the chucks' surfaces without specimen, two different amplitudes were obtained by adjusting the voltage, as preliminary tests showed that vibrations with amplitudes above 11 μm caused premature failure of the specimens. Each configuration was tested six times in a random order with the objective to provide statistical meaning of the results.

3. Results

3.1. *Stress–strain evolution*

Figure 3 shows the typical results of tests cases presented in Table 2, where it can be observed that the ultrasonic vibration reduced the total elongation of the SUS304 stainless steel specimens. This reduction can be explained by the transformation of austenite into martensite, activated by the ultrasonic vibration: as the martensite content increases, the dislocation movement is limited, thus reducing the ductility of the material.

The experimental results also indicated that the yield strength and the mean flow stress reduce with the introduction of ultrasonic vibration. This phenomenon is commonly referred to as the Blaha effect or acoustic softening (Andrade et al. 2004). The mean flow stress reduces with the increase of the amplitude of the vibration, registering a difference of 103 MPa from case 1 to 2, and 195 MPa from case 1 to case 3. The same level of stress reduction was also registered for the tests with different rolling directions.

The test temperature was maintained at room temperature (25° C) and an infrared thermal imaging camera (InfReC R300SR) was used to measure the temperature changes of the specimens. The temperature measurements revealed that, for case 1, temperature increased by 9°C throughout the test, while temperature for case 3 increased 12°C, indicating that the small temperature differences detected cannot justify the significant drops of the flow stress levels.

3.2. *FEM analysis on stress superposition*

Stress superposition, in this study, is defined by superimposing an oscillatory stress on a static stress, and it is one of the effects of ultrasonic vibration. The commercial finite element program ABAQUS was used to simulate and analyze the effects of stress superposition on stress reduction during the tensile tests of SUS304 stainless steel.

The specimen was modeled with a mesh using four-node shell elements, as this type of element is computationally more efficient than solid elements. The upper and lower chucks were assumed to be rigid bodies, modeled as analytical rigid surface. The mechanical properties of SUS304 stainless steel used in the simulations were: Young's Modulus, E, of 195 GPa, Poisson's Ratio, v, of 0.3, and Yield strength at 0.2% offset, $\sigma_{0.2}$, of 720 MPa. The material was considered isotropic and its average true stress–strain curve was obtained by means of GTT and can be approximated by the following Ludwik-Hollomon's equation,

$$\sigma = 1655\varepsilon^{0.27}(\text{MPa}) \tag{1}$$

The convergence of the numerical simulation was stable and the simulation time for a model with a total number of 678 elements was around 4 h 30 min on a standard desktop computer.

The 3D finite element model used in this analysis is shown in Figure 4, with both ends of the simulated specimen fixed on the upper and the lower chucks, assumed to be rigid bodies. However, due to hardware and software limitations, only a short period of high-frequency vibration was simulated for the upper chuck. The high-frequency vibration was simulated at the strain value of 0.1354 during 3 s, in a region away from the elastic regime, by a cycle of reciprocating displacement of 11 μm at a frequency of 20 kHz, and the lower chuck was simulated moving at a constant speed of 2 mm/min.

The comparison between the FEM analysis and experimental results is shown in Figure 5. The test is similar to case 1 from Table 2, but the main difference is, for this case, a high-frequency vibration with amplitude of 11 μm for 0.2 s. The average stress level lowered 24 MPa from a normal tensile test with the introduction of ultrasonic vibration. A difference of 10 MPa is registered between the experimental average stress and the simulation; this deviation can be attributed to other softening effects associated with ultrasonic vibration, namely the dislocation energy absorption and dislocation-induced microstructural changes. In addition, there is still a significant difference of 19 MPa between the FEM results with UAT case 3 from Table 2 (the corresponding test case). Somehow, currently, the finite element software was not sufficiently mature to simulate the energy absorption induced by dislocations and/or the influence of microstructural changes. The impact of the microstructural changes of the material caused by the ultrasonic vibration will be discussed in the following paragraphs.

