# ULTRASOUND STUDY OF MECHANICAL PROPERTIES OF A STRUCTURAL Al-BASED ALLOY OF THE SAV-1 TYPE

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Mechanical properties of some constructional materials are studied with the use of acoustic methods. The data on a number of elastic properties, dispersion relations for basic moduli of Al-based alloys of the SAV-1 type before and after the action of ionizing radiation are obtained on the basis of the registered spectra of bending vibrations. A considerable stability of the elasticity moduli of alloys under ordinary conditions of storage is established, and a nonlinear dependence of elastic parameters of specimens on the dose is traced in a wide range of absorbed doses. The possible reasons for discovered effects related to a modification of mechanical properties of irradiated alloys SAV-1 are analyzed.

## 1. Introduction

The studies of mechanical properties of materials and their structure acquire the important meaning for the solid-state physics and the physics of irradiated materials. We note the particular informativeness of acoustic methods [1, 2] because, first, the information obtained within these methods allows one to analyze the elastic properties of solids in a wide range of frequencies, and, second, a rather wide circle of questions can be solved with their help which are of great importance for physico-mechanical studies of solids (the state of a structure, its change, deformation, the character of intracrystalline forces, diffusion of impurities and defects, *etc.*).

The recent literature includes the works where various mechanical properties of materials were determined with the use of the indicated methods [3–6]. For example, the response of steels to neutron irradiation and, in particular, their swelling were studied in [3]. On the basis of these methods, a setup for the permanent control over a leakage in the first and second contours of a water-moderated reactor was designed and fabricated [4], the calculations of the structure and the elastic parameters of wurtzite-like oxides were carried out in [5], and a tensile deformation of some alloys was considered in [6]. At the same time, it is worth to note that the available publications contain a little information about new Al-based constructional materials. This fact yields the topicality of the study of mechanical properties of Al-based constructional materials performed in the present work on the basis of acoustic methods.

## 2. Objects and Methods of Studies

We studied a series of specimens of Al-based alloys of the SAV-1 mark: specimens No. 1 (disks 15.7 mm in diameter and 1.7 mm in thickness), No. 2 (disks 15.5 mm in diameter and 2.8 mm in thickness), and No. 3 (disks 15.7 mm in diameter and 3.0 mm in thickness). The source of ionizing radiation was $Co^{60}$, and the dose absorbed by materials was varied in the limits $(10^3 - 3 \times 10^7)$ Gy. The determination of required mechanical parameters of the materials under study was performed within the method of ultrasound resonance on a setup mounded by the scheme taken from [1], by registering the spectra of bending vibrations in the range of frequencies 20–200 kHz.

The goals of the present work are the study of mechanical properties of constructional materials on the basis of Al-based alloys with the help of acoustic methods and their stability under the action of external factors; the establishment of regularities of radiation-induced variations of elastic characteristics of alloys; the determination of resonance frequencies and dispersion relations for bending vibrations by measurements of the corresponding spectra; and the clarification of the nature of the observed effects.

## 3. Main Results and Their Discussion

The determination of elastic properties of Al-based alloys of the SAV-1 mark was realized within the method of resonance ultrasound spectroscopy, whose essence and the device for necessary measurements were described in [1]. The main task consisted in the determination of values of one of the basic characteristics of the elasticity of materials, the normal elasticity modulus (the Young modulus $E$), as well as the moduli of shear and compression and the Poisson's ratio. The experiment was carried out on a series of preliminarily processed specimens (specimens Nos. 1–3) of Al-based alloys of the SAV-1 mark produced by the method of sintering of an Al powder and the introduction of necessary doping impurities into its composition. The chemical composition of the specimens of alloys under study is presented in Table 1 (for brevity, we will use the term "alloy SAV-1" for all alloys in what follows).

By exciting ultrasound vibrations with the help of the method of ultrasound resonance, we registered the corresponding spectra of bending vibrations and their main characteristics of the preliminarily processed specimens such as the amplitude of vibrations ($A$) and the resonance frequencies ($f$). On the basis of these data for the collection of specimens with regard for the tables in [1], we determined the elastic characteristics, the coefficients of elasticity $K(m,n)$ and the resonance frequencies $f(m,n)$, and then calculated the normal modulus of elasticity E by the formula

$$f(m,n) = [K(m,n)/d][\sqrt{(E/\rho)}], \quad (1)$$

where $d$ and $\rho$ are, respectively, the diameter and the density of specimens.

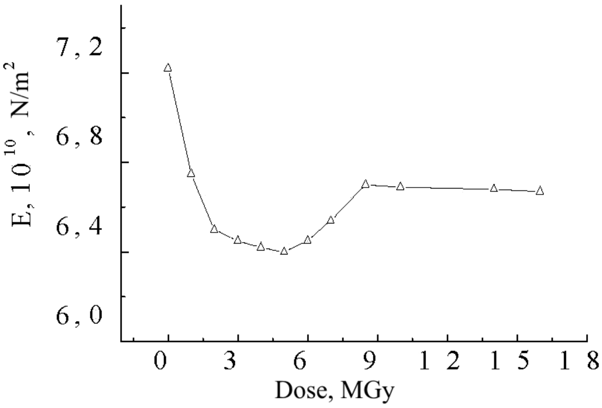
The results of calculations of the elasticity modulus of specimens Nos. 1–3 are given in Table 2. By the data in Table 2, we obtain the mean elasticity modulus for the alloys: $\bar{E} = 7.2 \cdot 10^{10}$ N/m$^2$. This value is close to that for metallic aluminum: $E$=7.1×10$^{10}$ N/m$^2$. This fact allows us to conclude that the doping of Al with a number of impurities (Mg, Si, Fe, *etc.*) does not affect significantly its elastic properties. With the purpose to trace the effect of natural conditions of storage at a temperature of about 25 °C on the mechanical properties of specimens (the storage time was taken 2 days), we measured the dispersion relations in 2–4 h. The results obtained testify to a significant stability of mechanical properties of alloy SAV-1 under ordinary conditions of storage.

