Estimation of the elasticity module of Al-Si alloy samples in cast and deformed states by the frequency spectrum of sound vibrations

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Abstract: *Using fast Fourier transform the frequency spectra of sound vibrations of sound obtained by impacting a suspended material sample were obtained and analyzed. For this, the corresponding short sound files were recorded, which were then subjected to computer analysis. It was found that the frequency spectra of sound vibrations for cast silumin and for those after deformation-heat treatment have a different character. So in these spectra obtained for samples that have passed the deformation-heat treatment, a set of narrow, clearly peaks at certain frequencies have been observed. In the spectra obtained for cast samples, such clear, narrow peaks are not observed. The position of the characteristic peaks in the frequency spectra of sound vibrations was used to estimate the elastic modulus for samples that have passed various regimes of deformation-heat treatment.*
***KEYWORDS**: SILUMIN, FAST FOURIER TRANSFORM, ELASTIC MODULUS, DEFORMATION-HEAT TREATMENT*

1. Introduction

The *objective* of this research is to study the effect of deformation-heat treatment of alloys of the Al-Si system on the nature of the frequency spectra of sound vibrations obtained by fast Fourier transforms [1] of a recording sound emitted when hitting a suspended sample, as well as evaluating the elastic modulus of the material studding the values of natural frequencies.

Alloys of the Al-Si system are used for the cast products manufacture and practically do not undergo plastic deformation. This is because of the low ductility of such materials. We have proposed and investigated a method for increasing the plasticity of such alloys by deformation-heat treatment, which consists of a series of small hot deformations with intermediate annealing. As a result of this treatment, the plasticity of the alloy actually increased, and the silicon inclusions were crushed and acquired a shape close to spherical or equiaxial “tumbling“ fragments. Annealing without deformation, both simple and cyclic, even for the time of 4–5 h at temperatures above 500 ºC, did not have such a significant effect on silicon inclusions as the combination of a series of hot deformations with intermediate cooling and annealing.

When working with the samples, an interesting detail was noticed – the sound emitted when the sample was struck or dropped onto a hard surface was different for cast and annealed samples, and for samples that underwent deformation-heat treatment. In other words, the samples after forging produced a pronounced prolonged ringing sound; for cast and annealed samples, a short, indefinite rattling was observed. This difference in sound prompted the idea of a more detailed study of this difference. The sound obtained by impacting the samples was recorded and subjected to both the analysis of the time dependence of the vibration amplitude and the Fourier transform to obtain the spectrum of the vibration frequency intensity in the corresponding recorded sound.

2.1. Experimental material and technique

The study used samples of alloys of two types – with 4.5% Si and with 7% Si. The chemical composition of both types of samples is shown in Table 1.

Table 1

Chemical composition of the test samples (wt%)

Sample type	Al	Si	Mn	Cu	Fe
1	base	7.0	0.1	0.5	0.75
2		4.5	0.5	0.7	0.5

The samples had shapes of rectangular rods of various lengths and sections. Table 2 shows the geometric dimensions of the samples. At the same time, it also indicates the type of sample, which depends on the nature of the processing to which it was or was not subjected.

Table 2: *Geometric dimensions of samples, mm*

Sample type by the chemical composition (see table 1)	Sample type by the material state (see table 3)	№ of sample	Sample dimensions		
			a	*b*	*l*
1	1	1	7.8	6.9	59.9
		2	7.9	7.1	52.2
	2	3	6.4	7.2	79.8
		4	6.65	7.5	70.15
2	3	5	7.3	6.5	82.1
		6	7.2	6.1	91.0
1	4	7	5.9	6.6	67.9
	5	8	8.8	8.4	40.8
	6	9	9.4	8.7	41.5
2	5	10	14.2	13.9	37.9
	5	11	13.0	11.5	30.8

Table 3 shows brief characteristics of the sample processing modes, the numbering corresponds to the numbers from the column "Sample type by the material state" in Table 2.

