Measurements of dynamic Young modulus of AlSi10Mg alloy cast in vibrating field

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The goal of this paper is to test the vibrations influence on dynamic longitudinal elastic modulus. AlSi10Mg alloy (EN 1706-2010) was used for the samples. The solidification was done static and in vibration conditions. Six lots of specimens were casted in cold and preheated moulds, without and with vibrations from 50 Hz to 1050 Hz. In order to determine the dynamic modulus of elasticity it was necessary to have the density and the resonance frequency of the samples. The density used was computed as average of two values, first from the volume calculation and second one from the volume measuring by immersion in liquid. The resonant frequency determination was performed on cantilever samples using a dedicated setup. An increasing of the dynamic elastic modulus was observed with increasing of vibration frequency and with the increasing of the material density. The results were mathematically modelled having a good correlation.

1. Introduction

By analyzing the behavior of a material under the action of variable mechanical vibration frequency, several conclusions on the microstructure and mechanical properties were established. Thus, the method can be used for non-destructive testing of different products, which can measure the overall status: dimensions, microstructure, stress state, the presence of internal defects.

Abu-Dheir et al [1] have analyzed the Al – 12.5 % Si alloy solidification in vibrating field at a frequency of 100 Hz. The vibrations produced the increasing of the elongation up to 68%. Moreover the increasing of the ultimate strength was observed.

Appendino et al. investigated in [2] the solidification of A356 alloy, casted into sand molds under 3000Hz maximal vibration frequency and accelerations of 0.1g ... 15g. Excitation was in vertical direction. They used two types of sand mould casting: the first type made of a mixture of sand + bentonite + water, the second using phenolic resin and isocyanate. The microstructure and porosity were investigated by optical microscopy and image analysis. The mechanical properties were studied by tensile test. In static casting, secondary dendrite arms spacing of 40 μm was achieved, and in the casting case with low accelerations (3g), the interdendritic space was 28 μm. At high accelerations (5g) the obtained globular structure was without dendrites. In the case of the sample with 3mm diameter an increase of 66% elongation was established, and in the case of the sample with 5mm diameter there was an increase of 52% elongation.

Pirvulescu and Bratu analyzed in [3] crystallization under the mechanical vibrations influence. Frequencies from 17 to 75 Hz were applied and accelerations from 140 to 617.74 m/s2, both in vertical and horizontal plan. Two

materials were analyzed: AlSi alloy (Si6-18%) and AlSiMg alloy (Si12.5% Mg0.25% Mn0.2%). By applying vibrations the structure was improved and the shrinkages reduced. In addition, by vibration an increase of the mechanical properties was obtained (tensile strength at yield, elongation and toughness) compared to static casting.

Omura et al. [4] analyzed the effect of applying vibration during AC4C aluminum alloy solidification. The influence of vibrations with frequencies of 0...157 Hz on the grains size was investigated; also the distribution of defects and the mechanical properties were studied. Excitation was applied horizontally. By applying vibration the grain finishing structure was observed, also the decreasing of the casting defects, the spreading increased and the mechanical strength too, elongation was substantially improved.

Taghavi et al analyzed in [5] the effect of applying low frequency vibration (50 Hz max.) during solidification of A356 aluminum alloy on grain sizes of solid solution α and on the density. Frequency vibration were applied increasing from 10 to 50 Hz for 5, 10, 15 minutes. The best results were obtained at 50 Hz for 15 minutes, when the grain size of the α solid solution reached 173 micrometers, 53% grain refining achieved. At the same parameters an increase in density from 2.40 g/cm^3 to 2.66 g /cm^3 was obtained.

In [6] Puga et al. investigated the effect of ultrasonic vibrations on the properties of die-cast AlSi9Cu3, for different levels of electric power and at different distances to the waveguide/mold interface. The ultrasonic treatment of AlSi9Cu3 improved the alloy mechanical properties. Increasing the electric power between 200 and 600 W, the average UTS was improved from 270 to 338 MPa and also the strain increased from 1.1 to 2.9%.

In [7] Plachy et al. used impulse excitation method and standard compression test to determine the Young's moduli of concrete specimens. Using impulse excitation method, the dynamic Young's moduli were calculated based on measured resonant frequencies of longitudinal vibration of concrete specimens. The advantages of the first method are the non-destructive technique, the small variation of evaluated resonant frequencies and also of the dynamic Young's moduli (the standard deviation of determined dynamic Young's moduli is two times less than the standard deviation of the static Young's moduli). The second method was less accurate than the first one. The authors concluded that static Young's modulus is about 30% lower than dynamic Young's modulus.

