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# RESEARCH ON VIBRATION PROPERTIES OF COPPER-TITANIUM ALLOYS

The article addresses a method proposed for comprehensive research of vibration properties dedicated to new structural materials. The method in question comprises three-stage studies, thus enabling the related costs to be reduced on each stage of the process. Subjects of identification and assessment are both the properties and the material structure as well as numerically determined dynamic characteristics and actual vibration characteristics of materials. The article provides preliminary research results obtained for Cu-2Ti-1Co and Cu-6Ti-1Co alloys, the mechanical properties of which are very prospective. An additional advantage of the method proposed is the capability of identifying alloy types by application of non-destructive vibratory methods.

*Keywords*: vibration properties, Cu-Ti alloys, non-destructive method

## 1. Introduction

On account of growing demands towards structural materials, particularly those used in means of transport, further research must be conducted in order to analyse and identify numerous parameters of these materials. Due to environmental reasons and the nature of the work people perform in transport, a fair share of the material parameters studied is a set of vibration properties. Vibration propagation characteristics prove to be particularly important in this respect. In times when load bearing structures of automotive vehicles and other means of transport tend to be "trimmed down" more and more and at all costs, the range of materials used is constantly growing. It is therefore important that studies dedicated to assessment of vibration properties of new structural materials be conducted before they are implemented on a wide scale. The research undertaken by the authors in this field required extensive analyses and a multidisciplinary approach, which could only be ensured a widened team of researchers.

Due to the deleterious effect of beryllium compounds typical of both production and processing, melting of copper beryllium alloys was banned in the European Union countries. Cu-Ti alloys are currently considered to be among materials which may prove as potentially the best substitutes of copper beryllium alloys. They are characterised by mechanical properties comparable with copper beryllium alloys, and electrical properties nearly as beneficial as those of the latter. A specific set of these properties is developed by choosing appropriate chemical composition, including particularly the Ti content, as well as conditions of mechanical working and final heat treatment [1].

Adding Co to Cu-Ti alloys improves their properties significantly. However, it also triggers certain grain breakdown, hardness and conductivity reduction compared to Cu-Ti alloys as well as a decrease in the values of temperature and time needed to attain maximum hardness under conditions of ageing. The function of cobalt is also to prevent the effect of overageing, which is the feature decisive of the similarity between Cu-Ti-Co alloys and copper beryllium alloys [2-4].

## 2. Material

The research material was an array of three-component Cu-XTi-Co alloys with the chemical composition assumed to be Cu-2Ti-1Co and Cu-6Ti-1Co (wt. %). The material was melted in the VIM 20-50 vacuum induction furnace manufactured by SECO–WARWICK. The charge material used included high-purity oxygen-free copper, master alloy of Cu-30 wt.% Ti and cobalt of 99.99 purity. The material was melted in a magnetite crucible and poured into a graphite mould to form an ingot of 40 mm in diameter and the length of ca. 350 mm.

TABLE 1

Chemical composition of research alloys

| Chemical composition assumed | Element content, wt. % | | |
|---|---|---|---|
| | Ti | Co | Cu |
| Cu-2Ti-1Co | 1.4182 | 1.6674 | Balance |
| Cu-6Ti-1Co | 3.5060 | 1.5524 | |

Studies of the microstructure were conducted using the Nikon Epiphot 200 optical microscope. The qualitative and

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quantitative microanalysis was performed by means of the Hitachi S-3400N scanning microscope featuring the EDS X-ray spectrometer manufactured by Thermo Noran. Hardness measurements by the Vickers method were conducted within a cross-section of ingots using the Zwick hardness tester and applying the load of 1 kG (HV1). Electrical resistivity was tested in accordance with a classical constant current four-contact method.

The Cu-XTi-Co alloys produced in the induction furnace, in the as cast condition, were characterised by a dendritic microstructure (Fig. 1) with clear intermetallic phases scattered around interdendritic spaces. The morphology of these phases has been provided in Fig. 2. An analysis of the images obtained implies that as the content of Ti increases in the alloys studied, the surface share of these phases and their magnitude also increase. On Ti contents of ca. 6%, the phases distributed around the interdendritic spaces assume the form of a continuous lattice of precipitates (Fig. 1b).

