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Improved microstructure and mechanical properties of sheet metals in ultrasonic vibration enhanced biaxial stretch forming

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ABSTRACT

Ultrasonic energy is used for applying severe plastic deformation on metal surfaces. In the present work, the effect of ultrasonic vibration on the formability, microhardness and microstructural properties of St14 steel sheet has been investigated. To be precise, a semi-hemispherical-head forming tool had shaped the specimens until the necking started to happen. Conventional as well as the ultrasonic-assisted biaxial stretch forming test has been performed on St14 steel sheets and obtained data has been used to compare the hardness and microstructure of the specimen with and without superimposing the ultrasonic vibration. It was observed that the hardness of the samples which have been shaped by applying ultrasonic vibrations to the tool with an amplitude of 15μm at 20.5 kHz increased significantly in compared with the samples which have been shaped without using ultrasonic vibration, revealing the efficiency of the ultrasonic operation in increasing the hardness.

1. Introduction

Mechanical surface treatment operations play a pivotal role in metal forming industries. The purpose of these processes is to enhance tribological properties of materials [1]According to the Hall-Petch equation, grain refining can be an effective way of improving mechanical properties

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of materials[2]. This goal can be achieved by the propagation of high-intensity vibration into the sheet metal that influences the microstructural and mechanical properties [3]. Generally, volume effect and surface effect are brought by superimposing ultrasonic vibration. The volume effect (acoustoplastic effect) has been discovered by Blaha and Langenecker [4]. Considerable flow stress reduction was observed throughout plastic deformation of a Zink crystal when ultrasonic vibration at 800 kHz was superimposed. Also, the surface effect is related to friction as evidenced by Storck's work [5]. They claimed that the average force reduction is due to the friction reduction. Application of high-intensity ultrasonic waves has been investigated during the past few decades. Therefore, some researchers have tried to design and produce ultrasonic transducers with different frequencies. *Pak et al*. [6] analyzed two configurations of piezoelectric transducer with different resonant frequencies. They used theoretical, numerical and experimental methods. Finally, they have found that ultrasonic transducers have two resonant frequencies which correlate with the half-wave and the all-wave modes of vibration. In recent decades, ultrasonic-assisted manufacturing processes have been considered very useful due to their significant effects on mechanical and microstructural properties [7, 8]. Ultrasonic energy, as a method for achieving severe plastic deformations on surface of materials, brings mechanical enhancements to microhardness, yield stress, and smoothness of the surface. *Long et al*. [9] have studied an ultrasonic-assisted incremental sheet metal forming process. Force reduction and temperature variation due to changes in process parameters have been examined. According to its given result, the forming force can be greatly reduced by imposing ultrasonic vibration during the process. Also, they have indicated that adding ultrasonic vibration gave rise to significantly higher temperature of the specimens. *Karimi et al*. [10] studied the effect of ultrasonic nanocrystalline surface modification (UNSM) process on the hardness of steel using a vibrating tool. Finer grains was found by investigating the surface structure of steel 7225, the surface hardness also became greater by higher number of impacts. *Bagherzadeh et al*. [11]. investigated the effects of integrating high-power ultrasonic vibration with equal channel angular extrusion (ECAE) of Aluminum 1050. The obtained results illustrated that, higher hardness and lower forming load have been achieved in ultrasonic-assisted ECAE. *Vahdati et al*. [12] investigated the ultrasonic-assisted incremental sheet metal forming. Decrease in forming force, spring-back and surface roughness due to superimpsed ultrasonic vibration have been observed. Many other researchers have examined the application of ultrasonic vibration on different manufacturing processes such as [13]upsetting [14], ECAP and press forming [15].

The purpose of the present work is to examine the hardness of two similar St14 steel sheets, shaped by a hemispherical-head tool with and without applying ultrasonic vibrations to the tool to investigate the effect of ultrasonic vibrations on microstructure and hardness of the steel sheets ,respectively. In this paper, a biaxial stretch forming apparatus with a forming tool vibrating in a longitudinal mode was constructed in order to measure the enhancement of forming limit diagram due to applied ultrasonic vibration. The conventional FLD as well as ultrasonic-assisted FLD have been attained for as received St-14 steel sheet. Prediction of failure in ultrasonic-assisted deformation, also a comparison of the influence of ultrasonic vibration on various metal sheets are possible using this method. Eventually, the effect of ultrasonic vibration on microstructural properties and hardness of the deformed specimens have been studied.

