Original Research Article

Ultrasonic testing of grain distortion direction in cold formed aluminium profile

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ABSTRACT

Cold deformation process of metals causes distortion of crystalline structure. When a material is formed, the grains are usually distorted and elongated in one or more directions which make the material anisotropic. Anisotropy can be defined as a difference in a material's physical or mechanical properties in different directions of taking of testing samples. In exploitation, it is very important to recognize the direction of grain elongation so that the best orientation of working part can be chosen. For that purpose ultrasonic testing is used. The ultrasonic velocity of the material is determined by using a digital oscilloscope under condition that thickness of the material is known. Testing shows the difference in wave velocity for different orientations of grain structure. In order to determine whether there is a significant difference in the ultrasonic velocity, the measurement results were statistically analyzed and graphically presented. The results are verified by performing the same measurement procedure on annealed homogenous testing samples. The result of this work leads to a non-destructive, simplified way of anisotropy recognition, without more expensive, destructing, testing by cutting out a large number of testing samples.

1. Introduction

Cold forming is a cold metal working process by which metal is shaped at room temperature. More specifically, the metal material is squeezed into a die, or pushed through the die hole and the finished part assumes the shape of the die. Cold formed products offer many significant advantages over hot formed products and even more so over cast or machined metal products. Advantages of cold formed products are significant material saving, no heating is required, superior

dimensional accuracy, high production rate, exceptional forming die life, minimized contamination, and the first of all – better mechanical properties.

During cold working the part undergoes work hardening and the microstructure deforms to follow the contours of the part surface. Unlike hot working, the inclusions and grains distort to follow the contour of the surface, resulting in anisotropic engineering properties. Although the distorted grain structure gives the workpiece its superior strength, overdistorded grain can lead to residual stresses. Anisotropy of sheet metal is usually tested by taking test pieces in different

directions. Each test piece shows different mechanical properties: yield strength, tensile strength, true stress and strain, ductility, toughness. For this reason, it is very important to discover the direction of grain elongation before any cold formed, semi manufactured metal product goes to further processing into a finished metal product.

If grain distortion of semi product is not forth known, it is necessary to investigate it. Usually used methods include cutting in two directions (transversal and longitudinal), and microstructure scanning. These methods take a lot of time. This paper suggests the use of non-destructive testing methods that can offer faster response to basic question: what is the distortion direction? Proposed method is ultrasonic testing.

Ultrasonic velocity is an important acoustic parameter in material characterization. It is the parameter that correlates to structural inhomogenities, elastic parameter, precipitates, dislocations, phase transformations, porosity and cracks, concentration of different components of alloys, vacancies in lattice sites, size of the nanoparticles in nano-structured materials, electrical resistivity, specific heat, thermal conductivity and other thermoplastical properties of the materials depending upon the different physical conditions [1,2].

The beginnings of material characterization using ultrasound reach in the middle of 20th century. Scientific work was dedicated to provide a good diagnosis of material property and process control in industrial application [3–6].

These researches have been followed by themes in wave propagation in cubic and hexagonal structured materials [7,8].

The different mechanical properties like tensile strength, yield strength, hardness and fracture toughness at different composition, direction/orientation and temperature can be determined by the measurement of ultrasonic velocity which is useful for quality control and assurance in material producing industries [9].

Ali [10] carried out measuring the longitudinal and transverse ultrasonic velocity in the standard block and on that experimental basis he determined mechanical properties of the reference standard and calculated modulus of elasticity of material.

Many authors have dealt with the problems of ultrasound speed measuring in a variety of materials, and thus showed how the changes in the microstructure reflect the differences in propagation speed of the ultrasonic pulses. Gur et al. [11] measured the differences in the ultrasound speed in material caused by changes in microstructure. They created patterns of the two steel types that have been subjected to different heat treatments and have different microstructures: martensitic, bainite and pearlite-ferrite microstructure of fine and coarse grains. For each sample they measured the velocity of longitudinal and transverse waves. The obtained results presented that the change of ultrasound speed depends on the microstructure and material hardness. The difference in speed between samples is a consequence of changes in the elastic properties of the material due to different microstructures. Beside the microstructure, the ultrasound speed in the material depends on the degree of deformation of the crystal lattice as well as on the microstructure anisotropy, i.e., the grain orientation. Using the difference in the speed and ultrasonic waves damping between samples due to

microstructure differences, Freitas et al. [12] dealt with the materials characterization.

