Changes in metal properties after thermal and electric impulse processing

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Abstract. Abstract – The results of the experiments on processing metal melts by powerful electromagnetic impulses are given. The generator used in the experiments has the following characteristics: pulse height – 10KV, duration – 1ns, leading edge – 0,1ns, repetition rate – 1KHz, the output – 100KWt. The duration of the processing is 10-15min. The comparative analysis of the processed and unprocessed samples results in the changes of structure, increase of density, solidity, plasticity and resilience of cast metal. The result analysis of different external physical processing methods on alloys shows full agreement with the results of the ultrasonic processing of metals. The hypothesis of ultrasonic shock wave formation at the pulse front was adopted as the main mechanism of the electromagnetic impulse impact on alloys. The theoretical part of the research describes the transformation process of electromagnetic impulses into acoustic ones.

1. Introduction
The cast iron structure is eligible to be changed by various methods of external melt processing methods that can be subdivided into two main groups: chemical and physical methods. Chemical methods (impurity doping, modification, finishing) make changes in the chemical composition of metals. Physical methods (thermal, barometrical, gravitational, mechanical, electromagnetic, high-energy) provide interaction between the metal and the environment. Electromagnetic mixing, vibration and ultrasonic processing are the examples of the most common methods of external physical processing of metals. Each of the above methods possesses its own advantages and disadvantages but all of them are able to specifically change the structure and properties of cast metal. Our research makes use of a new external melt processing method by powerful electromagnetic impulses [1].

2. Experiment samples and methodology
Aluminum alloy Al–6 mass% Si (about 3kg of the processed melt), copper alloy BrAZh10-3 (300 kg of the melt) and 35L steel (1.9 tons) are taken as the samples for the experiment. The chemical composition of the alloys is given in Table 1.

All the alloys underwent two melt operations under the identical temperature-time conditions. During the first melt operation the temperature exceeded the melt temperature by 100°C and the alloys were left for homogenizing annealing. Then the furnace was switched off and the melts were exposed to powerful electromagnetic impulses for 10-15 min. The generator of impulses used in the experiments has the following characteristics: pulse height – 10 kV, duration – 1 ns, leading edge – 0,1 ns,
repetition rate – 1 kHz, output – 100 kW. One of the generator electrodes was put into the melt; another one was connected to the graphite crucible.

### Table 1. The chemical composition of the alloys, mass %.

| Alloy               | Element composition                                      |
|---------------------|----------------------------------------------------------|
| Al–6 mass % Si      | 6.44 % Si, 0.06 % Cu, 0.01 % Mn, 0.27 % Mg, 0.02 % Ti,   |
|                     | 0.04 % Zn, 0.27 % Fe, the rest is Al.                    |
| BrAZh10-3           | 9.4 % Al; 3.4 % Fe; 0.01 % Sn; 0.09% Si; 0.26 % Ni; 0.05% |
|                     | Pb; 0.83 % Zn, the rest is Cu.                           |
| 35L steel           | 0.32–0.4 %C, 0.2–0.52% Si, 0.5% Mn, до 0.3% Ni, до 0.045% S, |
|                     | до 0.04% P, до 0.3% Cr, the rest is Fe.                   |

The second melt operation was done under the same temperature-time conditions but instead of electromagnetic processing the melt was exposed in the furnace for 10-15 min before casting. During both operations the temperature was registered before casting and sand-clay molds were used. The samples for mechanical testing and microstructure researches were cut out of the obtained moldings.

### 3. The impact of electromagnetic impulse processing on alloy structure

The following differences were identified in the macro and microstructure of the initial and processed Al–6 mass % Si alloy. The initial metal template has two well-defined crystallization regions: a region of columnar crystals near the mold and a region of equiaxed coarse grains in the center of the ingot. The region with crust columnar crystals in the processed ingot template is less defined. The presence of bigger equiaxed grains should also be noted in the center of the ingot. The microstructure of the cast silumin samples is shown in figure 1.

It is known that in the state of equilibrium with slow cooling of silumin ingots the erratic eutectic appears: $\alpha$-solid solution, silicon crystals and lamellar structures being a compound of AlSiFe [2]. The crystals of the initial $\alpha$-phase in both samples have a tree-like form. The amount of the eutectic in the structure after the electromagnetic impulse processing reduces from 30–35% to 10–15%. The particles of eutectic silicon become of a needle-like form with the length up to 25–30 μm. For unprocessed metal the eutectic silicon phase is dispersed with mean linear parameters up to 5–10 μm. Due to the decrease of eutectic release at the boundaries of dendrite cells $\alpha$-phase dendrites increase insufficiently in size from 66 to 85 μm (linear parameters were define by the secant method) and become more of a round shape.