In [8] Nemcova et al. compared two methods for dynamic Young's modulus determination: the resonant method and the ultrasound method, applied on gypsum. The values obtained from the resonance method were lower and also the dissipation of values is better than for the ultrasound method.

In [9] Azenha et al. applied the non-destructive technique of ambient vibration testing and the continuous identification of the frequency of vibration of the first flexural mode for monitoring the E-modulus evolution of concrete since casting. The results provided by this method were compared with the results given by standard compressive tests. This comparison was satisfactory, having some differences given by the size and boundary conditions of the samples.

Analyzing the published results it was established that vibrations have a favorable influence on the microstructure and physical-mechanical properties of metallic materials because they lead to a significant increase in the rate of solidification, microstructure finishing, a shrinkage reduction and advanced gas release. This is explained by energy nucleation increasing and growth of certain pressures acting on dendritic arms forming, causing their fragmentation.

To obtain these advantages, the applied vibration must have high energy and the wavefront orientation must be controlled, perpendicular on dendrites axes; the fragmentation of dendrites generates new crystals seed.

From the results obtained by different researchers [10-14], the idea to study the vibration influence on the crystallization process under resonance conditions emerged. In research conducted so far, vibrating systems at low frequencies up to 100 Hz have been developed, using electromechanical vibrator devices with eccentrically mass or high frequency 18...30 kHz produced by magnetostrictive effect [15, 16].

The positive results presented in the specific literature determined the research of the present paper, which tests the vibrations influence on dynamic longitudinal elastic modulus of cast AlSi10Mg alloy (EN 1706-2010).

2. Experimental

For sample preparation, a steel mold with vertical separation plan placed on a vibrating platform was used, moved by an electrodynamic exciter of vibrations type Robotron 11076 (fig. 1). Six cylindrical samples with dimensions 20 x 150 mm were made. Chemical composition of the samples was obtained with the spectrometer Spectro Analytical Instruments (table 1).

The casting and vibration conditions are presented in table 2.

Table 1. Chemical composition of the samples

%Si	%Fe	%Cu	%Mn	%Mg	%Cr	%Zn
9.928	0.1826	0.333	0.031	0.288	0.02	0.123
%Ni	%Pb	%Sn	%Ti	%Sb	%V	%Al
0.0059	0.72	0.2027	0.0981	0.0324	0.01	88.05

In input power for electrodynamic exciter was provided by low frequency generator type IEMI E0508 and power amplifier Metra Meb Frequenztechnic LV 103.

Frequency measurement was done using a portable multimeter UNI-T M890F and the infrared thermometer Omegascope OS523E was used for temperature measurement.

Table 2. Casting and vibration conditions

Sample	A	B	C	D	E	F
Frequency Hz	0	0	50	350	675	1050
T_{mold} °C	25	107	108	107	129	148
T_{liquid} °C	720	720	720	720	720	720

A vibration meter Lutron VT-8204 was used for measurement of the oscillations parameters.

The measurement of the vertical acceleration (a_z) of the vibrating table was carried out directly on the vibrating platform surface without the mould. The mould accelerations (table 3) were measured by placing it on an asbestos base with 8 mm thickness. Asbestos plaque is to protect the electrodynamic exciter membrane against the heat of the metal mould. The asbestos support acts as a shock absorber, so that acceleration differences are registered at the level of the vibrated platform and the metal mould.

Taking into account that metal mould dedicated to samples casting was designed with a relatively large height, there are oscillations both in vertically and horizontally plan. In order to get a resultant acceleration at which the crystallization of the melt were produced, vertical acceleration tests were done at the top of the mould (a_y) in addition to horizontal acceleration tests in the middle of the mould (a_x). The vibration frequencies have been chosen to ensure the maximum accelerations of the mould (table 3).

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Fig. 1. Setup of the electrodynamic exciter (1) and metallic mould (2).

Table 3. Accelerations of the mold

Sample	A	B	C	D	E	F
Frequency [Hz]	0	0	50	350	675	1050
a_x [m/s²]	0	0	0.6	0.8	0.6	4.4
a_y [m/s²]	0	0	0.4	1.4	4.1	10
a_z [m/s²]	0	0	0.8	0.4	1.2	2.7
a_{rez} [m/s²]	0	0	1.08	1.66	4.31	11.25

Before the density measurement, samples were machined at ϕ20x100 mm size. To measure the volume two methods were used:
  a) by geometric calculation (V_1). The dimensions were determined with an accuracy of 0.01 mm.
  b) by measuring the volume of fluid displaced by immersion in a graded cylinder (V_2).
Weight was measured with Kern & Sohn ABJ 220-4M analytical balance.