All these researches and ideas are used in following research of grain distortion in aluminium samples produced by cold extrusion.

2. Numerical simulation

Convenient way to visualize stress state and grain distortion is to use numerical simulation of the forming process. Observed extrusion process has been modelled and numeric model has been prepared for finite element analysis. Fig. 1 presents the mesh distortion in the first phase of cold extrusion process of cylindrical body. Grain distortion is equivalent to the mesh distortion.

The numerical analysis was performed using MSC Marc Mentat elasto-plastic program package. In the presented extrusion problem, the full Newton–Raphson iterative procedure is chosen to solve the iteration process and nonlinear equations of motion. This method has quadratic convergence properties and the stiffness matrix is reassembled in each iteration. Since material elements rotate during extrusion process, large displacement, finite strain plasticity and updated Lagrange procedure need to be adopted in calculation. In the Lagrangian approach, the element stiffness is assembled in the current configuration of the element, and the stress and strain output is given with respect to the coordinate system in the updated configuration of the element.

The stiffness is formed using four point Gaussian integration. Because of large displacements request, an additional contribution needed to be made to the stiffness matrix. By default, the analysis program uses the full stress tensor at the last iteration, which results in the fastest convergence.

As it can be supposed, the greatest mesh distortion happens in the area of material-tool contact. This confirms precondition that grain distortion is maximal in that area.

It has to be noticed that the most equable grain shape remains in the area around the axis of symmetry. Further ultrasonic measurements will be oriented to that note.
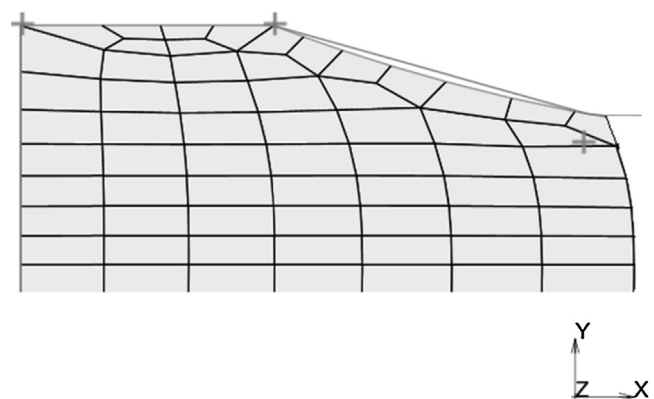
Fig. 1 – First phase of extruding process shows areas of greatest stress and mesh distortion in tool contact area where stresses caused by deformation and friction are the largest.

3. Ultrasonic velocity

Nowadays many methods that are based on the processing of the ultrasonic pulses are developed in terms of determination the ultrasonic velocity. Ultrasonic impulses are mechanical and elastic vibration of particles in the materials which shape depends on microstructure and mechanical properties of the materials. Accordingly the type of material, through which ultrasonic impulse propagates, significantly contributes in change of the ultrasonic velocity. Furthermore, the ultrasonic velocity will also depend on the density of the material, elastic properties and internal stresses. Also, the temperature of the material significantly affects on the ultrasonic velocity. The ultrasonic velocity of the material can be determined by using a digital oscilloscope under condition that thickness of the material is known.

In regard to the processing of ultrasonic pulses, it is necessary to distinguish the ultrasound group and phase velocity.

4. Phase and group velocity

Ultrasonic pulses (wave packet) are composed of a set of monochromatic waves whose superposition receives ultrasonic pulse. Expanding monochromatic wave (wave that vibrates only one frequency) along the x-axis is described by sinusoidal function:

$$\sin\left(\frac{\omega t - 2\pi x}{\lambda}\right)$$

where ω presents angular frequency ($\omega = 2\pi\nu$) and t presents time. If the argument sine function (phase wave) equates to zero, the phase velocity v_f is obtained, as defined above. Velocity v is called phase velocity because it presents the velocity of the one component that is spreading through the space. However, in many physical situations, a wave packet consists of more frequencies. In that sense this kind of wave is obtained by superposition of sinusoidal function that is similar to previous sinusoidal function. Superposition of monochromatic waves with nearly, but not quite, the same frequency leads to the generation wave groups or wave packet that is shown in Fig. 2 for two waves. Movements of the envelope carry energy as they propagate and travel with the group velocity v_g. Group and phase velocity could be the same just if the phase velocity of all monochromatic waves different frequencies is the same.