2. Material and method

As received St-14 steel sheet with the chemical composition which is indicated in Table 1 was used so as to prepare two similar sets of specimens. Each of them consists of 4 different-sized samples. After preparing the samples using wirecut, they were placed between a blank-holder and a matrix.

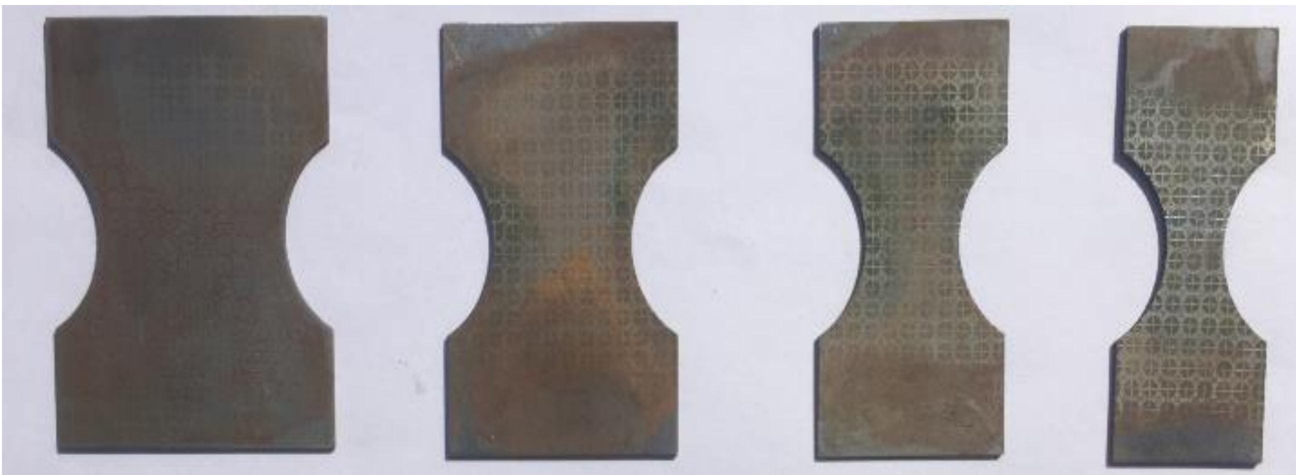

Fig 1: One set of prepared samples of St14 steel sheet.

In the next step, a semi-hemispherical-head forming tool, connected to a CNC machine made by Tabriz Company, moved downward with the speed of 2 mm/s and shaped the sheet till the necking occurred, as it is shown in Figure 2.

Table 1: Chemical compositions of st14 steel sheet

Fe	**C**	**Si**	**Mn**	**P**	**S**	**Cr**	**Ni**	**Mo**	**Cu**	**V**	**W**
Base	0.05	0.008	0.20	0.006	0.006	0.005	0.02	0.01	0.01	Trace	Trace
Ti	Co	Al	Sn	Pb	As	Sb	Nb				
Trace	0.004	0.04	0.005	0.002	0.002	Trace	0.002				

The first set of samples has been shaped conventionally without applying ultrasonic vibrations to the tool, while the second set of samples has been formed by superimposing ultrasonic vibration to the tool using a high-power ultrasonic transducer with the frequency of 20.5 kHz and the amplitude of 15μm. A sudden drop in the load-displacement diagram of the tool was considered on the verge of necking for each sample. The deformed samples are depicted in Figure 3.

Fig 2: Test set-up used to measure the influence of ultrasonic vibration on prepared samples.

After the test was carried out, the samples were ground, polished and etched respectively to obtain a better surface condition for microstructural observation. To evaluate the influence of superimposed ultrasonic vibration on the microstructure of steel alloy, an optical microscope has been used. Moreover, the micrographs were taken at 50× and 20×. The average grain size of the deformed specimens was determined by a Leco Image Analysis System. Values were calculated from 5 randomly selected micrographs and measurements were made in both longitudinal and transverse directions of each specimen.

Micro-Vickers hardness measuring of samples has been implemented using Koopa Pazhoohesh hardness testing machine at a load of 100 N to the polished surfaces for 10 seconds. The measurements were repeated at least five times to minimize the possible errors. Figure 4 presents a schematic view of the test equipment.

Fig 3: Samples after the necking.