For the complex analysis of material many properties have to be considered. Starting from metallurgical [5-7], repair (i.e. welding) [8-16] and finishing on wear properties [17-19].

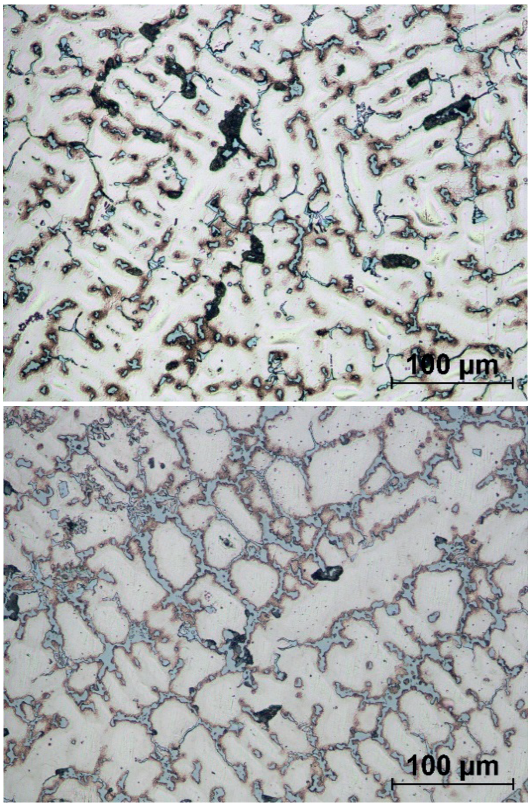



Fig. 1. Microstructure of research alloys: a) Cu-2Ti-1Co and b) Cu-6Ti-1Co as cast

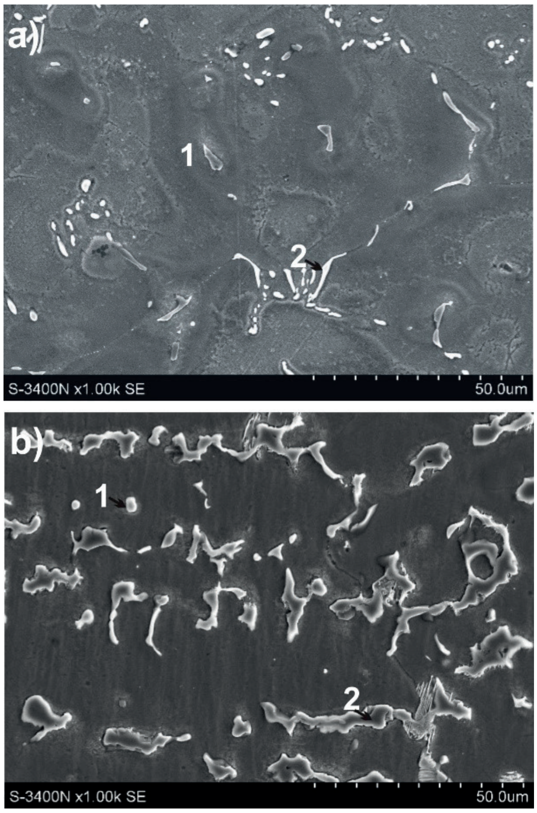



Fig. 2. Precipitates in interdenditic spaces of alloys: a) Cu-2Ti-1Co and b) Cu-6Ti-1Co after casting

Both the qualitative and the quantitative analysis of the precipitates implies presence of Ti-enriched phases (20-35 wt. %) and a small number of spheroidal phases rich in Co (40 wt%). Sample results of analysis of both alloys studied have been provided in Fig. 3. The intermetallic phases occurring in Cu-Ti-Co alloys are usually of the $Ti_2Co$ and TiCo type.

As the titanium content increases, so does the hardness of alloys, and on the test contents of 2 and 6 wt. % of Ti, its average value is 150 and 278 HV1, respectively. What the Ti content increase also affects is the alloy uniformity reduction, this to be evidenced by distributions of harness examined along the ingot's longitudinal section (Fig. 4).

