IOP Conference Series: Materials Science and Engineering

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To cite this article: N A Shepeta *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **560** 012158

Stress-wave change in the copper structure: covering magnetic response

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Abstract. The work presents the results of the investigationof deformation processes occurring in copper after stress-wave influence. Structural changes analysis is carried out by direct research methods (X-ray phase analysis and optical microscopy) along and perpendicular to the spreading direction of the stress wave front in the copper foil plane. For more information, investigations have been conducted by an indirect method using ferromagnetic resonance of magnetic characteristics. As a magnetic covering, Co/Ni-type multilayer films are deposited on the copper foil, which makes it possible to apply magnetic research methods. The magnetic response of the multilayer covering correlates with the modification of the copper structure observed by direct methods. The information obtained in the course of research allows us to conclude that the wave character of the deformation processes occurring in copper is natural. The value and direction of structural modifications vary along the sample length as a function with a long-wave period is about 30 mm, which is consistent with the inhomogeneous distribution model of internal stresses. Throughout the sample length, alternating areas of stretching and compression of copper grains are fixed along the spreading direction of the stress wave front. The greatest stretching of the structural elements is observed at a distance equal to almost half the wavelength of the mechanical deformation field. Thus, the translational (shear) mode of the mechanical field of material plastic flow appears as the results of the investigation.

1. Introduction

During operation, metal elements of engineering constructions are subjected to intense mechanical influences, including stress-wave, such as hydraulic hammer damping systems in pipelines, docking and landing units of moving objects, etc. [1,2]. Determining the mechanical system response to a dynamic effect is one of the tasks solved during products engineering. The presence of mechanical influence leads to the need to determine the intense-strain state parameters of the most vulnerable structural elements [3]. Shock-wave phenomena lead to deformation changes in the materials structure, which affects the products performance and reliability.

At present, on the basis of theoretical views and experimental data, during plastic deformation a wave process develops, the length and speed of which are determined by the material structure and loading conditions [4-6]. Analysis of the mechanical field differential equations obtained in [7] shows that they allow solutions in the form of waves of the translational and rotational modes, respectively. And experimental proof of a certain amount of the plastic flow wave has already been obtained for various classes of solids [8,9].

The main methods of studying the materials structure subjected to stress-wave influence (SWI) are X-ray structural, X-ray phase analyses and metallography. Recently, speckle interferometry has also been used to study solids plastic deformation. The experiments results show that plastic deformation is almost non-uniform from the very beginning, and it is localized in separate zones, whose position may change over time. That is, compression occurs in some parts of the material, while other areas are stretched [9]. However, traditional investigation methods do not always make a complete picture of the structural changes in materials. On the other hand, the use of indirect methods for studying the materials properties modifications (electrical, dynamic, magnetic, etc.) provides additional information about the ongoing structural changes.

The task of this work is to investigate the deformation processes occurring during stress-wave influence in copper – a widely used structural material. Analysis of structural changes was carried out both by direct methods (X-ray phase analysis and optical microscopy) and indirect methods for determining magnetic characteristics. Multilayer Co/Ni films were deposited on the copper foil, which made it possible to use investigation magnetic methods. This choice of magnetic coating is due to the fact that the methods for producing multilayer materials make it possible to form spatial structural inhomogeneities of any size by varying the thickness of individual layers and their number [10]. It can be assumed that by applying a magnetic coating on the material, which then undergoes a stress-wave influence, and the covering magnetic characteristics investigation after the SWI can obtain information about the deformation processes occurring in the material-basis.

2. Investigated samples and techniques for their preparation

In this work we investigate deformational changes in the copper structure, which, unlike most metals, has a wide plastic flow area. The stress-wave influence on the samples is in the sliding detonation mode at pressure 10.4 GPa. Hexogen bulk density with a constant thickness is used as an explosive.

As a covering that allows the use of research magnetic methods, we use multilayer films Co/Ni. A multilayer magnetic film [Co(20 nm)/Ni(20 nm)]*5 is prepared by chemical deposition onto a rolled copper foil 30 μm thick. The total thickness of the ferromagnetic covering is 0.2 μm, the sample length is L = 40 mm. The selected thickness of the multilayer layers makes it possible to form the spatial inhomogeneities size, on which the translational and rotational modes of the deformations wave process are best manifested. A feature of the chemical precipitation method, which is based on the reduction reaction of pure metals from the relevant salts, is the presence of elemental phosphorus in the obtained precipitation. The phosphorus contents in layers are supported constant and equal 6 at.%. We determine coverings crystalline structure with FCC lattice [11]. Research showed that during the Co on copper deposition, the cobalt structure repeats the structure of the Cu material-basis [12]. Since the metalloid percentage is not change, the P sign in the text is omitted. After SWI, no damage to the film surface and upper magnetic layer detachment is observed on our samples. Thus, we can expect a change in the samples magnetic characteristics after SWI.

