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THE ANALYSIS OF MICROSTRUCTURAL CHANGES DEPENDING ON THE ELECTRO-ACOUSTIC EFFECT UNDER THE ULTRASONIC WELDING PROCESS OF ALUMINUM FOILS

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The ultrasonic welding is a new and useful welding process. The base of this joining technology is represented by the crystal structure changing under the pressure and due to the electro-acoustic effects. The atoms of the solid-state metals are joining by each other and established a metallic cohesion joint. In this article was described the ultrasonic welding process of aluminum (EN 485-2:2016) foils, the experiments were made using a piezoelectric transmitter USMW. The microstructures analyses for studying the dislocation density were performed by means of Transmission Electron Microscopy (TEM-JEOL, Model-JEM 2100F) highlighting the "Moiré Fringes" aspect (dislocations in the range 7.8 - 8.2 nm) and also, was measured the Vickers micro-hardness of the welded joint, in an attempt to find an relationship between the welding parameters (welding pressure, time, vibration amplitude and frequency) and the resulted microstructure and mechanical parameters of the welded joint.

Keywords: ultrasonic welding, dislocation density, crystal structure, micro-hardness, "Moiré Fringes", TEM

1. Introduction

The ultrasonic welding is a newly developed joining technology and very useful for bonding thin metal materials. The physical base of this technology is represente by the electroacoustic and plastic deformation effect, assisted by the heat established from the friction caused by deformation in the metal crystal structure. The ultrasound high-frequency vibration transmit energy to the crystal structure [1]. During ultrasonic welding, the metal is affected by pressure and caused plastic deformation, due to high-frequency vibration and the vibration

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amplitude limited friction. These effects establish a metallic joint between the metal sheets.

The physical and technological properties depend on the lattice parameters and defects. The mechanical properties of the materials can be understood based on the dislocation theory. The plastic deformation theories in the case of the FCC crystal structure materials are well understood [2, 3, 4]. The elastic properties of a solid body could be interpreted by the elastic theory of crystals. The theoretical investigation of plastic deformation was carried out by means of the dislocation theory [5, 6]. Well known that in the case of the real crystals it can be found a great number of defects. The used material in this study was the high purity aluminium. The simplest structural defects of this metal created by thermal motion are the punctiform defects (such as the vacancies and the interstitial atoms defects). Under the plastic deformation process, it can detect a glide plane, which contains slipped and un-slipped areas. The boundary between these areas creates new crystal defect - dislocation. The first applied concepts of the dislocation theory were Taylor and independently the Orowan and Polányi theories for the phenomena of the plastic deformation. During the deformation, the edge dislocation sweeps through the crystal creating a slip of one atomic distance. This edge dislocation can insert an extra atomic layer into the cut up to the dislocation line (extra half-plane shown in Fig. 1).

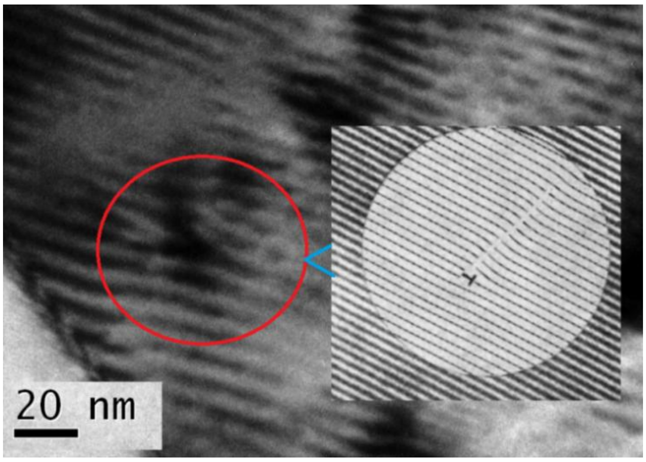


Fig. 1. Dislocation line [2]

The dislocations do not a thermodynamically stable formation, which means the crystals always contains a certain number of dislocations [7-9]. The multiplication of dislocations reason is the thermal stresses. Dislocations may classify in three groups: spatially distributed dislocations, low angle grain boundaries and dislocations produced by plastic deformation and arranged in a glide plane [2].