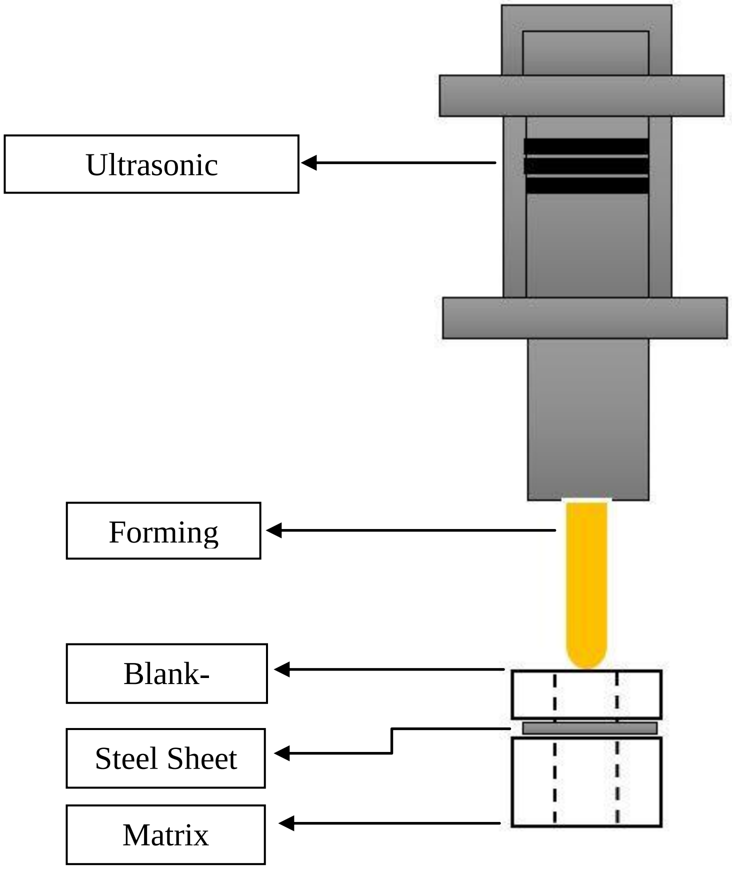

Fig 4: Schematic view of the test equipment.

In order to investigate the effect of superimposed vibrations on the formability of deformed samples forming limit diagram of ultrasonic-assisted, deformed samples and conventionally deformed samples have been created. To evaluate the limiting strains used for creating FLDs, principal strains (ε_1 and ε_2) have been measured after performing the biaxial stretch-forming test by means of a 2 mm diameter circular pattern which has been printed on the samples using an electrochemical etcher.

3. Results and discussion

The hardness of the samples has been measured. For samples which have been shaped without applying ultrasonic vibrations to the tool, the average hardness was 143.9 HV, and for the set which has been shaped using ultrasonic vibrations, the average hardness was 184.9, suggesting that increase of hardness is a correlative of superimposing ultrasonic vibrations to the tool. It can be deduced from the results that hardness increased about 28% due to ultrasonic vibrations of the tool. Figure 5 represents a comparison between the hardness of the aforementioned sets of samples:

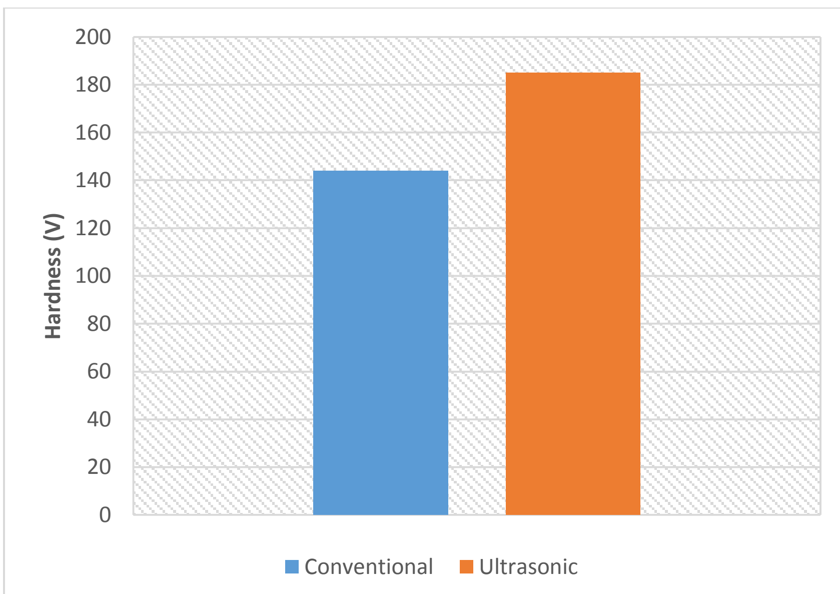

Fig 5: Micro-Vickers hardness of samples.