3. Investigation results by direct methods

X-ray phase studies were performed on a DRON-4 apparatus in the K_α-copper line radiation with λ = 1.54 Å. On the initial sample's X-ray pattern (before the SWI), three peaks were observed, which were definitely identified as reflection lines from the fcc-copper structure. Peaks from cobalt and nickel were not observed. This is due to the small thickness of the magnetic covering compared with the copper foil thickness. It is known that upon reflection from fcc-copper with a polycrystalline structure of the greatest intensity there should be a reflection line from the (111) plane. However, on X-ray pattern of the studied samples, the peak has the greatest intensity, due to the reflection from the plane (220). This peak intensity distribution is a result of the copper cold rolling, which creates a texture in the rolling direction. After SWI on the samples, on X-ray pattern, peak intensity transfer is visible – the peak from the (111) plane intensity increases significantly. This fact indicates structural changes in copper. The selected stress wave mode indicates that we are working in the plastic deformation area of the material, as a result of which a texture is removed.

In addition, relative deformations direct measurements are carried out. For this purpose, a square measuring grid with a step of 1 mm is applied to the samples. Before and after SWI, the distance between the risks is measured using an optical microscope. The relative deformation value ε was calculated by the formula:

$$\varepsilon_i = \frac{(L_i - L_0)}{L_0}, \tag{1}$$

where L_0 is the initial distance between the risks, L_i is the distance between the corresponding risks after the SWI.

Figure 1 shows the samples longitudinal deformation $\varepsilon_{\uparrow}$ dependence along the stress wave front spreading along the samples length. It can be seen that the relative deformation reaches a maximum in the sample middle part at 20%.

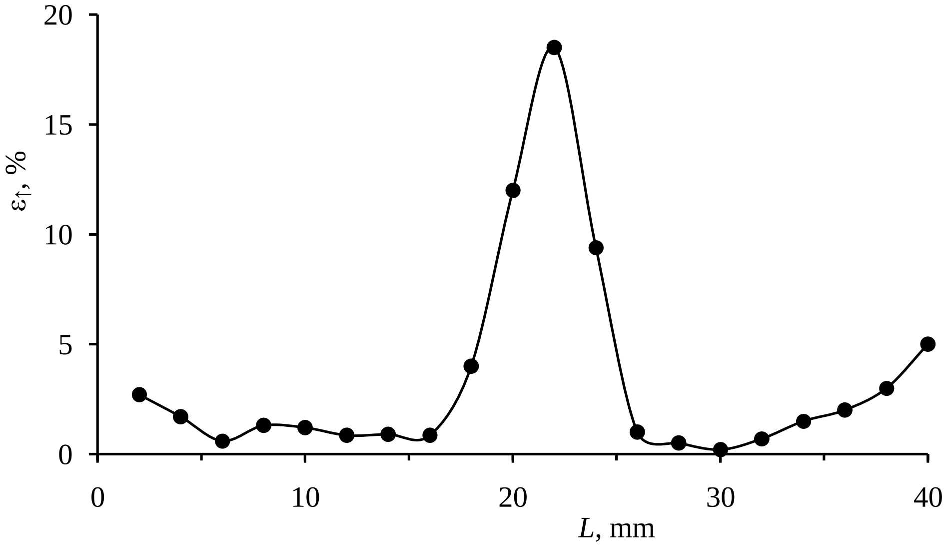

Figure 1. Field value dependence of relative deformations along the length of the samples after the stress-wave influence.

Changes in the relative deformation indicate the copper polycrystalline structure modification. In the sample middle part, the grains are strongly stretched along the spreading direction of the stress wave front.