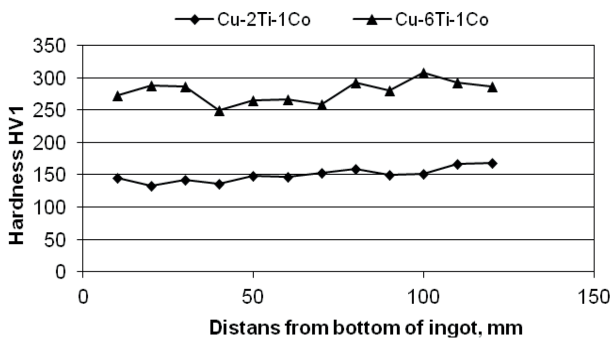



Fig. 4. Hardness distribution on the longitudinal section of ingots

Results of studies of electrical resistivity have been collated in Table 2. As one may have expected, an increase in the content of Ti within the range examined causes an increase in the electrical resistivity from the value of 1.5 up to 2.1 for alloys of the Ti content of 2 and 6 wt.%, respectively.

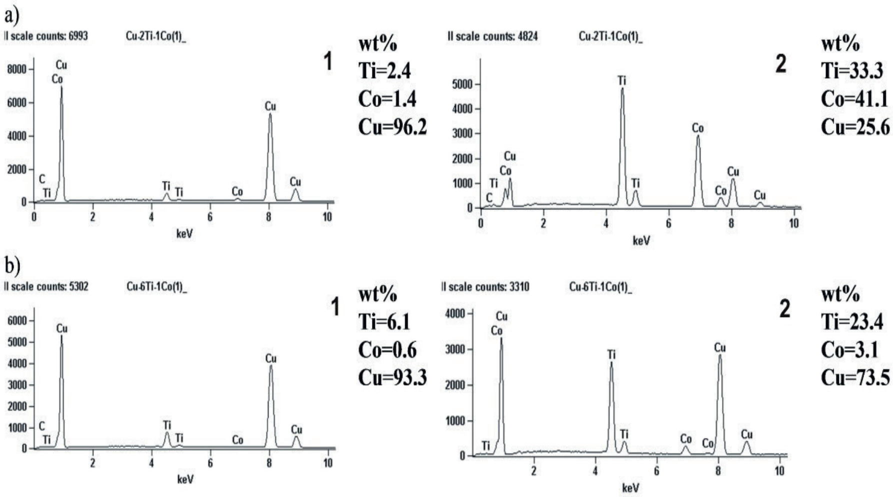



Fig. 3. Sample results of the EDS analysis of: a) Cu-2Ti-1Co (points marked in Fig. 2a) and b) Cu-6Ti-Co (points marked in Fig. 2b)

TABLE 2

Electrical properties of research alloys

| Alloy | Electrical resistivity, [Ω · m] | Electrical conductivity, $[\Omega \cdot m]^{-1}$ |
|---|---|---|
| Cu-2Ti-1Co | $1.562\times10^{-7}$ | 6402048.656 |
| Cu-6Ti-1Co | $2.106\times10^{-7}$ | 4748338.082 |

## 3. Simulation studies of vibration properties

The vibration properties of materials and mechanical systems become very important [20-25]. Also the current state of art presents many applications of vibroacoustics methods in material science and mechanical engineering [26-34]. Material samples assumed to be used in studies were formed by mechanical working. The sample shape envisaged for the studies has been depicted in Fig. 5. The figure also shows the points available for mounting of vibration acceleration sensors.