Work-hardening phenomenon is one of the most important elements of dislocation theory. The plastic deformation caused phenomenon can be occurring by the stress-dependent glide [2, 10-12]. In the Fig. 2 is shown a typical stress-strain curve of the FCC lattice metals. It can observe that the strain increasing begun over a minimal strain level, which means the work-hardening phenomenon, needs to be over a critical deformation.

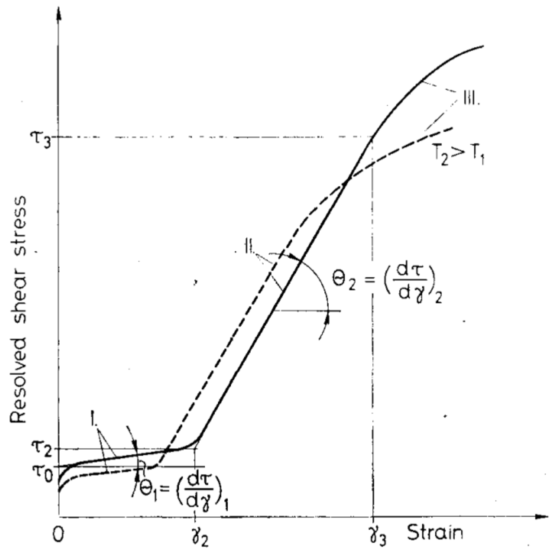


Fig. 2. The stress-strain curve of the FCC lattice metals [2]

Influence of softening effects in the heat affected zone is shown in Fig. 3. It was observed that whenever the deformation is interrupted and then later resumed at some higher temperature the stress flow on the resumption of the deformation decreases after a transitional maximum and then slowly increases again [2].

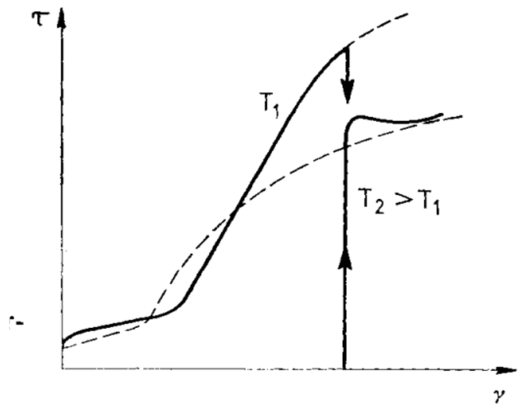


Fig. 3. Influence of work-softening in the heat affected zone [2]

Acoustic softening phenomenon (Blaha and Langenecker) represent an elastic effect to decrease the stress flow in the solid materials. This effect is shown in Fig. 4 in the case of poly- and monocrystals materials [13]. The stress-strain response of three different orientations of single-crystalline aluminium with no ultrasonic energy and with ultrasonic intensity = 150 kW/m^2 is shown in Fig. 4.

Based on serious research results it can be found a relationship between the ultrasound introduced softening and the intensity (stress amplitude) [13-15]. The relationship is shown by the next equation (1), where ρ is the density; c is the sound speed in the solid material [14].

$$I = \sigma_m^2 / 2\rho c \tag{1}$$

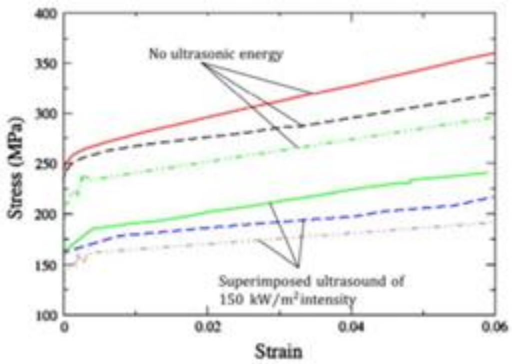


Fig. 4. The stress-strain response

Also was determined that the softening is independent of the oscillation if the frequency finds between 15-80 kHz and the pre-deformation is up to 16% even when the process temperature is between 30 – 500°C. The ultrasound supports the dislocation movement and stress relaxation on solid materials. Ultrasound's effect on dislocation density reduction or subgrain formation was experimentally observed [10, 13-15].