The assembly chart made for the construction of the resonance curves is shown in figure 2.
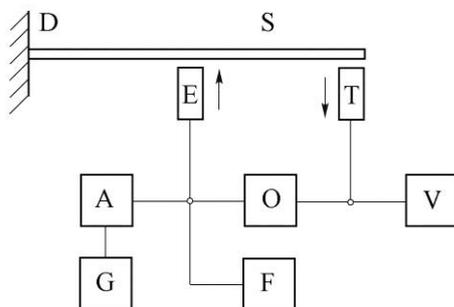

Fig. 2. Scheme of the equipment used for resonance curve testing: D – fixing device; S – sample; G – sinusoidal low frequency signal generator; A – power amplifier; F – digital frequency meter; V – digital voltmeter; O – oscilloscope; E – electromagnetic excitatory; T – electromagnetic vibration sensor.

For tests, the casted samples were machined at 10x89 mm dimensions. As the material under research is not ferromagnetic, two ferromagnetic lamellas, 6x8x0.2 mm dimensions were attached on the samples with a very thin glue film. The mass of these lamellas is insignificant compared to the samples weight and therefore the measurement errors caused by these additional masses are also ignorable. The two thin lamellas are required for generating mechanical vibrations by the electromagnetic exciter and for recording the amplitude of vibration of the electromagnetic transducer.

By changing the sinusoidal current frequency produced by the frequency generator, the sample is vibrating with different amplitudes. The electromagnetic transducer detects samples' oscillations and generates different voltages recorded by a digital voltmeter. When it gets to resonance, the voltage level is maximum, the frequency oscillation can be recorded with high accuracy using a digital frequency meter. By reducing or increasing the frequency near the resonant frequency, the logarithmic decrement can be calculated as a measure of the internal friction of the sample, and from the resonant frequency the dynamic longitudinal elastic modulus is resulting:

$$E_d = \frac{64\pi^2}{\lambda^4} \rho \frac{l^4}{d^2} f^2, \qquad (1)$$

where:
  Ed – dynamic Young modulus;
  λ – factor according to harmonic number: λ_1=1.875; λ_2=4.694; λ_3= 7.855;
  l – sample cantilever length;
  ρ – material's density;
  d– sample's diameter;
  f_r – resonance frequency.

3. Results

The obtained density values, obtained using both methods, are presented in table 4.

Table 4. Sample densities computed (1) and measured (2)

Sample	A	B	C
f [Hz]	0	0	50
m [g]	82.348	83.313	83.466
h [mm]	99.92	99.56	99.75
R [mm]	9.925	10.005	10.005
V_1 [cm³]	30.922	31.309	31.369
V_2 [cm³]	31.45	31.6	31.2
ρ_1 [g/cm³]	2.663	2.661	2.661
ρ_2 [g/cm³]	2.618	2.636	2.675
ρ_{med} [g/cm³]	2.641	2.649	2.668

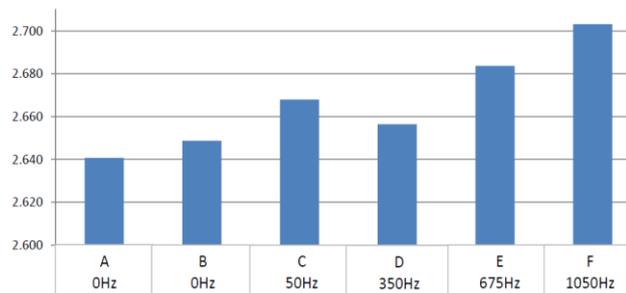| Sample	D	E	F
f [Hz]	350	675	1050
m [g]	83.597	83.647	83.91
h [mm]	99.93	99.51	99.6
R [mm]	10.015	9.98	9.975
V_1 [cm^3]	31.488	31.137	31.134
V_2 [cm^3]	31.45	31.2	30.95
ρ_1 [g/cm^3]	2.655	2.686	2.695
ρ_2 [g/cm^3]	2.658	2.681	2.711
ρ_{med} [g/cm^3]	2.656	2.684	2.703

Fig. 3. Influence of the vibrations frequency on the density.

The static casted sample no-preheated is characterized by the lowest density (fig. 3). In these conditions it is expected the growth of numerous intra- and interdendritic shrinkages with a high total volume during crystallization.

Specimen F has the highest density, because of vibrated casting at a frequency of 1050Hz and acceleration a_{rez} = 11.25 m/s^2 (table 3). The following question is whether frequency or vibrations acceleration influence to a greater extent the crystallization process.