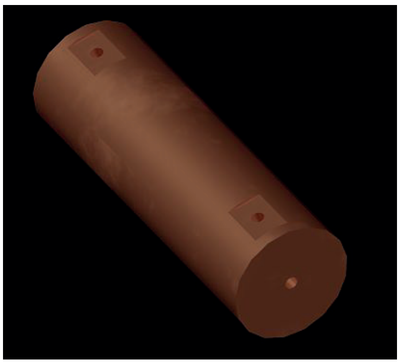
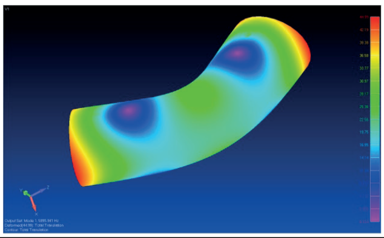
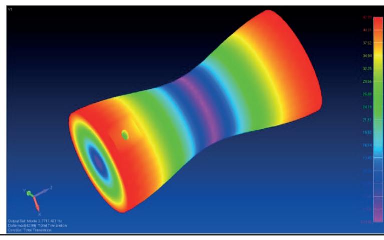
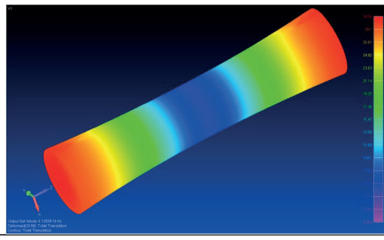
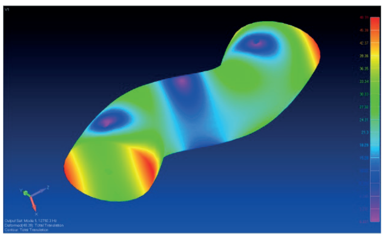


Fig. 5. Shape of test samples

Experimental studies of modal properties were conducted in two stages. On the first stage, for the sample shape assumed, simulation studies were performed to enable preliminary determination of a useful frequency band. The results thus obtained enabled determination of the form of potential mechanical deformations which may occur for the pre-set sample shape and the corresponding free vibration frequencies. Results of the simulation analysis obtained for the alloy designated with the working symbol of Cu-2Ti-1Co have been provided in Table 3. For the material designated as Cu-6Ti-1Co, the respective results have been collated in Table 4. The initial five successive forms of free vibrations were selected for further analysis.

TABLE 3

Results of modal simulation analysis for the Cu-2Ti-1Co alloy

| Item | Vibration form | Free vibration frequency [Hz] |
|---|---|---|
| 1 |  | 5,895 |
| 2 |  | 7,711 |
| 3 |  | 12,559 |
| 4 |  | 12,792 |

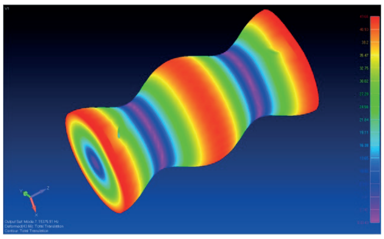
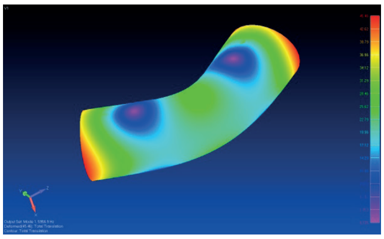
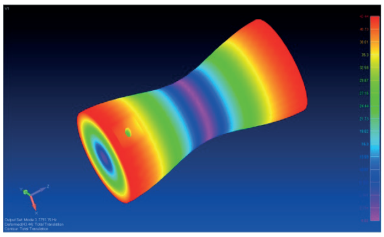
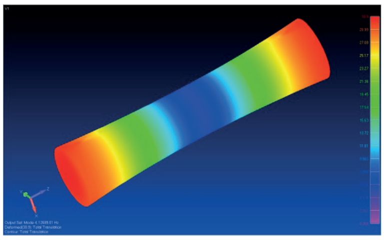
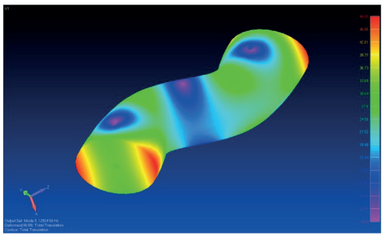
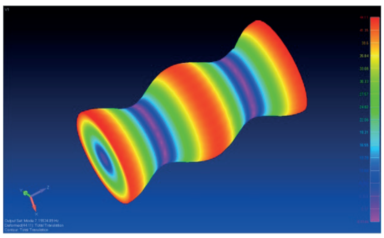
| | | |
|---|---|---|
| 5 |  | 15,375 |