Applying ultrasonic vibration on the surface of the samples led to smaller grains, and obviously, the hardness of the samples increased because of the aforementioned microstructural changes. It is totally due to the fact that the grains on the surface of the samples have been refined. Also, the density of dislocations considerably increased because of superimposing ultrasonic vibration to the forming tool [16].

Figure 6 shows the microstructure of the samples after the test, indicating that the grain size has been decreased by applying ultrasonic vibrations to the tool. Figure 7 depicts the average grain size of the samples. The measurements have been done in longitudinal and transverse directions.

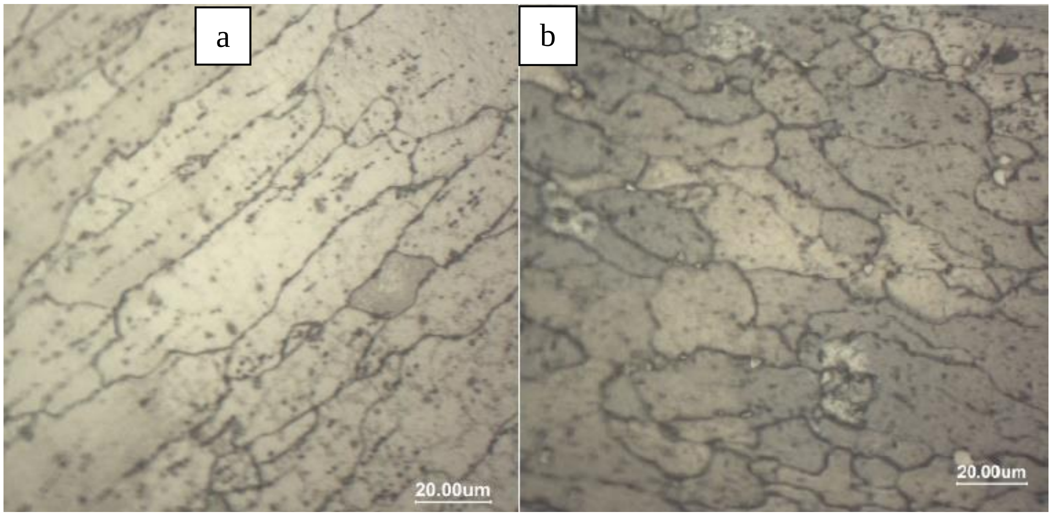

Fig 6: Microstructure of two sets of samples; a) shaped without applying ultrasonic vibrations, b) shaped by applying ultrasonic vibrations.

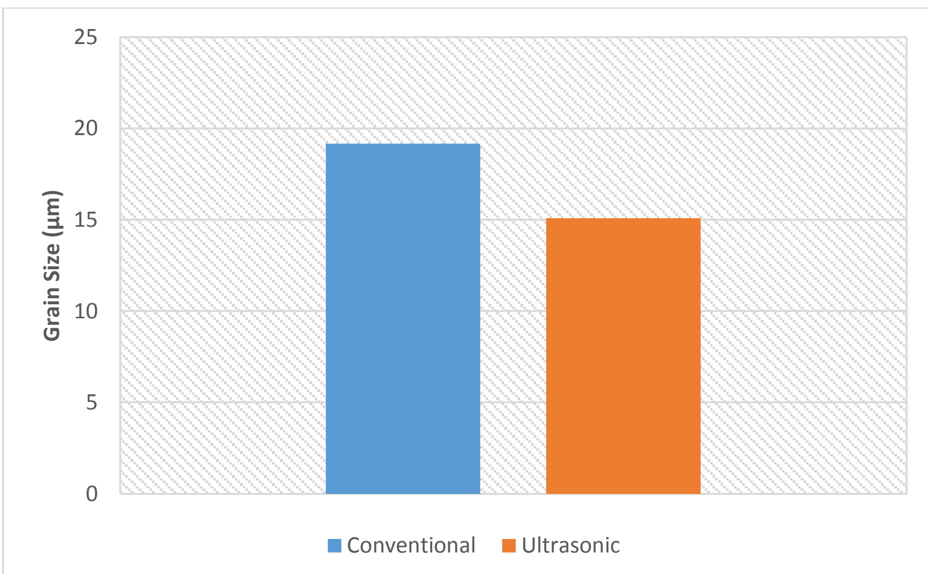

Fig7: Grain size of the samples

Some researchers have evaluated the influences of ultrasonic waves on different materials. They have found that superimposing ultrasonic energy refined the grain sizes thus enhancing their mechanical properties[17-19]. It could be indicated by microstructural observations and Micro-Vickers test that the grain refinement has a direct effect on increase of the hardness.