Dynamic recrystallization is due to the plastic deformation and heat input by friction and the electroacoustic energy, resulting in grains refinement in the welded joint [10, 16-19]. These complex effects in the crystal structure as a function of the process and the used welding parameters is not well understood and tested.

2. Materials and methods

The used metal for our welding experiments was aluminium (EN 485-2:2016), with the chemical composition showed in the Table 1. Aluminium has an

FCC lattice, with good formability and plasticity [20]. The aluminium sample used was annealed and cold worked at low degree.

Table 1

Chemical composition of the aluminium (EN 485-2:2016) sample

Element	Si	Fe	Cu	Mn	Zn	Ti
Concentration, [%]	0.25	0.40	0.05	0.05	0.07	0.05

The tests samples were in rectangle shape with the dimensions 10x60 mm and with a thickness of 0.7 mm, the welding test setup is shown in Fig. 5.

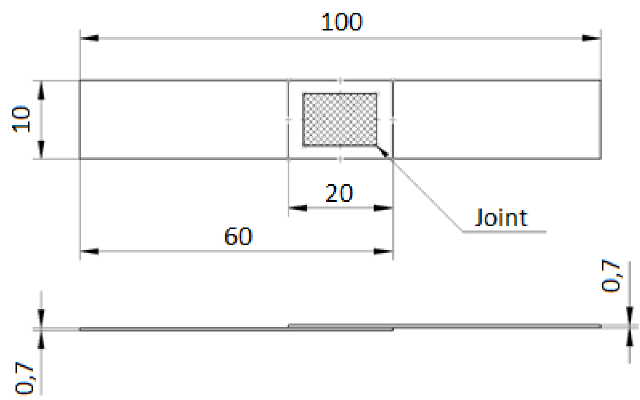


Fig. 5. The welding test setup

The experiments were made using the equipment Telesonic Ultrasonics Ultraweld L20 installed with piezoelectric transmitter USMW with the optional frequency 20000Hz ± 50Hz, and the setup is shown in Fig. 6

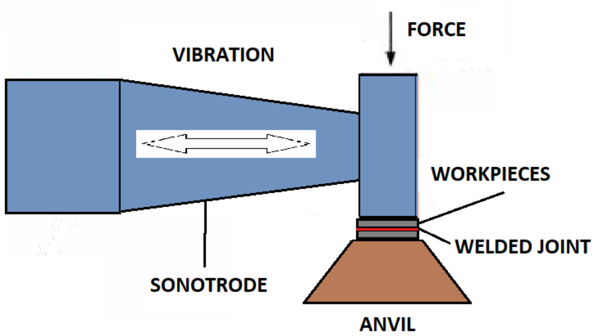


Fig. 6. The setup of the equipment used for ultrasonic welding

The ultrasonic welded samples were analysed by transmission electron microscopy (TEM). TEM Instrument Detail: TEM-JEOL, Model- JEM 2100F, Specification- Resolution: Point: 0.19 nm Line: 0.1. TEM images are formed using transmitted electrons (instead of the visible light) which can produce magnification details up to 50 x - 1.5M x with accelerating Potential: 200 kV Attachment Systems: EDS, STEM. The images can be resolved over a fluorescent screen.

The samples for TEM analysis were prepared by cutting in size of Φ 3 mm, the mechanical grinding (on wet diamond paper using large grit size 500, 1200, 2400 and finally 4000) and polishing (using 1 and 0.25 μm oil based diamond paste, followed by a short polishing stage using 0.05 μm alumina suspension) was used to thin the substrate and to produce smooth, scratch-free surfaces before dimpling.

The mechanical polishing was performed on a sample of Φ3 mm in diameter until a thickness of 20 microns was obtained. Then, the sample was electrochemically polished until it was perforated, and in the vicinity where the perforation occurred the material was thin enough to be observed with the electron beam. In these conditions the parallel Moiré Fringes could be identified. When a lattice with a spacing d_1 and another lattice with a spacing d_2, where d_2-$d_1 < d_1$ or d_2, are superposed in parallel, an enlarged lattice with spacing $D = d_1 \cdot d_2 / (d_2 - d_1)$ that is parallel to the original lattice appears. The lattice fringes are called "parallel Moiré fringe" [21].