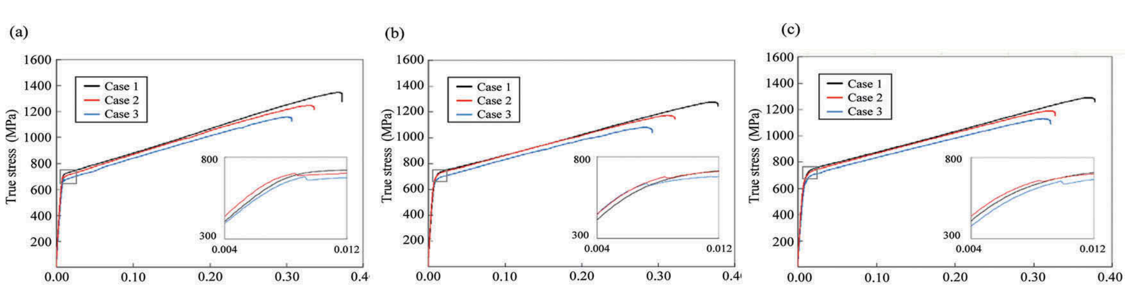

Figure 3. True stress–strain curve obtained from the test cases presented in Table 2 at (a) 0°, (b) 45°, and (c) 90° in respect to the rolling direction.

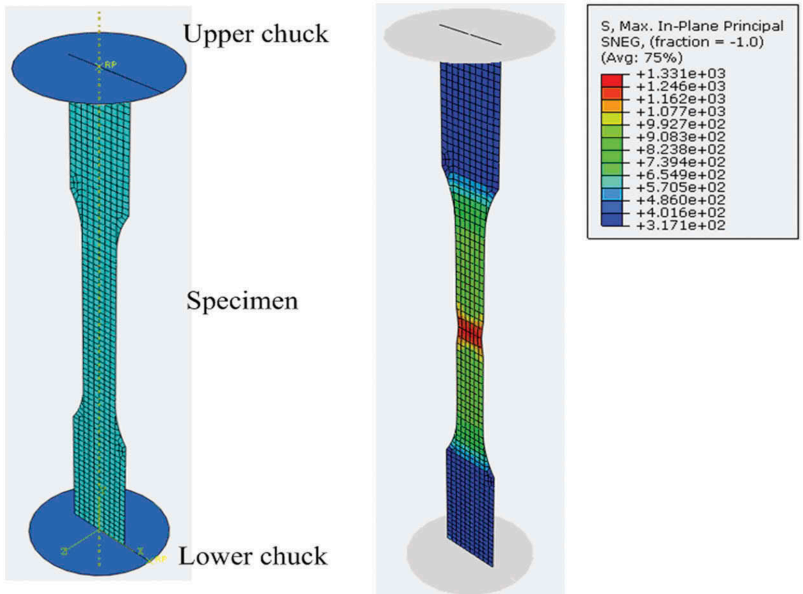

Figure 4. Finite element model of the tensile test: (left) original mesh and (right) deformed mesh.

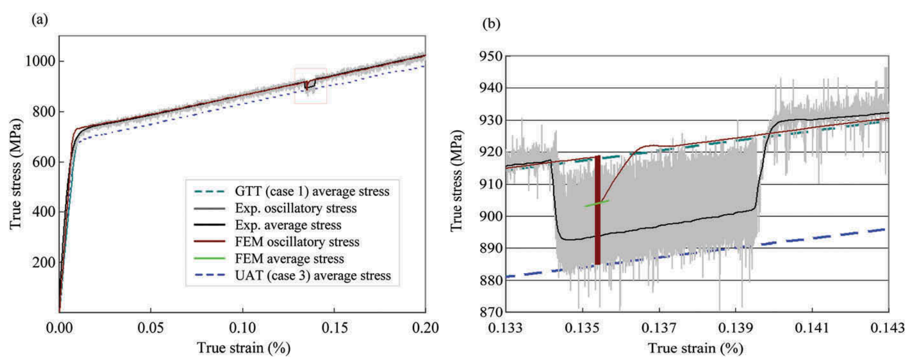

Figure 5. Comparison between the true stress–strain curves from different tensile test conditions and FEM analysis: (a) True stress–strain curves, (b) enlarged area of the simulation of the imposed ultrasonic vibration.