Fig. 2a and b shows two sinusoidal travelling wave different frequency at the moment $t = 0$ which superposition is shown in Fig. 2c. Fig. 2d and e shows the same sinusoidal travelling wave, but at the later moment $t > 0$ where we can notice that two travelling waves have different phase velocity. Phase displacement is proportional to the phase velocity v_f. Fig. 2f shows superposition of two waves at the moment $t > 0$. The group moved a lot less than the individual phases of the waves. Group velocity, v_g is proportional to the movement of the maximum envelope and is given by [13]:

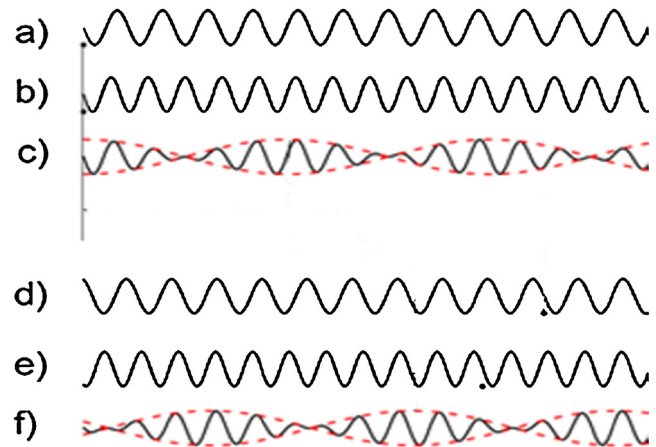$$\text{Group velocity} = v_g = \frac{d\omega}{dk}$$

Fig. 2 – Phase and group velocity.

where ω presents angular frequency and k is wave number. Angular frequency and wave number are related by a dispersion relation:

$$\omega = \omega(k)$$

5. Ultrasonic velocity measurement of cold extruded part

The behaviour of ultrasonic velocity in distorted grain structure was observed in cold extruded aluminium samples. Cold deformation processes generally cause greater grain distortion than it is the case with hot worked parts. Also, the parts are hardened and mechanical properties are significantly changed. These parts show a strong anisotropy and it is very important to be familiar with their grain orientation for any further exploitation. Although it could be important to examine grain orientation in i.e. rolled sheets, ultrasonic technique demands testing area that is large enough to cover the whole area of ultrasonic probe. It has to be noticed that mentioned demand limits ultrasonic testing application.

As it was imaged in numerical simulation, the most equable grain shape remains in the area of the axis of symmetry. That is why samples were prepared in a way that only this area can be observed. Full cylindrical profile Φ50 mm, 25 mm high, was plane parallel cut on two sides so that cut thickness was also 25 mm. The samples suffered 25% reduction over deformation process before cutting. Fig. 3 presents schematic overview of extrusion process and cut sample. Ultrasonic measurements were conducted in places 1a and 2a, on the axis of symmetry.

Ultrasonic velocity measurement was conducted on a digital oscilloscope by using the method of pulse overlap. Pulse overlap method is based on the time of flight measurement (TOF) between two back wall echoes in time domain what is the basis for determining the group velocity of ultrasound.

Time of flight measuring of ultrasonic pulses to determine the velocity of ultrasound are carried out on a SAMPLE whose
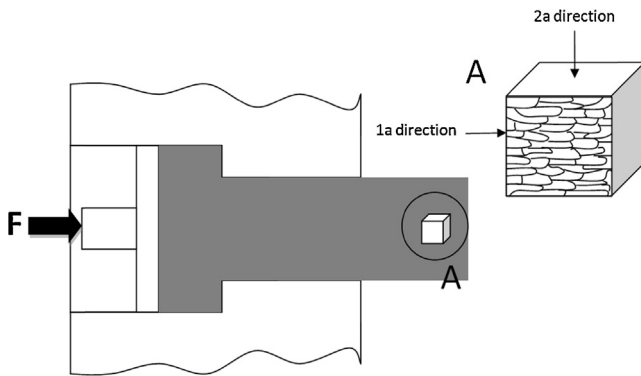
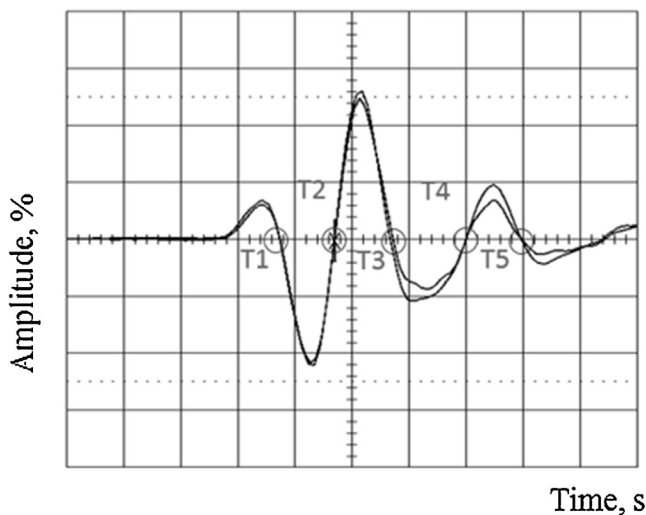Fig. 3 – Aluminium part – detail A, tested by ultrasonic measurement.