TABLE 4
Results of modal simulation analysis for the Cu-6Ti-1Co alloy

| Item | Vibration form | Free vibration frequency [Hz] |
|---|---|---|
| 1 |  | 5,956 |
| 2 |  | 7,791 |
| 3 |  | 12,689 |
| 4 |  | 12,924 |
| 5 |  | 15,534 |

## 4. Experimental modal analysis

Mechanical properties of the materials examined were assessed by application of experimental modal analysis. Based on previous simulation studies, it was found that free vibration forms of the samples tested displayed a high degree of similarly. Differences in the free vibration frequency values resulted directly from the properties of the materials studied. For the alloy with the Ti content of 6 %, one could observe an effect of the free vibration frequency increase for all vibration forms analysed. Another step in the research conducted was the study of real objects conducted in a free-free system. Once the test samples had been mounted at the chosen measuring point of the vibration acceleration sensor, they were freely suspended (without any contact with the surrounding). Thus the test samples were deprived of any bonds, and so one could assume that, after being induced by an impulse of a force, their dynamic response would be closely associated with their shape and properties of the material they were made of. A sample prepared for the tests in question has been illustrated in Fig. 6.

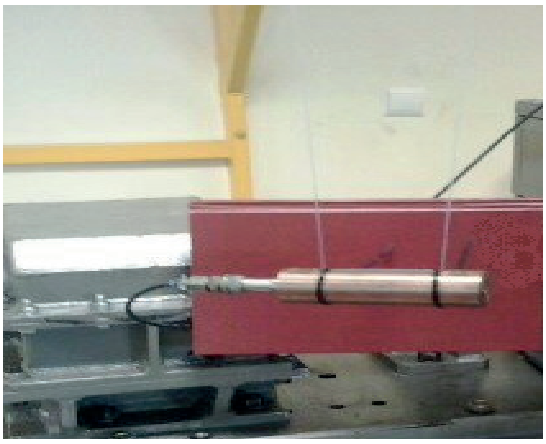


Fig. 6. Suspension of the sample prepared for testing of dynamic properties of the material

The experiments conducted in order to establish dynamic properties of the materials studied consisted in inducing vibrations of the test sample by means of an impulse of a force while simultaneously measuring and recording the course of the input function and of the vibration response. The inducing instrument used was a PCB modal hammer of an appropriately pre-set frequency band. The test sample's dynamic response was measured by means of a piezoelectric sensor manufactured according to the ICP standards. A two-channel DSP module by SIGLAB was used to record time courses of the input function and of the test sample's response. A follow-up analysis of the results thus obtained was conducted in the MATLAB environment.

Modal parameters of the material samples tested were estimated by application of the Frequency Response Function (FRF). Firstly, the Fourier Transform was applied to establish frequency spectra of the recorded time courses of the input function and of the vibration response:

$$P_x(\omega) = \int_{-\infty}^{\infty} x(t)^{-j\omega t} dt$$
$$P_y(\omega) = \int_{-\infty}^{\infty} y(t)^{-j\omega t} dt \quad (1)$$

where:

$P_x(\omega)$ – input signal spectrum
$P_y(\omega)$ – response signal spectrum

Next, own spectra of the input signal, designated as $P_{xx}(\omega)$, as well as mutual spectra of the input and vibration response signals, designated as $P_{xy}(\omega)$, were determined and identified as follows:

$$P_{xx}(\omega) = P_x(\omega)P_x*(\omega)$$
$$P_{xy}(\omega) = P_x(\omega)P_y*(\omega) \quad (2)$$

where:
$P_x*(\omega)$ – conjugated complex spectrum of the input signal
$P_y*(\omega)$ – conjugated complex spectrum of the response signal
$*$ – complex conjugate of the signal