4. Magnetic response covering

For more information, the magnetic response of Co/Ni multilayer covering was investigated by the ferromagnetic resonance method [13]. The measurements were carried out on an EPA-2M standard spectrometer at a frequency of 9.2 GHz. As a magnetic characteristic, the resonance absorption field H_r was obtained with parallel orientation of the samples in an external magnetic field. Before the stress-wave influence, the resonance field value H_r sample was equal to 56 kA/m. After the stress-wave influence along the spreading direction of the stress wave front, pieces of 1.5*2 mm in size were cut. For each sample-piece, the resonant field values were measured along $H_r^{\uparrow}$ and perpendicular to $H_r^{\perp}$ to the spreading direction of the stress wave front.

The resonant field value dependences along the films length are presented in figure 2. The symbols "↑ - along" and "⊥ - perpend" denote graphs of the resonant field value along and perpendicular to the stress wave spreading in the films, respectively. The straight solid line indicates the initial sample resonant field value. It is visible that for example after SWI the dependence $H_r(L)$ has an oscillating character with a long-wave period of the sample length order. The graphs of dependencies $H_r^{\uparrow}(L)$ and $H_r^{\perp}(L)$ are antisymmetric relative to each other; the maxima of one curve correspond to the minima on the other curve and vice versa.

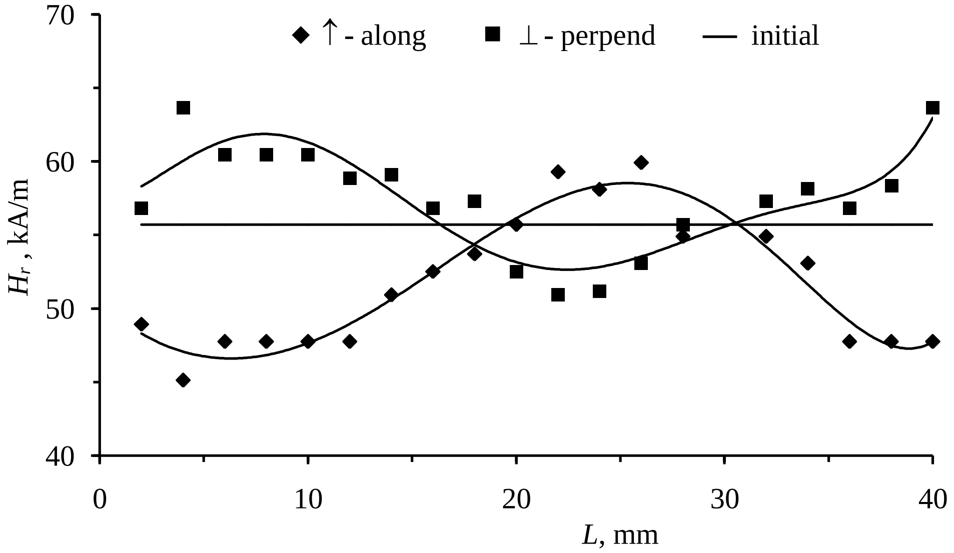

Figure 2. Resonant field value dependence along the length of the multilayer film [Co(20 nm)/Ni(20 nm)]*5 deposited on copper before and after the stress-wave influence.

As is known, the resonant field value depends on the sample anisotropy field. If a sample with uniaxial anisotropy is placed in an external field parallel to the sample plane, then the resonant field along the easy magnetization axis direction will be defined as:

$$H_r^{\uparrow} = \frac{1}{4\pi M} \cdot \left(\frac{\omega}{\gamma}\right)^2 - H_k; \tag{2}$$

and perpendicular to this direction:

$$H_p^{\perp} = \frac{1}{4\pi M} \cdot \left(\frac{\omega}{\gamma}\right)^2 + H_k. \tag{3}$$

From equations (1) and (2), it follows that the crystallographic anisotropy field H_k [14] will be equal to:

$$H_k = \frac{H_r^{\perp} - H_r^{\uparrow}}{2}. \tag{4}$$

With an error of ~ 5% (which does not exceed the experimental error) for the samples after the SWI, the equation is fulfilled:

$$H_r(initial) = \frac{H_r^{\perp} + H_r^{\uparrow}}{2}. \tag{5}$$

This clearly indicates the presence of the uniaxial anisotropy field in the samples after the SWI.

Figure 3 shows the dependence of the anisotropy field value calculated by formula (4) along the length of the sample [Co(20 nm)/Ni(20 nm)]*5 on the cooper.