Table 3: *Processing modes for the samples*

№ of treatment type	Processing characteristic
1	11 stages of deformation by forging with intermediate annealing for 12 – 18 minutes at a temperature of 520 ºC. Start of forging at 520 – 510ºC, end of forging at ~ 250 – 300 ºC. The total degree of deformation is ~ 29%, elongation is ~42%.
2	17 stages of deformation by forging with intermediate annealing for 10 – 12 minutes at a temperature of 510 ºC. Start of forging at 510 – 490ºC, end of forging at ~ 100 – 150 ºC. The total degree of deformation is ~ 52%, elongation is ~98%.
3	11 stages of deformation by forging with intermediate annealing for 15 – 20 min at a temperature of 540 ºC. Final annealing 30 min. Start of forging at 540 – 520 ºC, end of forging at ~100 – 200 ºC. The total degree of deformation is ~70%, elongation is ~ 138%.
4	19 stages of deformation by forging with intermediate annealing for 9 – 15 minutes at a temperature of 510 ºC. Start of forging at 510 – 490ºC, end of forging at room temperature. Final cold deformation. The total degree of hot deformation is ~ 33%, the final cold deformation is ~ 12%, and the total elongation is ~ 63%.
5	Initial cast condition

6	Annealing at a temperature of 520 – 540 ºC for ~4.5 h.

The samples were hung on a string, and the sample was struck with a wooden stick. The sound produced by this was recorded and saved as an audio file of the .wav format. This file was passed to a program that performs fast Fourier transforms and visualizes the results as a plot. The program is written in Python, for the implementation of fast Fourier transforms, the functions of the program library numpy [2, 3] were used in it, and matplotlib [4] was used to visualize the results. The resulting graphs were saved as graphic files in .jpg format. The positions of the peaks on the graphs were measured using the jMicroVision program [5]. For each sample, 10-15 such acoustic spectra were recorded to identify and exclude the effects of random noise and to confirm the repeatability of peak locations.

In addition, the study of the microstructure of the samples, measurement of their Vickers hardness, microhardness of the metal matrix and plasticity during deposition were carried out.

2.2. Research results

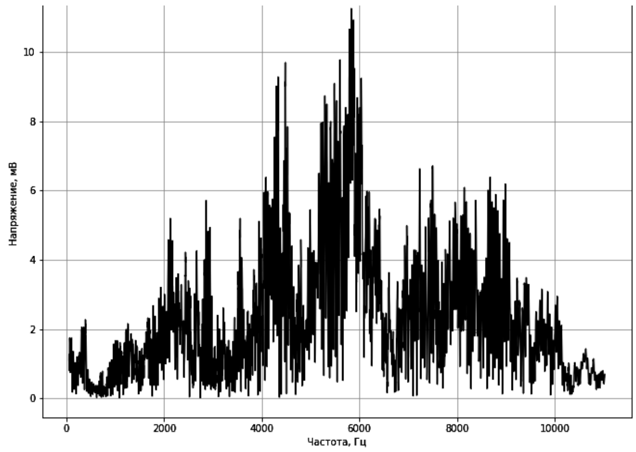
It was noticed that in the acoustic frequency spectra obtained for samples that were subjected to deformation-heat treatment, pronounced peaks appear at certain frequencies. Peaks were observed from time to time at fixed locations for a given sample. The peaks could have different intensities, which in each case, in some cases, individual peaks might not appear at all, but if they appeared it was at the same frequencies. No certain narrow peaks were observed for the acoustic spectra of cast and annealed samples.

Figure 1 shows examples of graphs of acoustic spectra for a cast sample (a) and a sample after deformation-heat treatment (b). In the case of a cast sample, if some peaks can be noticed in the acoustic spectrum, then they are unstable, have low intensity, and their boundaries are blurred.

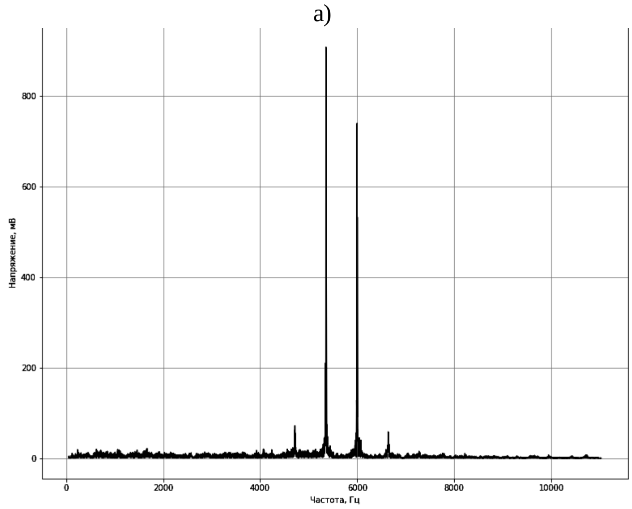
Thus, the first thing that this method allows is to distinguish a specimen in a cast or annealed state from a specimen that has been subjected to deformation-heat treatment.