To determine the mechanical properties, samples were tested after ultrasonic welding to obtain the microhardness values. The hardness test was made using the Zwick 3212 equipment, microhardness tester with diamond (136°) Vickers indenter. The used test load was 0.2 kg, test time 30 s. Also, the measured tensile strength of the samples used was R_m = 70 MPa.

3. Experimental results and discussion

After several experiments we obtain the optimal parameters for the ultrasonic welding process, shown in Table 2.

Table 2

The optimal parameters for the welding process

Parameter	Value
Trigger pressure [PSI]	40
Welding time [s]	1.5
Welding pressure [PSI]	40
Maximal welding power [W]	1080; 1300
Amplitude [μm]	37

The micro-hardness results are shown in Table 3 as a function of the test location area. The used metal hardness before the welding test was 17 $HV_{0,2/30}$. In Fig. 7 can observed the hardness changing as function of the ultrasounds effect. The hardness increased in the welded joint and the affected zone also. The increasing depends on the distance of the welded joint and the used power level.

Table 3

Vickers micro-hardness test results

Location	Power level	
	1080 W	**1300 W**
Base metal	21 $HV_{0,2/30}$	27 $HV_{0,2/30}$
Affected zone	28 $HV_{0,2/30}$	32 $HV_{0,2/30}$
Welded joint	24 $HV_{0,2/30}$	28 $HV_{0,2/30}$

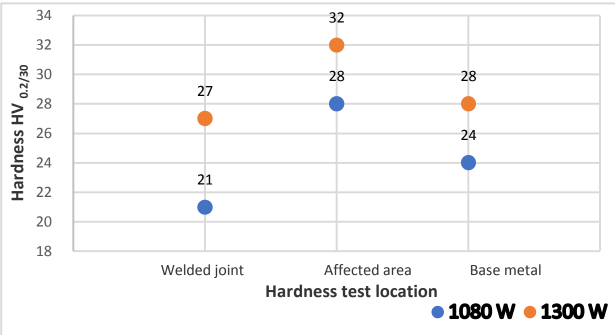
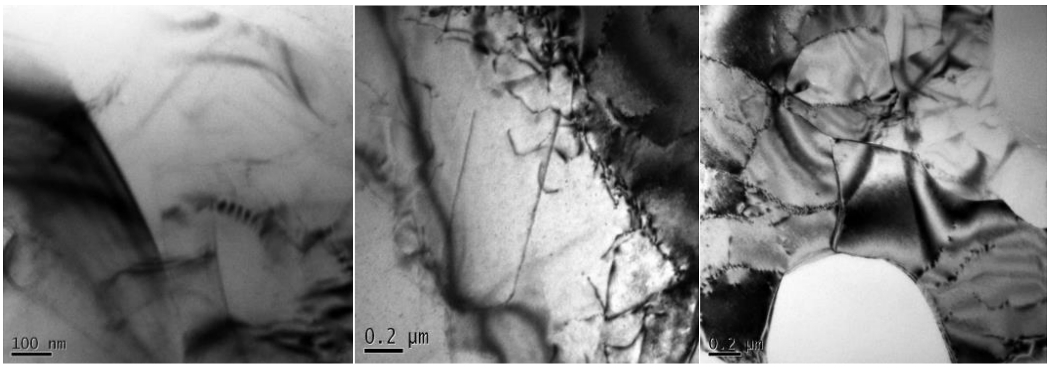


Fig. 7. Microhardness test values depending on the distance of the welded joint

The samples were checked under an optical microscope, to determine scratches or defects. After mechanical grinding, the samples were subjected to the punching machine.