What followed was the determination of Frequency Response Functions:

$$FRF = \frac{P_{xy}(\omega)}{P_{xx}(\omega)} \quad (3)$$

Since the FRF determined was a complex function, in order to establish the amplitude and frequency spectrum, moduli of the former were calculated. Results of the experimental modal analysis of the material samples studied have been provided as Frequency Response Functions in Fig. 7. On account of the large range of dynamics of the amplitude values established for the free vibration frequencies determined, precluding their analysis in a linear range, the study results obtained have also been provided in a logarithmic scale in the figures below.

c) d)

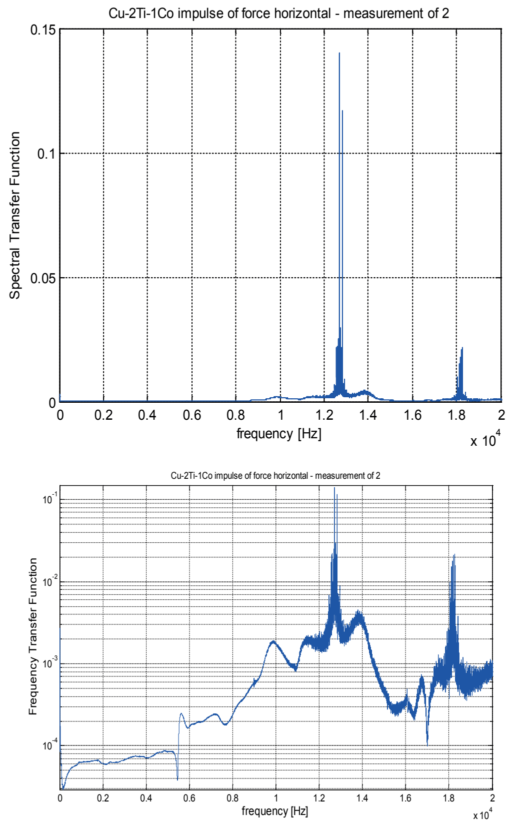



Fig. 8. Frequency Response Function established for the sample marked as Cu-2Ti-1Co, assuming the input impulse of a force in a direction concurrent with the sample axis: a) in the linear scale, b) in the logarithmic scale

a) b)

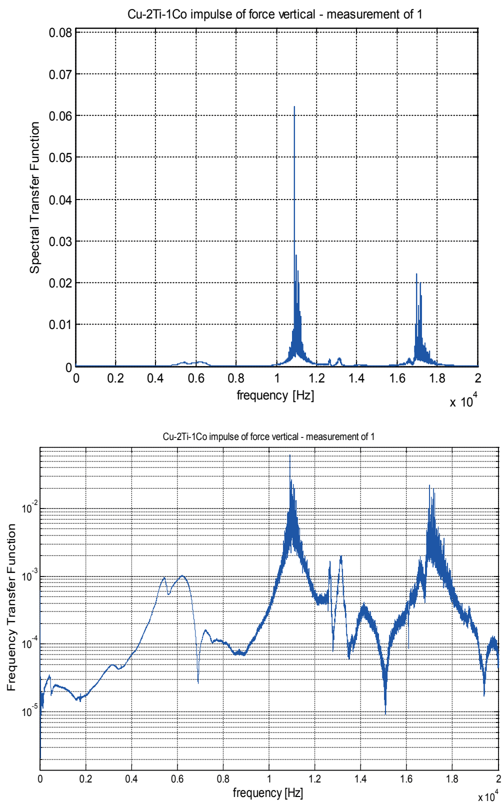



Fig. 7. Frequency Response Function established for the sample marked as Cu-2Ti-1Co, assuming the input impulse of a force in a direction transverse to the sample axis: a) in the linear scale, b) in the logarithmic scale

a) b)