The observed difference in the acoustic spectra of cast and deformed samples is apparently caused by the difference in the shape of silicon inclusions in them. Figure 2 shows examples of silicon inclusions photographs in cast (a), annealed (b), and deformed (c, d) samples.

Apparently, inclusions of silicon in cast samples, representing a skeleton of silicon wafers, dampen the propagation of sound in the material. In the samples after annealing, the inclusions are more separated, but on the whole retain their plate-like shape. In specimens after deformation-heat treatment, silicon inclusions are globular and to a much lesser dampen the propagation of sound in the metal. In addition, it was noted that in samples with a higher degree of spheroidization of inclusions, the sound, on average, with the same force and nature of impact on the sample, is louder and more sustainable. The hardness of the metal material apparently does not affect the qualitative difference in the frequency acoustic spectra of cast and deformed samples. Thus, the highest hardness was observed in the as-cast state in specimens of composition 1 (67.0 ± 12.1 HB), the hardness of annealed specimens and specimens processed in modes 1 and 2 was lower than in the as-cast state and was about 50 HB. For specimens of composition 2, the hardness in the cast state and after deformation-heat treatment practically did not differ. Thus, we do not observe any significant influence of hardness on the peaks appearance in acoustic spectra and on the degree of their blurring.



a)



b)

***Figure1** – Examples of acoustic frequency spectra – a) cast sample; b) deformed specimen*

It is known from theory that the frequency of sound vibrations of a rod depends on its geometric dimensions and shape, the pattern of its ends pinching, as well as the density and modulus of elasticity of the material [6]. The frequencies of natural vibrations of the rod are described by the formula (1):

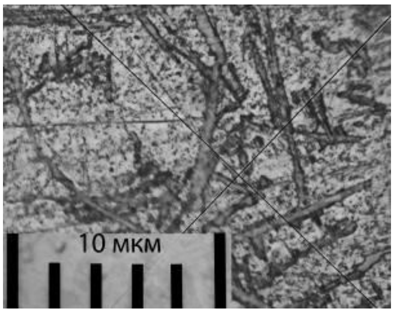
$$f = \frac{k}{L^2} \cdot \sqrt{\frac{E \cdot I}{\rho \cdot A}} \qquad (1)$$

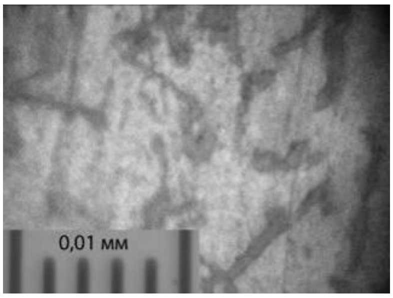
where L is the length of the rod, *m*; E is the modulus of elasticity, *Pa*; ρ is the density of the material, kg/m^3, I is the axial moment of inertia for the cross section of the bar, m^4; A is the cross-sectional area of the bar, m^2, k is a coefficient that depends on the boundary conditions (pinching schemes) and the order of the harmonic.

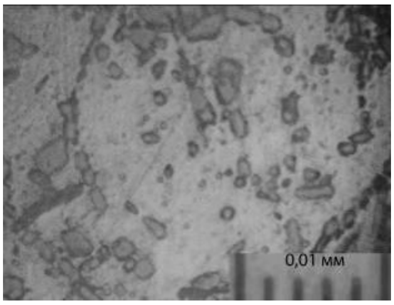
In this case, the cross section of the sample is rectangular. Thus, there are two axial moments of inertia determined by the formula (2) [7]:

$$I_x = \frac{b \cdot a^3}{12} \qquad I_y = \frac{b^3 \cdot a}{12} \qquad (2)$$

where a, b – cross-sectional dimensions, m

a) 

b) 

c) 

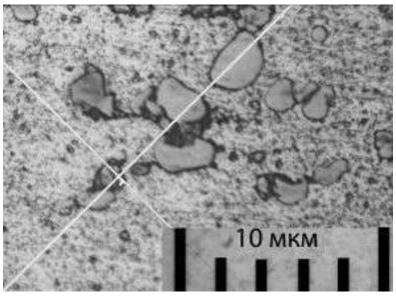
d) 

***Figure 2** – Silicon inclusions in silumin samples with 7 % Si:*
a) cast sample, magnification × 500;
b) annealed sample, magnification × 400;
c) sample after deformation-heat treatment, magnification × 400;
d) sample after deformation-heat treatment, magnification × 500;

The presence of two axial moments of inertia leads to split pairs of peaks observed in the frequency spectra of sound vibrations. Also, in a number of cases, harmonics are clearly visible.