3.3. *Effect of ultrasonic vibration on the microstructure*

Metallographic analyses were conducted to investigate the changes that ultrasonic vibration caused in the microscopic structures of SUS304. Aqua regia solution (HNO_3:50%, HCl:25% and H_2O:25%) was used as etchant. After etching (17 s, at room temperature), the microstructure of SUS304 stainless steel was analyzed by using an optical microscope (Zeiss Axioskop 40). Ten different areas were selected from each specimen to measure and determine the average of martensite content for statistical purposes.

Figure 6 depicts the original grains in an undeformed SUS304 stainless steel specimen, and the circle included in the micrography marks some grains from annealing twins, which can be observed on most metals with FCC crystal structure after annealing.

The typical metallurgical structures of specimens with a 0.5-mm elongation are shown in Figure 7. In the martensite phase, a high amount of lath-type martensitic structure can be observed and measured by using software ImageJ: The specimens of case 1 (without ultrasonic vibration) exhibited low content of martensite structure (3.3%), case 2 specimens present a similar percentage (3.6%), while a much higher percentage were found in case 3 specimens (31.5%). In previous studies, the effects of ultrasonic

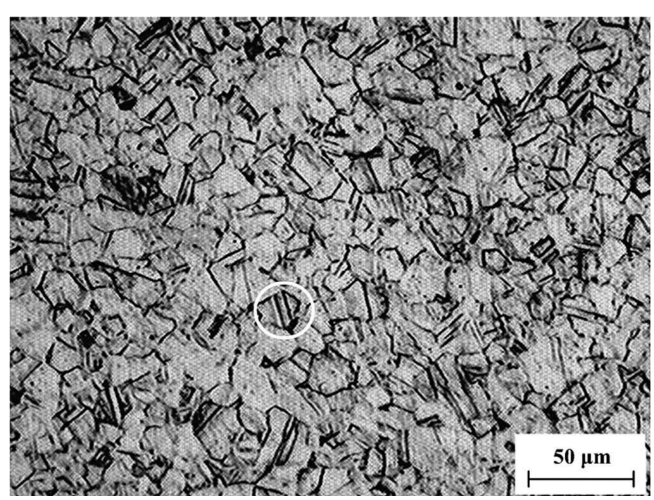

Figure 6. Metallurgical structure of an undeformed SUS304 stainless steel specimen.

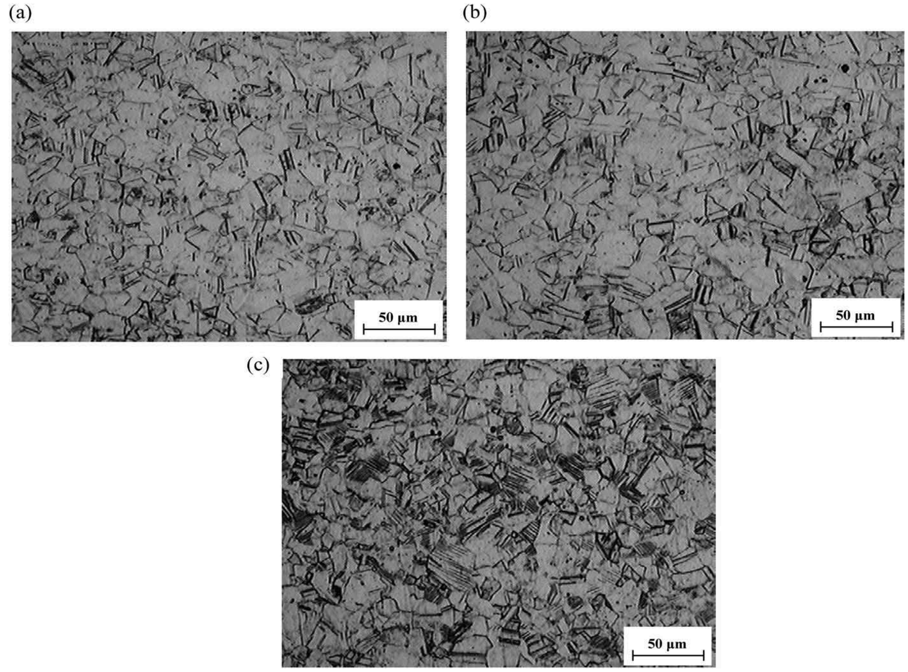

Figure 7. Metallurgical structures of specimens with 0.5-mm elongation: (a) case 1, (b) case 2, and (b) case 3 from Table 2.

vibration on deformation-induced martensite transformation are usually associated with the influence of other parameters like temperature, alternating stress, and dislocation accumulation (Xu and Hu 2004) (Odnobokova, Belyakov, and Kaibyshev 2015). However, as addressed previously in Section 2.1, only small temperature changes were registered during the tests (a maximum difference of 12° C), ruling out temperature as the origin of the martensite formations.