Figure 4 shows the samples density variation depending on mechanical oscillations acceleration which has undergone the alloy during the crystallization. It can be seen that on the density variation curve according to vibrations acceleration is obviously a maximum point corresponding to the sample F (f = 1050Hz, a = 11.25 m/s^2).
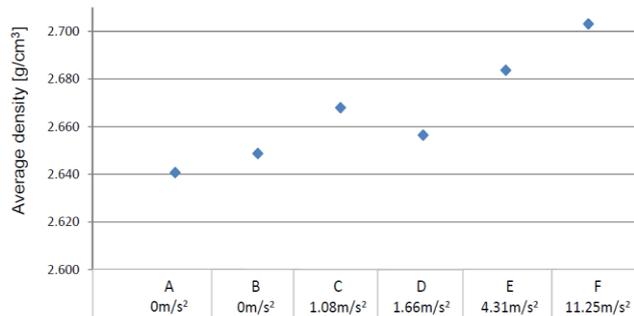

Fig. 4. Influence of the vibrations acceleration on the casted alloy density.
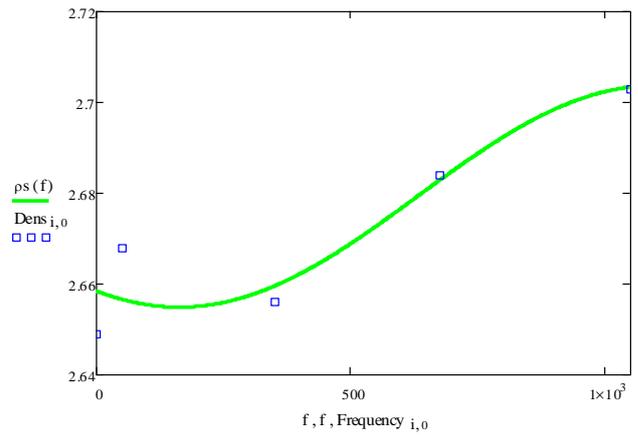

Fig. 5. Density variation depending on the frequency: Dens– experimental data, ρs– sinusoidal interpolation.

The conclusion is that both the frequency and the vibrations acceleration influence the crystallization conditions and for the analysis of their shares on the phenomena, the evaluation of the microstructure [17] and mechanical properties are required. According to literature review [10-14] it is necessary to be close to the resonance frequency.

The best fit for density vs. vibration frequency (fig. 5) is sinusoidal interpolation (2), having a standard error 0.0084608 and a correlation coefficient 0.9617091.

$$\rho s(f) = 2.6791582 + 0.024414221 \cdot \cos(0.0033518712 \cdot f + 2.5914904) \qquad (2)$$

Taking into account the size of the samples, the previously determined density and the frequencies therewith was recorded the resonance on the fundamental harmonic, the dynamic Young mechanical modulus of the samples could be calculated (table 5).

Table 5. Resonance frequencies and dynamic Young modulus

Sample	A	B	C
Casting frequency [Hz]	0	0	50
ρ_{med} [g/cm^3]	2.641	2.649	2.668
D [mm]	10.15	10.07	10.17
L [mm]	88.6	88.8	89.2
f_r [Hz]	916	953	934
Ed [GPa]	67.73	75.39	72.81
Sample	D	E	F
Casting frequency [Hz]	350	675	1050
ρ_{med} [g/cm^3]	2.656	2.684	2.703
D [mm]	10.9	10.12	10.14
L [mm]	89.3	89.2	88.9

Sample	D	E	F
f_r [Hz]	963	972	1068
Ed [GPa]	67.39	80.10	95.72

The highest dynamic modulus was recorded through tests carried out on sample F, which had the most homogeneous phase's distribution [17].

For mathematical modeling the experimental data of table 5 were used. From this table the first value was excluded, because casting of sample A was achieved without preheating. For Lagrange interpolation an own application made in Mathcad 15.0 was used [18].

In the first sequence of the application the input data is inserted and the interpolation nodes (Edyn) are graphical plotted. In the following sequence the Lagrange interpolation coefficients are calculated when items are not in ascending order sorted and when they are ordered. In the last sequence the Lagrange interpolating polynomial is shown, corresponding to 4grade polynomial (EDp4) and also the interpolation function determined with CurveExpert 1.3 program, in this case the 3grade polynomial (EDp3).

Both the nodes and the interpolation functions are plotted at the end. In CurveExpert program, after the introduction of experimental data, the CurveFinder function was used, resulting the interpolation function with the smallest standard error and the largest correlation coefficient, calculated to nodes.