In addition, the forming limit diagram could be divided into three different sectors: FLD_0, The left hand side, and the right hand side of the curve. Thus, as it is clear in Figure 8, the ultrasonic vibration has significantly increased FLD_0. The increase in FLD after superimposing ultrasonic vibration is also appreciable in both sides of the curve.

Adding acoustic stress to the main stress brings about larger overall stress, and while the dislocation velocity is consistent with stress[20], the velocity of dislocations rises enormously. So, applying ultrasonic vibration makes the movability of dislocations easier, resulting in larger strains at a same load[21].

4. Conclusion

Throughout this research, the effect of ultrasonic vibration on microstructure and hardness of St14 steel sheet have been investigated. Thus, two sets of steel St14 samples were shaped using a semi-hemispherical-head tool with and without applying ultrasonic vibrations to the tool, respectively. Conclusions are as follows.

The microstructural observation showed a 25% reduction in the average grain size of the samples shaped by ultrasonic vibration in comparison to the samples shaped conventionally. The microhardness of the sample increased due to applying ultrasonic vibrations. A maximum of 28% enhancement was obtained because of superimposing ultrasonic vibration to the forming tool.

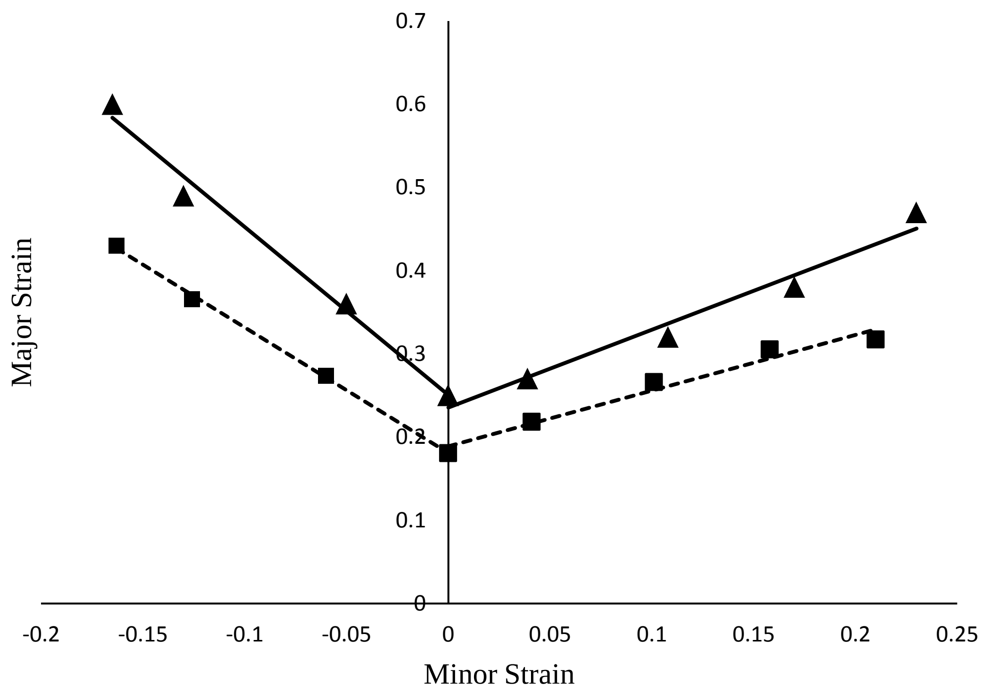

Fig 8: Forming limit diagram of deformed samples. (Straight line: ultrasonic-assisted forming; dashed line: conventional forming)

The results of the experimental study illustrate a significant enhancement in[15] FLD of the samples which have been deformed by superimposing ultrasonic vibration to forming[14] tool in [16]comparison with conventionally deformed specimens. Further investigation is needed to expand our understanding of ultrasonic effects of vibrations on mechanical and microstructural properties of sheet metals. Future studies could concentrate on evaluating the impact of ultrasonic vibrations with different frequencies and amplitudes on sheet metals.

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