By comparing the experimental data with the theory, it was established that for the considered case – a sample hung on a thread – the boundary conditions for the hinge fixation of the ends are most suitable for determining the frequency of natural vibrations. With such a scheme, the coefficient k from formula (1) is $(n \cdot \pi) / 2$, where n is the harmonic number. Most often, the 1st harmonic of natural vibrations (fundamental tone) manifested itself most clearly in the samples, the 2nd one manifested itself relatively seldom (in samples 3, 4, and 7 it was practically not observed), but the 3rd was often intense. The reason for this behavior is still unclear.

Knowing the geometric parameters of the sample and its density, based on the position of the peaks in the acoustic frequency spectrum, it is possible to estimate the value of the elastic modulus of the material, according to formula (1). The material density of the samples of composition 1 was determined to be 2670 kg/m^2, and of type 2 – 2680 kg/m^2. The calculated estimate of the elastic modulus of type 1 specimens processed by mode 1 was 72.0...72.9 GPa, by mode 2 – 75.2...76.2 GPa, and by mode 4 – 78.3...81.1 GPa. This is not a huge but statistically significant difference.

Considering the fact that the hardness of the metal matrix of specimens processed according to mode 2 (48.2±9.8 kgf/mm^2) is slightly higher than that of specimens processed according to mode 1 (41.8±3.8 kgf/mm^2), it is possible to assume the relationship between the modulus of elasticity and the hardness of the metal matrix of the material, while the total hardness practically does not differ. Mode 4 includes additional cold deformation, which increases the hardness of the material. Obviously, its modulus of elasticity increases, as is known, correlates with the hardness of the material [8].

The acoustic frequency spectra for samples of composition 2 (4.5 % Si) are characterized in a similar way: there do not have certain narrow peaks for the cast state, but they appear after deformation-heat treatment. The calculated estimate of the elastic modulus for sample 5, deformed by ~ 70%, is 75.4...75.7 GPa. Although the hardness of these specimens (35.2 ± 5.0 HB) is lower than that of specimens with 7% Si, their estimated modulus of elasticity is approximately at the level of specimens processed according to mode 2. This still indicates a not quite direct dependence of the modulus of elasticity on hardness and, apparently, shows the role of the large degree of deformation to which these samples underwent.

Thus, the considered approach makes it possible to estimate the values of the elastic modulus of the material in a fairly simple way without special equipment.

3. Conclusions

The study has been carried out of the frequency spectra of sound vibrations obtained by fast Fourier transforms of audio files with a recording of the sound emitted when struck by suspended samples of alloys of the Al-Si system. This method was used to study samples with 4.5 and 7.0% Si in cast and deformed states.

A significant qualitative difference in the frequency spectra of sound vibrations for cast and deformed samples is shown. The observed difference is apparently associated with the damping and scattering of sound vibrations by silicon inclusions in the cast material, where they form a frame of lamellar precipitates. The globular shape of silicon inclusions in the material after deformation-heat treatment does not lead to such scattering of sound vibrations; therefore, certain narrow frequencies appear in the acoustic spectrum, corresponding to the natural vibrations of the rod.

The position of the characteristic peaks in the frequency spectra of sound vibrations for the samples after deformation-heat treatment is in good agreement with the theoretically calculated frequencies of natural vibrations of a rod with hinged ends. This makes it possible, knowing the geometric dimensions and shape of the sample and its density, to estimate the value of the elastic modulus of the material.

The evaluation of the elastic modulus carried out on the basis of determining the position of the natural vibration frequencies of the rod (sample) showed that it somewhat increases with an increase in the total degree of deformation during the deformation-heat treatment of the silumin and additionally increases with the combination of the basic multistage hot and final cold deformation. It is also shown that the values of the elastic modulus for samples with 4.5 % of Si after deformation-heat treatment with a total deformation greater degree than that of the samples with 7 % of Si were subjected to, is approximately at the same level as in one with 7 % of Si. Despite the fact that the hardness of this material is noticeably lower.

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