Table 1 – Results of ultrasonic velocity measurements at 1a and 2a.

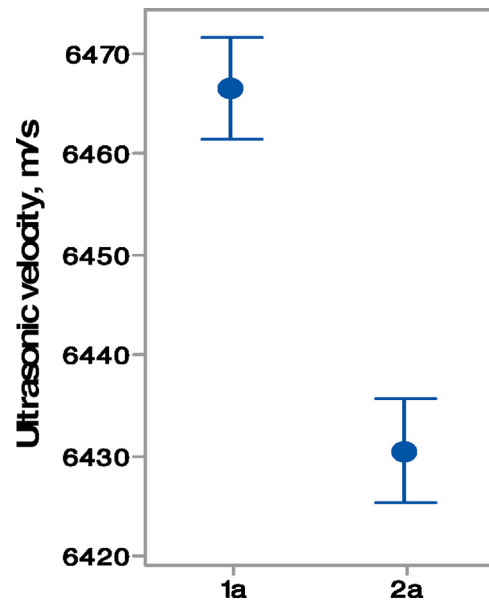| Measuring point	Ultrasonic velocity (m/s)	Measurement uncertainty, U, $k = 2$; $P = 95\%$ (m/s)
1a	6467	4.5
2a	6431	4.5

Fig. 4 – Time – domain between two overlap signals reflected from the back wall of specimen.

Fig. 5 – Graphical overview of measurement results at 1a and 2a.

reference thickness is measured of the granite slab measuring digital altimeter "Mitotoyo" resolution of 0.1 μm and 1a is 24.99 mm and 24.97 mm 2a. The time of flight is measured through the specimen in accordance to the standards EN 12223 [14]. In that sense it was used the probe type G5KB that has a nominal frequency of 5 MHz, broadband pulse with a crystal size of 10 mm. It was measured the time difference between the first and second back wall echoes. On the pulse overlap it was selected 5 points (T1, T2, T3, T4, T5) where the results of time of flight were measured (Fig. 4). The measurements were repeated five times.

Measurement results of ultrasonic velocities at places 1a and 2a, are presented in Table 1 and Fig. 5.

The difference between ultrasonic velocities at places 1a and 2a is equal to 36 m/s which is much higher than the declared expanded measurement uncertainty, $U = 4.5$ m/s. In order to determine whether there is a significant difference in the ultrasonic velocity in places 1a and 2a, a detailed statistical analysis was performed. Measurement results were statistically analyzed and graphically presented.

By applying the Anders–Darling test it was determined that the data follows a normal distribution (Fig. 6a and b).

A histogram of the results of measuring ultrasonic velocity is presented in Fig. 7.

Furthermore the measurement results were analyzed using the F test and the T test. Results are presented in Tables 2 and 3.