Figure 6 shows that most appropriate polynomial interpolation is the 3rd grade, with the following formula, having a standard error 0.5480536 and a correlation coefficient 0. 9996765:

$$EDp3(f) = 75.702275 - 7.4684197 \cdot 10^{-2} \cdot f + \\ + 1.7562898 \cdot 10^{-4} \cdot f^2 - 8.2220727 \cdot 10^{-8} \cdot f^3 \quad (3)$$

Figs. 7 and 8 present the microstructures of the samples solidified with vibrations at different frequencies. It can be observed the fragmentation and the refinement of inferior rank dendrites axis.
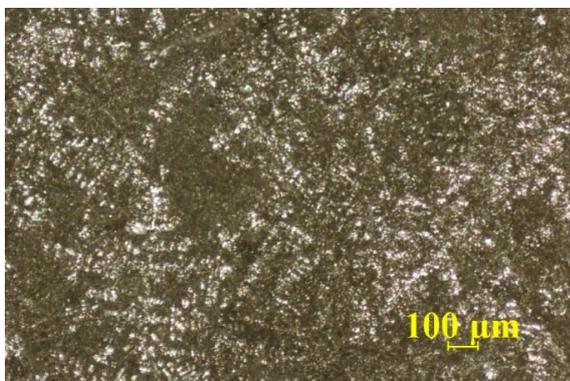

Fig. 7. Casted sample preheated, vibrations 50Hz, a=1.08m/s², etched with hydrofluoric acid 5%, magnification 50x, microstructure with dendrites incomplete fragmented.
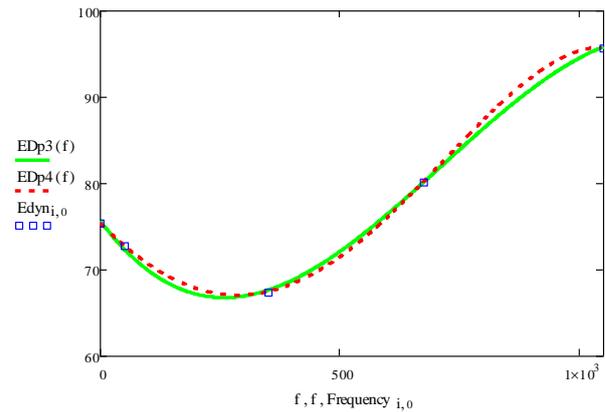

f , f , Frequency $_{i,0}$

Fig. 6. Dynamic Young modulus variation depending on the frequency: Edyn – experimental data, EDp3 – polynomial interpolation grade 3, EDp4 – polynomial interpolation grade 4.

In order to explain more accurate the variation of the dynamic Young modulus, the samples were characterized by microscopic analysis. This investigation was performed using the optical microscope Nikon Elipse Ma 100.
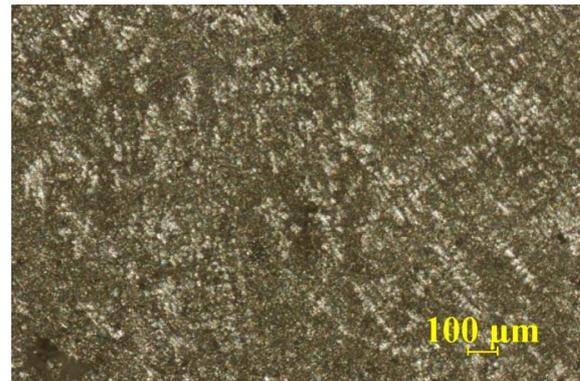

Fig. 8. Casted sample preheated, vibrations 675Hz, a=4.31m/s², etched with hydrofluoric acid 5%, magnification 50x, finished microstructure with fragmented dendrites.

Increasing of the oscillations frequency, the structure is finished, in accordance with the increasing of the dynamic Young modulus.

4. Conclusions

Experimental research aimed to determine the effect of vibrations in chill casting metal alloy AlSi10Mg. The research confirmed the positive effects that applied vibrations are caused during the crystallization process, effects reported also in various articles [19, 20, 21].

As the frequency and vertical vibrations acceleration increases the density and elasticity modulus also increases.

One can observe a good accordance between the results obtained by microscopic research with those recorded by dynamic tests for determining the dynamic elastic modulus. Also, there is a connection between the

samples' microstructures, as the grains size, the distribution and size of the constituent phases and the elastic modulus determined from the resonance frequency of the samples.

The good correlation of these results demonstrates the favorable effect of vibrations on the properties of the alloy AlSi10Mg.

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