The metallurgical structures of specimens, inside the reference length, with 6-mm elongation are depicted in Figure 8. The average martensite content increases from 15.0%, without ultrasonic vibration (case 1) to 40.2%, for case 2, reaching to a maximum value of 65.8% for the highest tested vibration amplitude, case 3, or in other words, higher amplitude of ultrasonic vibration causes more martensite transformation in the material, reducing ductility, and in turn, the elongation of the specimens.

Although the UATs produced more martensitic structures, the forming stress levels associated with the UATs are lower than those of GTTs, which indicates that the softening effects of both stress superposition and dislocation energy absorption

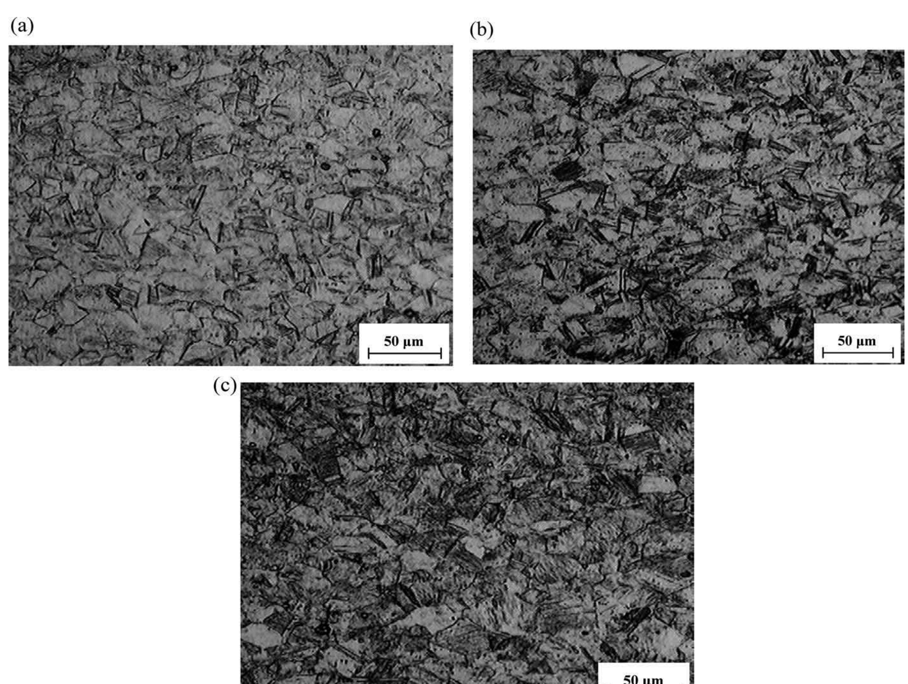

Figure 8. Metallurgical structures of specimens with 6-mm elongation: (a) case 1, (b) case 2, and (c) case 3 from Table 2.

overcomes the hardening effect caused by the induced martensitic transformation.

4. Conclusions

A series of experiments and analyses were conducted to investigate the effects of ultrasonic vibration on SUS304 stainless steel under tensile testing. The experimental results show that the introduction of ultrasonic vibration reduces both forming stress levels and specimens' elongation.

FEM was utilized to analyze the impact of the stress superposition on the tensile force reduction, and the results showed that this phenomenon can only partially explain the softening effect, while the additional phenomena of dislocations energy absorption and material phase transformation activated by the ultrasonic vibration can be other possible causes. However, current FEM software technology is still unable to simulate the complex effects of energy absorption or the impact of microstructural changes in the material.