![Figure 1](image-url)
The microhardness of the $\alpha$-phase grains in the sample after electromagnetic impulse processing increased by 10-15% to 750 MPa. The reduction of the eutectic amount and the increase of the $\alpha$-phase microhardness reflect the greater silicon content at this phase. The growth of silicon content is proved by the series of experiments carried out with the help of the JEOL JSM-6460LV scanning electron microscope with Oxford INCA X max 80 dispersion spectrometer for element analysis. According to the obtained data, the maximum silicon concentration at the $\alpha$-phase of the initial metal reaches 1.36–1.66 mass %, whereas in the processed sample – 1.48–1.80 mass % (with the absolute error 0.04 %). The microstructure examination of BrAZh10-3 bronze alloy samples on the scanning electron microscope showed the identical phase composition of the samples. Eutectic and lead phases of both samples are inhomogeneously distributed along the section plane and have irregular form. The microstructure examination of samples on the optical microscope showed the presence of dendrites of different sizes in the unprocessed sample. The dendrites in the processed sample are smaller and have more uniform sizes. Both 35L steel samples are characterized by the presence of ferrite-pearlite structure. The samples microstructures after etching are shown in figure 2.

![Figure 2. 35L steel microstructure: a – initial sample, b – processed with electromagnetic impulses](image)

The average size of grains in the initial sample is 700μm, in the processed with electromagnetic impulses 450μm. With the evident growth of the overall length of grain boundaries in the processed sample the grain-boundary ferrite phase becomes continuous along all grain boundaries and less defined (see figure 2). Note that there are no deformation regions in all of the examined processed metal samples, whereas they are present on the initial metal sample.

4. The impact of electromagnetic impulse processing on mechanical properties of alloys
The hardness measurement of Al-Si cast alloy samples displays that preliminary electromagnetic impulse processing of alloys increases hardness. Initial samples have 51 HB hardness, test samples – 63 HB. Using the method of tearing a ring plate off the alloy surface we measured surface tension. At 700°C it was 0.81 N/m and 0.74 N/m for initial and processed samples correspondingly. Castability defined by the State Standard 16438-70 was 195 and 295 mm for initial and processed samples correspondingly. Tensile strength was 170 MPa and 210 MPa, specific elongation 4.8 and 18.4 % for initial and processed metal correspondingly [3]. Density measurement of the bronze sample was carried out using hydrostatic weighing method that showed the density of 8.642 and 8.573 for initial and processed metal correspondingly. The slight hardness growth of 70 and 65 HRB was also noted for initial and processed metal correspondingly. The results of tensile strength tests are given in Table 2.
Table 2. Mechanical properties of BrAZh10-3 bronze samples.

| Sample   | Ultimate strength, MPa | Conventional yield strength, MPa | Specific elongation, % |
|----------|------------------------|----------------------------------|------------------------|
| Initial  | 50,6                   | 11,8                             | 21                     |
| Processed| 50                     | 14,4                             | 23,4                   |

The hardness growth for 35L steel samples after impulse processing of the alloy was also noted: average value of initial samples – 22 HRC, processed – 25 HRC.

The results of mechanical tests for tensile strength and resilience are given in Table 3.

Table 3. Mechanical properties of BrAZh10-3 bronze samples.

| Sample    | Yield strength, MPa | Ultimate strength, MPa | Specific elongation, % | Contraction ratio, % | Resilience at room-temperature, J/cm² | Resilience at 60°C, J/cm² |
|-----------|---------------------|------------------------|------------------------|----------------------|---------------------------------------|--------------------------|
| Initial   | 386                 | 520                    | 6                      | 12                   | 12                                    | 9,8                      |
| Processed | 454                 | 772                    | 15                     | 39                   | 45                                    | 13                       |

5. Discussion of results

Thus, the obtained results on electromagnetic impulse processing of metal alloys indicate the impact of this processing on the process of grain structure formation, composition and morphology of phases and mechanical properties of metals. The mechanism of this impact is not clear yet. Nonetheless, having compared the obtained results with various data of outer impact on alloys, we found out some similarities. The most similar results were obtained using ultrasonic processing of alloys (US).

The absolute majority of works on ultrasonic processing of aluminum, magnesium alloys and steels states that the form of initial α-phase products changes from tree-like to rosette and roundish. The paper [4] shows that in the crystallization phase of 0.35 kg of Al-5 mass% Si alloy 4 kW ultrasonic processing of the metal stimulates grain refinement from 1600 μm to 100 μm. The α-phase grain morphology changes to more roundish. The eutectic silicon particles become of the same rough shape as in the case of electromagnetic processing. The authors showed the roughening of eutectic for Al-11 mass %Si and Al-17 mass % Si alloys. Similarly to the paper [5] 1.5kW and 20 kHz US processing at temperatures close to those of crystallization results in the roughening of eutectic silicon.

At the same time the results of the experiments on 1.2 KW US processing of 0.4 kg AlSi9Cu alloy [6] exhibit the reduction in inter-lamellar space and refinement of eutectic silicon particles.