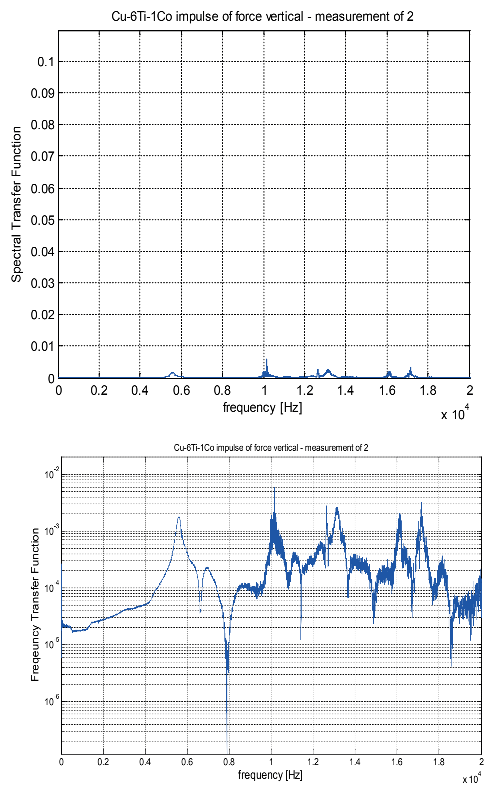
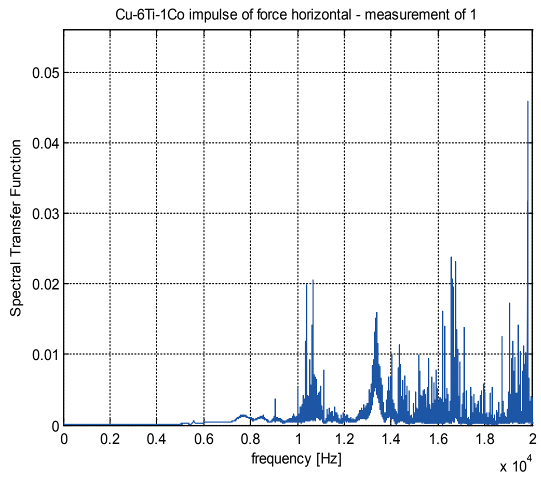



Fig. 9. Frequency Response Function established for the sample marked as Cu-6Ti-1Co, assuming the input impulse of a force in a direction transverse to the sample axis: a) in the linear scale, b) in the logarithmic scale

a)




b)

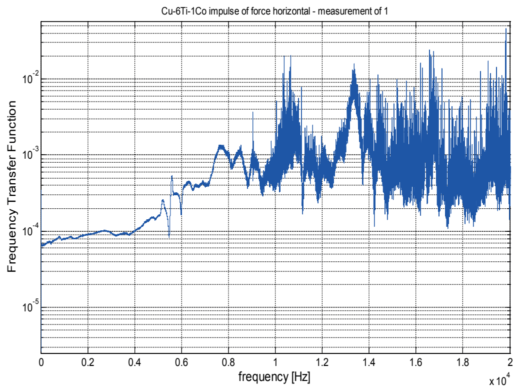



Fig. 10. Frequency Response Function established for the sample marked as Cu-6Ti-1Co, assuming the input impulse of a force in a direction concurrent with the sample axis: a) in the linear scale, b) in the logarithmic scale

## 5. Conclusions

The article provides a discussion concerning the comprehensive research on vibration properties of new copper-titanium alloys. It comprised material analyses, simulation studies and experiments conducted on real objects. What this approach enabled was a multi-criterion assessment as well as verification of the results obtained and a dedicated procedure of drawing conclusions. The article provides preliminary research results obtained for Cu-2Ti-1Co and Cu-6Ti-1Co alloys, the mechanical properties of which are very prospective. An additional advantage of the method proposed is the capability of identifying alloy types by application of non-destructive vibratory methods.

Having applied a method thus devised, one could determine that, for the Cu-2Ti-1Co alloy, slightly lower values of free vibration frequency could be observed, similarly to the simulation studies. It made it possible to distinguish between types of materials the samples were made of. Depending on the direction in which the vibration inducing force was acting, higher amplification occurred for those types of the test sample deformations where the main deformation direction corresponded to the force impulse direction of action. According to the authors, this method may be proposed as a supportive means for assessment of correctness of properties established for the given structural material examined. What was assumed for purposes of the research method developed was the invariability of geometrical dimensions of samples and input points as well as of the vibration response measurement. Hence the conclusion that differences between the results obtained were due to diversified properties of the new materials studied.

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