Because the p-value of 0.024 is less than a reasonable choice of α, ($\alpha = 0.05$) there is significant evidence to reject the null hypothesis stating the standard deviations are equal. This data provides enough evidence to claim that ultrasonic velocities in places 1a and 2a have unequal standard deviations.
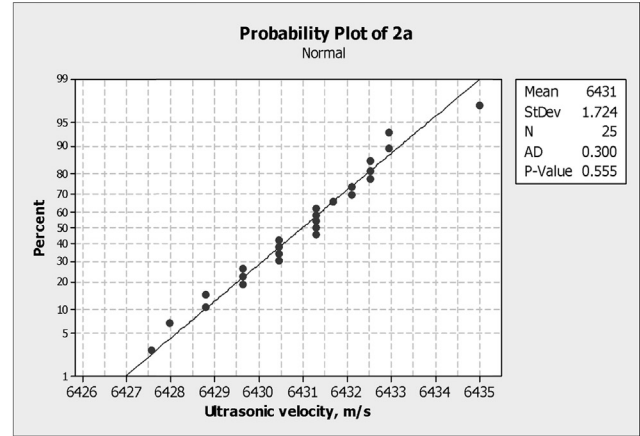
Comment:

It is evident that standard deviation of measurements in a place 1a is broader than standard deviation of measurements in a place 2a. This can be explained through uniform grain structure in forming direction. Deformation process elongates crystal grains in direction of forming force activity. Because of that, in a plane that is parallel with forming force, elongated structure becomes relatively uniform. Because of that, standard deviation of taken measurements is relatively small.

Since the p-value is less than the commonly chosen α-levels ($\alpha = 0.05$), there is significant evidence that ultrasonic velocities in places 1a and 2a are not equal.

Comment:
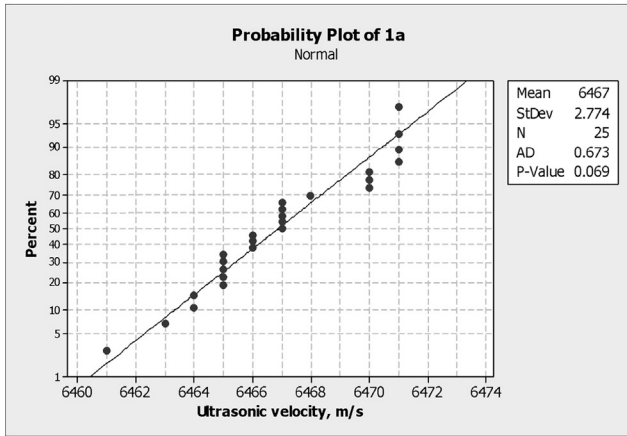
a - of velocity at place 1a   b - of velocity at place 2a

Fig. 6 – Probability plot.

As it is presented, measured ultrasonic velocity in a place 2a is smaller than in a place 1a. This result can be explained by number of obstacles to wave propagation through material. If we think of grain boundaries as they present obstacle, it is reasonable that the more grain boundaries – the slower is ultrasonic wave propagation, the lower is ultrasonic velocity. In a direction of forming force activity (measured in a point 1a) is less grain boundaries and ultrasonic velocity grows. In the direction parallel to forming force and parallel to elongated grain structure (measured in a point 2a) exists larger number of grain boundaries and ultrasonic velocity decreases.

The results of the ultrasonic velocity are given with the expanded measurement uncertainty

$$U = 4.5 \ \text{m/s}, \quad k = 2, \quad P = 95\%.$$

where U – expanded measurement uncertainty, k – coverage factor, P – probability.

The uncertainty of measurement results of the ultrasonic velocity was estimated in accordance with the ''JCGM 100: 2008 Evaluation of measurement data – Guide to the expression of uncertainty in measurement'' norm.
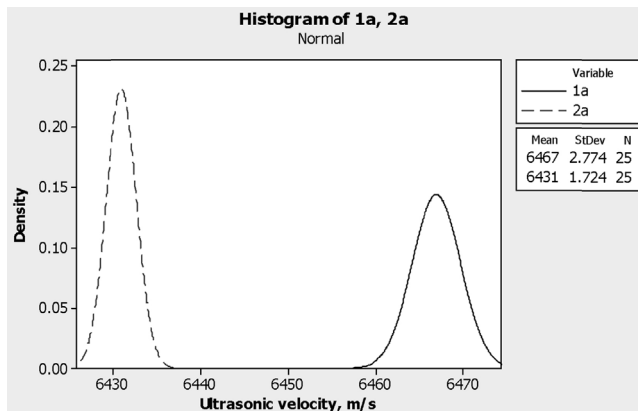

Fig. 7 – Histogram of ultrasonic velocity.

6.   Verification of ultrasonic velocity measurement on annealed samples

In order to confirm obtained results and applicability of suggested method, measurements were performed at two more samples of the same material in different conditions. The samples were annealed and two different grain sizes were obtained. Annealing process put the samples into isotropic form. Temperature/time regimes of annealing process and obtained microstructures are presented in Table 4 and Fig. 8.