The controversial data obtained by the scientists on the morphology of eutectic silicon particles can be explained with the choice of processing temperature. The refinement of silicon particles takes place with the processing at an early stage of crystallization as a result of cavity phenomena. At lower temperatures the thickened melt does not allow cavity flows and thus prevents the fragmentation of phases. Input energy heats the alloy and changes the growth condition of eutectic roughening it.

The reference to the increase of basic alloying elements in the initial α-phase at US processing is also made in the paper [7].

The growth of strength and plasticity characteristics with 600 W and 19.5 kHz US processing and retention of rough needle-like form of eutectic is shown in the paper [8]. The above mentioned papers [4-7] indicate the growth of ultimate strength and specific elongation simultaneously with the grain and eutectic refinement.

As the phenomena occurring at the impulse processing are similar to those of the US processing, there is a possibility of the acoustic fields produced by the electromagnetic impulse generator to exert pressure on the alloy.
The papers [9-11] indicate that ultrasonic oscillations are generated in metal melts exposed to electromagnetic oscillation. The calculations for the induction melting of aluminum [12] in a 300 mm diameter crucible with a constant $5 \cdot 10^4 \text{ A/m}$ field show the oscillation pressure on the alloy to be 2 atm. This pressure is considered sufficient to achieve useful metallurgical results.

Stimulation of the mechanical oscillation is practically produced by the contact method due to the specific design of the apparatus in use. The specific placement of the oscillator makes current flow from the oscillator along the surface of an alloy and, possibly, the efficiency of the generated oscillations is greater than stated in the above mentioned papers.

To support our hypothesis theoretically, we make comparative calculations for oscillation intensity. Some papers on US impact on alloys have data making it possible to calculate generated mechanical pressure.

For plane and spherical waves acoustic pressure and displacement of particles in metals are bound through a ratio [9]:

$$p = \rho c \omega \xi = z \omega \xi,$$

where the product of metal density and speed of sound $\rho c = z$ is the acoustic impedance (resistance), $\omega$ is the angular frequency ($\omega = 2\pi f$); $\xi$ is the displacement of particles from equilibrium.

The paper [13] on the oscillator in the aluminum alloy states: $f = 21 \text{ kHz}$, $\xi = 25 \mu\text{m}$, the generator output is 1 kW, oscillation intensity is 100 W/cm$^2$, the processed metal mass is not mentioned. The speed of the longitudinal wave in solid aluminum is 6200 m/sec [14]. The oscillation speed in the alloy can reach 70% of the solid metal [14]. The density of the melted aluminum is 2390 kg/m$^3$ [15]. The calculations with the equation (1) give the value of pressure in the oscillator equal to 29 MPa or 290 atm.

The paper [16] on the oscillator in the aluminum alloy states: $f = 20 \text{ kHz}$, $\xi = 4 \mu\text{m}$, the generator output is 150 kW, the processed metal mass is 200 g. The calculations of the acoustic pressure result in 4.6 MPa (4.6 atm.).

The paper [8] on the oscillator in the aluminum alloy states: $f = 19.5 \text{ kHz}$, $\xi = 30 \mu\text{m}$, the generator output is 600 kW, oscillation intensity is 109 W/cm$^2$, the processed metal mass is 210 g. The calculations of the acoustic pressure result in 34 MPa (340 atm.).

The paper [12] indicates that the electrodynamic pressure in the alloy should be 1-4 atm or $4 \cdot 10^5 \text{ Pa}$ to produce useful metallurgical results.

The calculation equation for the surface wave pressure can be applied to calculate the oscillation pressure:

$$p = E(1+R)/c,$$

where $p$ is the wave pressure, N/m$^2$; $E$ is the incident wave force attributed per unit area and time, W/cm$^2$; $R$ is the reflection coefficient ($R = 0$ at total absorption, $R = 1$ at total reflection); $c$ is the wave velocity, m/sec. The wave velocity in smelts is $4 \cdot 10^3 \text{ m/sec}$ [14].

At the impulse stimulation of oscillations the incident impulse force can be approximately calculated with the equation:

$$P = \frac{U^2}{r},$$

where $r$ is the cable wave resistance of 50 Ohm; $U$ is the generator voltage of 10 kW. When calculating the value of the incident impulse force with the equation (3) we obtain $P = 2 \cdot 10^6 \text{ W}$. The area of the metal free plane in the 80 mm crucible is $5 \cdot 10^{-3} \text{ m}^2$. Consequently, the impulse force per unit area is $4 \cdot 10^3 \text{ W/m}^2$.

If we insert the obtained value of the impulse force in the equation (1), we get $P_{\text{imp}} = 1,3 \cdot 10^5 \text{ Pa}$ (or 1.3 atm). This value is close to the values of the applied pressure stated in the papers [12] and [16].

6. Conclusion

The obtained results testify for the similarity between the mechanisms of the impact on metals by electromagnetic impulse and ultrasonic processing. Though the produced results are similar, the
impulse type of processing is void of disadvantages peculiar to ultrasonic processing (complicated, expensive equipment, harmful effects on human health, etc.) and more efficient.

7. References

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