Metallographic analysis on the tested specimens with different elongations showed that martensitic transformation in the material structure during plastic forming processes greatly increases with the amplitude of the ultrasonic vibration, especially at higher elongations.

It is verified that ultrasonic vibration causes large dislocation accumulations and the induced martensitic structures tend to reduce the specimen's elongation. However, the softening effects of both stress superposition and dislocation energy absorption were greater than the hardening effects of both increased dislocation density and induced martensitic transformation, lowering the levels of plastic forming stress.

Nomenclature

GTT	General tensile tests
UAT	Ultrasonic vibration-assisted tensile tests
σ	True strain
ε	True strain
E	Young's Modulus
v	Poisson's Ratio
FCC	Face-centered cubic crystal structure

Disclosure statement

No potential conflict of interest was reported by the authors.

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References

Andrade, M. S., O. A. Gomes, J. M. C. Vilela, A. T. L. Serrano, and J. M. D. Moraes. 2004. "Formability Evaluation of Two Austenitic Stainless Steels." *Journal of the Brazilian Society of Mechanical Sciences and Engineering* 26 (1): 47–50. doi:10.1590/S1678-58782004000100008.

ASTM International. 2013. *Standard Test Methods for Tension Testing of Metallic Materials*,ASTM Standard E8/E8M-13s. West Conshohocken, PA: ASTM. doi:10.1520/E0008_E0008M-13A.

Blaha, F., and B. Langenecker. 1955. "Elongation of Zinc Monocrystals under Ultrasonic Action." *Naturwissenschaften* 42 (20): 556. doi:10.1007/BF00623773.

Cigada, A., B. Mazza, P. Pedeferri, G. Salvago, D. Sinigaglia, and G. Zanini. 1982. "Stress Corrosion Cracking of Cold-Working Austenitic Stainless Steels." *Corrosion Science* 22 (6): 558. doi:10.1016/0010-938X(82)90055-5.

Huang, Z., M. Lucas, and M. J. Adams. 2002. "Influence of Ultrasonics on Upsetting of a Model Paste." *Ultrasonics* 40 (1–8): 43–48. doi:10.1016/S0041-624X(02)00245-7.

Iyer, K. J. L. 1988. "The Influence of Ultrasonic Vibrations on the Austenite to Martensite Transformation in 304L Stainless Steel." *Materials Letters* 6 (11–12): 413–417. doi:10.1016/0167-577X(88)90042-0.

Kempe, W., and E. Kroner. 1956. "Dislocation Damping of Aluminum Single Crystals at Room Temperature." *Zeitschrift Fur Metallkunde* 47: 302–304.

Langenecker, B. 1966. "Effects of Ultrasound on Deformation Characteristics of Metals." *IEEE Transactions on Sonics and Ultrasonics* 13 (1): 1–8. doi:10.1109/T-SU.1966.29367.

Liu, Y., S. Suslov, Q. Han, C. Xu, and L. Hua. 2012. "Microstructure of the Pure Copper Produced by Upsetting with Ultrasonic Vibration." *Materials Letters* 67 (1): 52–55. doi:10.1016/j.matlet.2011.08.086.

Mcguire, M. 2008. *Stainless Steels for Design Engineers*. Materials Park, Ohio, ASM International.

Müller-Bollenhagen, C., M. Zimmermann, and H. J. Christ. 2010. "Very High Cycle Fatigue Behaviour of Austenitic Stainless Steel and the Effect of Strain-Induced Martensite." *International Journal of Fatigue* 32 (6): 936–942. doi:10.1016/j.ijfatigue.2009.05.007.

Nevill, G. E., and F. R. Brotzen. 1957. "The Effect of Vibrations on the Static Yield Strength of a Low-Carbon Steel." *American Society for Testing and Materials* 57: 751–758.

Odnobokova, M., A. Belyakov, and R. Kaibyshev. 2015. "Development of Nanocrystalline 304L Stainless Steel by Large Strain Cold Working." *Metals* 5: 656–668. doi:10.3390/met5020656.

Xu, C., and G. Hu. 2004. "Effect of Deformation-Induced Martensite on the Pit Propagation Behavior of 304 Stainless Steel." *Anti-Corrosion Methods and Materials* 51 (6): 381–388. doi:10.1108/00035590410560921.