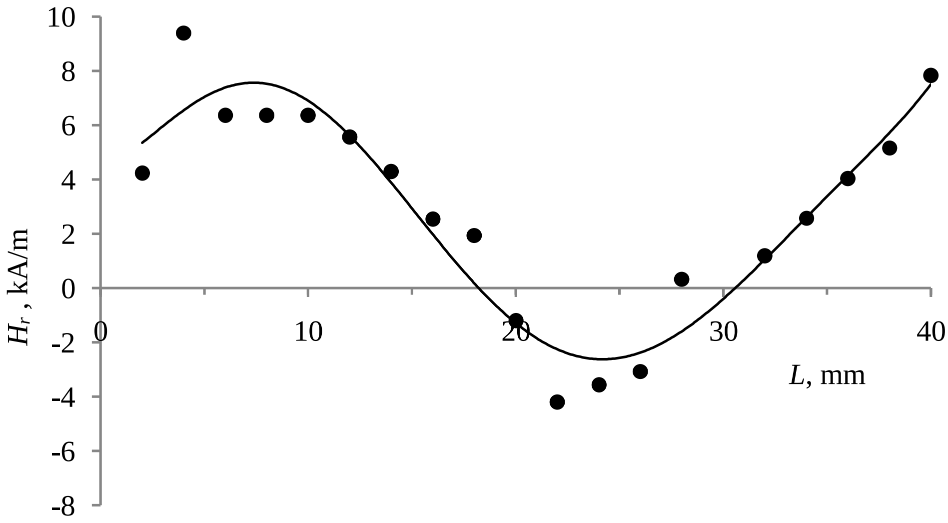

Figure 3. The crystallographic anisotropy field value dependence along the length of the multilayer film [Co(20 nm)/Ni(20 nm)]*5 deposited on copper after the stress-wave influence.

It is visible, that the anisotropy field changes its direction and value along the film length. Moreover, the stress-wave influence leads to the presence in the sample's middle part of the easy magnetization axis, perpendicular to the stress front spreading direction. This is indicated by the graph plot, where the curve $H_k(L)$ passes below the zero level. A similar behavior of the anisotropy field value along the length sample is due to the grains deformation.

Let us note the inverse correlation of dependency graphs $\varepsilon_\uparrow(L)$ and $H_k(L)$ presented in figures 1 and 3. There is a minimum in the anisotropy field value dependence graph $H_k(L)$ on the sample length, on the dependence graph $\varepsilon_\uparrow(L)$ there is a maximum curve. Since for ferromagnetic multilayer Co/Ni films, the magnetostriction constant λ is negative, and the anisotropy field value $H_k \sim \lambda$, the inverse correlation of the dependences graphs $\varepsilon_\uparrow(L)$ and $H_k(L)$ can be observed, which corresponds to the experimental results obtained in this work.

5. Results discussion

The results of investigation using direct and indirect methods show the wave nature of structural changes in copper after the stress-wave influence.

The value and direction of structural modifications vary along the sample length as a function with a long-wave period of about 30 mm, which is consistent with the internal stresses inhomogeneous distribution model [9, 15]. Along the sample length, alternating areas of stretching and compression of copper grains are fixed along the spreading direction of the stress wave front.

The greatest stretching of the structural elements is observed at a distance equal to about half the wavelength of the mechanical deformation field. Moreover, the polycrystals plastic flow is a self-consistent process: each link deformation in the structure depends on the neighboring regions deformation.

The stress field inside the material must also be self-consistent. The latter means that the system is self-balanced, that is, there are no changes in the material volume (area) due to the resulting stresses. If at any point the structure element is stretched along the stress front spreading direction, at the same point it is compressed perpendicular to the stress front spreading direction. Thus, in the plots of $\varepsilon\uparrow(L)$ and $H_k(L)$ dependences, the translational (shear) mode of the mechanical field of copper plastic flow appears after the stress-wave influence.

6. Conclusion

The study investigates the structural changes in copper after stress-wave influence. It turns out that the plastic flow deformation processes along the copper sample length can be described as a periodic long-wave function. Along the sample length, alternating areas of stretching and compression of copper grains are fixed along the spreading direction of the stress wave front.

The application of the magnetic covering on copper foil makes it possible to use an indirect method for studying the sample magnetic characteristics and to obtain additional information on the structural changes occurring in copper. The magnetic response of the multilayer covering correlates with the modification of the copper structure observed by direct methods. Thus, the translational (shear) mode of the material plastic flow mechanical field appears as the results of the investigation.

Knowledge of structural changes occurring in structural materials under stress-wave influence can be useful in developing methods and techniques for improving the wear resistance and engineering structures elements reliability, as well as in analyzing technological risks.

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