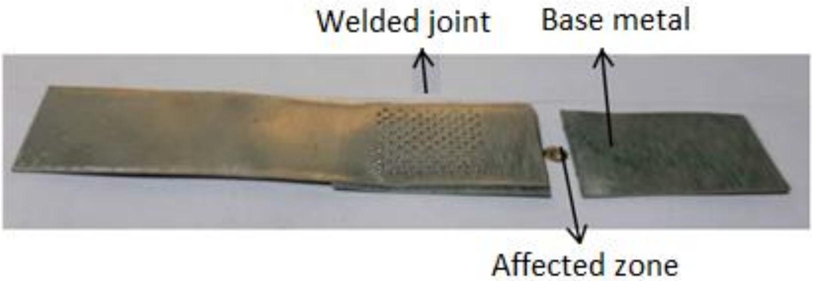


Fig. 8. Welded aluminium foils and TEM images of base metal

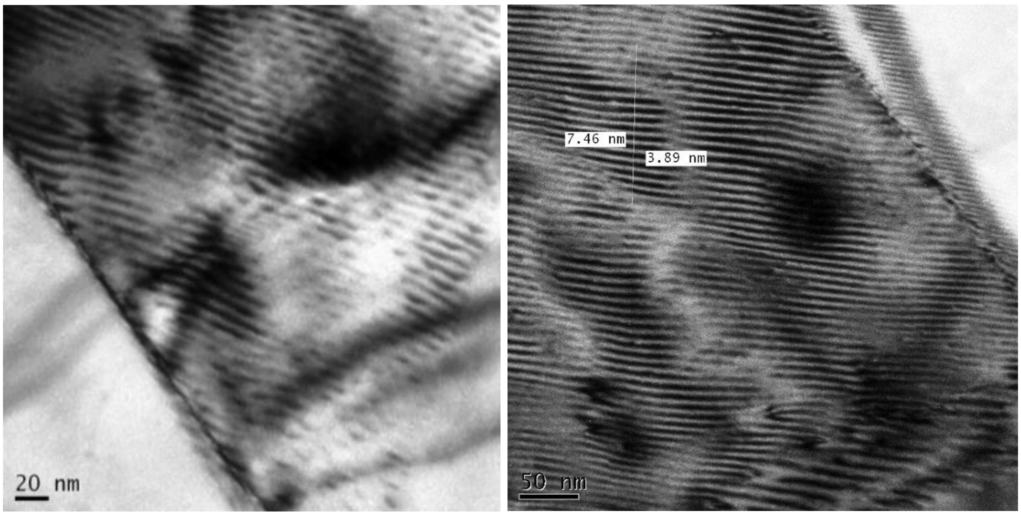


Fig. 9. TEM image of welded zone

The base metal TEM analysis result is shown in Fig. 8; as we compare Fig. 8 and Fig. 9, we can detect the difference between the dislocation densities. In the affected zone the dislocation density is higher than in the base metal, which is located far from the welded area.

The welded aluminium test samples TEM result is shown in Fig. 10. The observed edge dislocations in the affected zone were in the range of 7.8 nm to 8.2 nm.

3. Conclusions

During the ultrasound welding process, the created metal microstructure depends on the process effects. The first effect of the process is the plastic deformation made by trigger and welding pressure. The plastic deformation results are a work-hardening phenomenon the metal hardness increased in the welded joint. The metal hardness and yield strength increasing under the plastic deformation represent the plastic deformation magnitude.

The process part is also the used amplitude of friction under the trigger force load, during the joining process time (welding time). In the case of the ultrasonic welding effects analysis, it needs to be considered the friction established heat effect. The mentioned heat can be over the recrystallization temperature as a function of the used welding parameters (friction amplitude and welding time).

The dynamic recrystallization induced by plastic deformation is made over the recrystallization temperature. The recrystallization effect changes the material properties because the hardness and the yield strength have a relationship between the grain size and these properties. Under the joining process, the electroacoustic effect was kept constant at 20 kHz. This ultrasound effect causes a softening process of metal properties. The dislocation density is different in the welding affected area and the base metal. The ultrasound effects produce the dislocation movement in the crystal structure.

These complex effects establish a special physical property of metallic joint and affected zone of the metal foils. The physical properties depend on the microstructure, the crystal structure and dislocation density and form.

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