Ultrasonic velocity has been measured under the same conditions as they were on the first testing sample. Also testing samples were cut on the same dimensions as the first one. According to previously obtained results, it was expected that measured ultrasonic velocity should be the same in both directions at one sample but different from the other one. Measuring points are marked in accordance to the first testing sample. Measuring points on the testing sample with 39 μm

Table 2 – F-test.

Method	Degrees of freedom DF 1	Degrees of freedom DF 2	Statistic	p-Value
F-test	24	24	2.59	0.024

Table 3 – T-test.

	N	Mean	StDev	SE mean
		Two-sample T test for 1a vs 2a		
1a	25	6466.88	2.77	0.55
2a	25	6430.98	1.72	0.34
Difference = mu (1a) − mu (2a)				
Estimate for difference: 35.896				
T-test of difference = 0 (vs not =): T-value = 54.96, p-value = 0.000,				
DF = 40				

Table 4 – Annealing regimes and obtained grain size.

Temperature/time regimes	Obtained average grain size
350 °C – 2 h/slow cooling	39 μm
450 °C – 3 h/slow cooling	95 μm

Table 5 – Ultrasonic velocity at four measuring points of two samples.

Sample	Measuring point	Ultrasonic velocity (m/s)	Measurement uncertainty, U, $k = 2$; $P = 95\%$ (m/s)
39 μm	$1a^1$	6440	4.5
	$2a^1$	6436	4.5
95 μm	$1a^2$	6481	4.5
	$2a^2$	6478	4.5

grain size is marked with $1a^1$ and $2a^1$ and measuring points on the testing sample with 95 μm grain size is marked with $1a^2$ and $2a^2$. Measurement results of ultrasonic velocities at places $1a^1$, $2a^1$, $1a^2$ and $2a^2$ are presented in Table 5 and Fig. 9.

Differences between ultrasonic velocities in both cases ($1a^1$, $2a^1$ and $1a^2$, $2a^2$) are within declared expanded measurement uncertainty, $U = 4.5$ m/s with coverage factor $k = 2$ and probability $P = 95\%$. It can be concluded that the achieved differences between the ultrasonic velocities are a result of random errors and the limited possibilities of the applied method. In other words there are no significant difference between ultrasonic velocities at places $1a^1$, $2a^1$ and also at places $1a^2$, $2a^2$.

Comment:

Achieved measurement results are in accordance to the expectations and confirm first results that are obtained by measurement of distorted grain structure. These results show low dissipation and are equable in both measuring directions
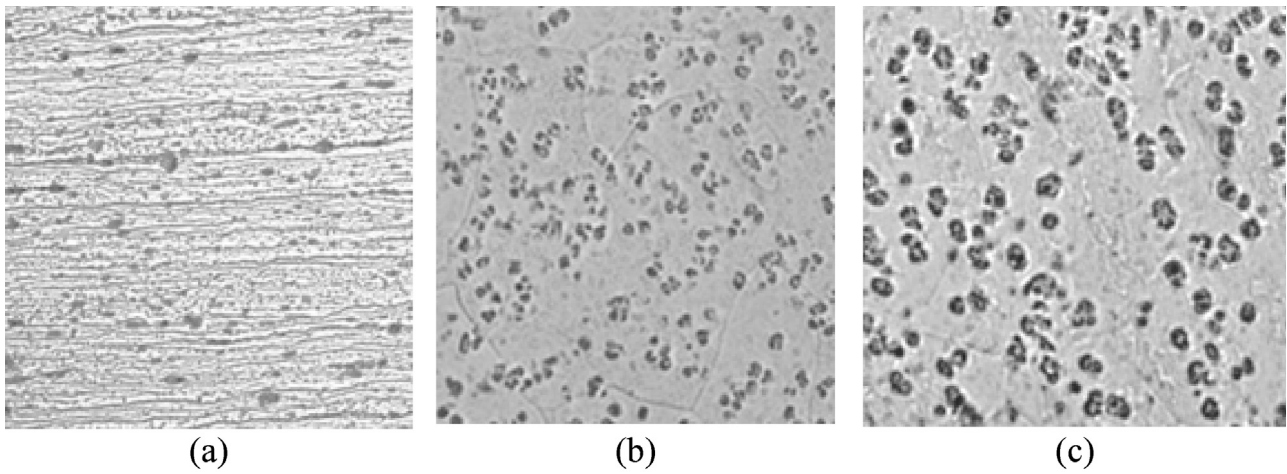
Fig. 8 – Obtained microstructure: (a) microstructure before annealing, (b) 39 μm grain size, (c) 95 μm grain size.
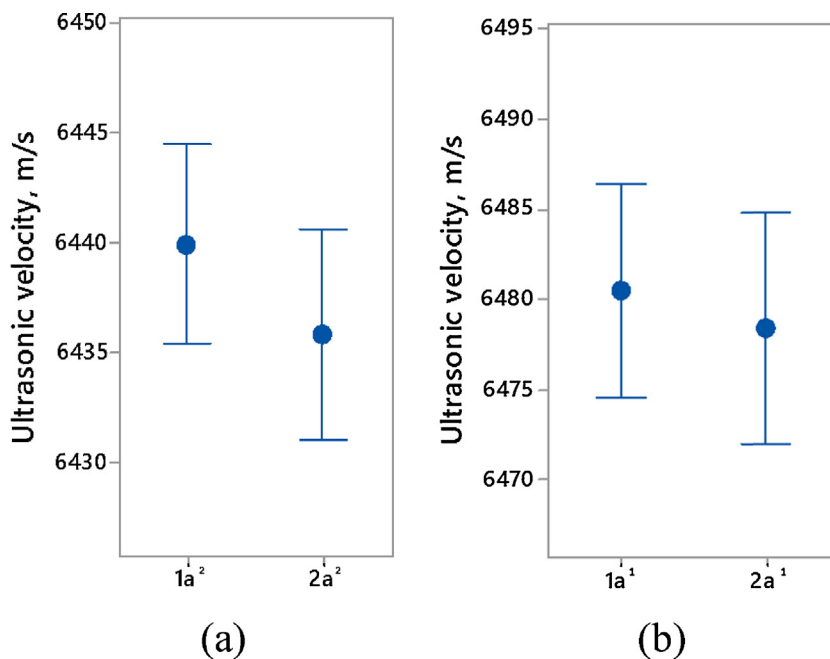
Fig. 9 – Graphical overview of measurement results at $1a^1$, $2a^1$, $1a^2$ and $2a^2$.

of one testing sample because of homogenous microstructure. On the other hand there is a difference between two samples, because of different grain size. Also, larger grain size shows greater ultrasonic velocity because of less grain boundaries, and smaller grain size shows lower ultrasonic velocity because of greater number of grain boundaries.

7. Conclusion

Grain distortion plays significant role in mechanical properties anisotropy of cold formed metal part. This fact must be considered when exploitation loading decision takes place. As a great help in determination of distortion existence and distortion direction non-destructive ultrasonic measurement can be used. Presented work indicates simple way of its utilization by measuring ultrasonic velocity in two perpendicular planes of the same cold extruded part. Measurement results and their statistical analysis shows the difference in ultrasonic velocity in the plane parallel to forming direction (extrusion direction) – 2a, and in the plane normal to extrusion direction – 1a. As it can be expected, distorted grain structure presents inhibition to ultrasound wave propagation. Grain elongation happens in forming direction, which means that greater distortion also happens in that direction. Greater ultrasonic velocity is measured in the plane normal to extrusion direction (1a). In the direction parallel to elongated grain structure (2a) exists larger number of grain boundaries and ultrasonic velocity decreases. Also, statistical analysis shows that standard deviation of measurements in a place 1a is broader than standard deviation of measurements in a place 2a. In a plane that is parallel with forming force, elongated structure becomes relatively uniform. Because of that, standard deviation of taken measurements is relatively small.

As a tool for verification of obtained result, annealed homogenous samples of the same material and size were made. Ultrasonic measurements were performed in the same way. Results show equable ultrasonic velocity in both directions of one sample, but differ from the other one. Larger grain size shows higher ultrasonic velocity, although smaller grain size shows lower ultrasonic velocity. These results confirm the previous one by following the same physical conditions: large number of grain boundaries slows down the ultrasonic velocity.

This work presents a way of ultrasonic measurement usage in exploitation decision of cold formed part. This concept has obviously many advantages in testing of different flat metal semi products. It is cost effective and relatively simple. Further questions lead us to explore more complex cold formed parts and also behaviour of ultrasonic velocity in cases of different deformation degrees.

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