For two lower frequencies of bending vibrations of the specimens, with the use of the coefficient of elasticity,

$$M = f(1,0)/f(0,2), \quad N = K(1,0)/K(0,2) \quad (2)$$

**T a b l e 1. Element composition of specimens made of alloy SAV-1 (in %)**

| Specimen | Mg | Al | Si | Mn | Fe |
|---|---|---|---|---|---|
| 1 | 1.00 | 98.42 | 0.45 | 0.00 | 0.14 |
| 2 | 1.04 | 98.24 | 0.54 | 0.00 | 0.13 |
| 3 | 1.15 | 98.12 | 0.51 | 0.02 | 0.14 |
| Mean | 1.06 | 98.26 | 0.50 | 0.01 | 0.14 |




Young modulus of alloy SAV-1 versus the dose

and the tables in [1], we determined another mechanical parameter, the Poisson's ratio ($\nu$). The results of calculations for the used collection of specimens are presented in Table 3. It is seen that numerical values of the Poisson's ratio are close to one another. The mean value of the Poisson's ratio was applied to the calculation of the other elasticity moduli of the alloy by the formulas

$$G = E/(2 + 2\nu), \quad B = E/[3(1 - 2\nu)], \quad (3)$$

where $G$ and $B$ are the shear modulus and the bulk modulus, respectively. Their values are given in Table 3. By comparing with the analogous moduli of metallic aluminum, we may conclude that the mean values of the Young modulus and the shear modulus for alloy SAV-1 are close to those of Al. As for two other mechanical parameters ($\nu$, $B$), their values for the alloy are somewhat greater than those for Al, which characterizes the improvement of elastic properties of the input material. For example, the resistance to a bulk compression increases.

As an example, we present the dependence of the calculated Young modulus for alloy SAV-1 measured for specimen No. 1 on the dose in the Figure. Its analysis indicates a nonlinear character of the modification of the given mechanical parameter. Three characteristic regions can be distinguished. At the start of irradiation (at $D_1 = (1-5) \times 10^6$ Gy), the relaxation is revealed, since the elasticity of the specimens decreases to some particular point. Then the character of changes becomes opposite [$D_2 = (5-8) \times 10^6$ Gy]. For the higher

**T a b l e 2. Elasticity moduli of specimens**

| Specimen | $E$, 10$^{10}$ N/m$^2$ |
|---|---|
| 1 | 7.22 |
| 2 | 6.90 |
| 3 | 7.48 |

doses ($D_3 > 8 \times 10^6$ Gy), the character of the kinetics changes again, and the third region with the point of inflection of the curve $E(D)$ is observed. On this stage of the radiative processing of specimens, we discovered the appearance of the stage of the stabilization of the process. Indeed, the Figure indicates that, in a rather wide range of absorbed doses [$(8 \times 10^6 - 1.6 \times 10^7)$ Gy], the elasticity of the material varies slightly, and the curve attains the level of saturation. Thus, we have experimentally established the three-stage extremal kinetics of the radiation-induced change in the normal elasticity modulus of SAV-1 which is completed by the appearance of a "plateau" at great doses. It is worth noting that similar dose dependences are observed also for the shear modulus and the bulk modulus. The above-indicated nonlinear character of the radiation kinetics for the basic modulus is preserved also in the case of a modification of these two elastic properties of the alloy in the mentioned wide range of $\gamma$-radiation doses.

As known [7, 8], the most spread defects in the majority of various alloys of metals (including the Al-based ones) are point defects, their accumulations, and dislocations. Moreover, the concentrations of these defects increase at a deformation of materials. In particular, the concentration of point-like defects (interstitial atoms, vacancies) increases first of all in the process of deformation of alloys and after it, which is caused by the stresses as a result of the action of external factors. In this case, the defects interact with one another and with dislocations. The first process can cause the formation of the aggregates of defects and vacancies (interstitial atoms) in the sliding plane as a result of a deformation of the alloy, and the second one leads to the condensation of vacancies (interstitial atoms) on dislocations.

We believe that, as a result of a deformation arising at the beginning of the action of radiation on alloy SAV-1, its ability to resist to a longitudinal tension deformation can decrease due to the formation of defects, accumulation of defects, tension of the material, and appearance of interfaces. This is manifested on the above-mentioned behavior of the curve $E(D)$ which indicates a decrease of the normal elasticity of the alloy. In addition, we consider that the second reason for such a course of $E(D)$ can be the presence of the second effect of condensation of vacancies (interstitial atoms) on dislocations, which promotes the curing of available defective dislocations due to the capture of vacancies. This leads to a decrease of both the defectiveness of the input alloy and the elasticity modulus.

**T a b l e 3. Elasticity moduli $\nu$, $G$, and $B$ of specimens**

| Specimen | $\nu$ | $G$, $10^{10}$ N/m$^2$ | $B$, $10^{10}$ N/m$^2$ |
|---|---|---|---|
| 1 | 0.350 | 2.654 | 8.201 |
| 2 | 0.352 | 2.536 | 7.849 |
| 3 | 0.382 | 2.750 | 8.500 |
| Mean | 0.361 | 2.647 | 8.183 |

At the medium doses ($D_2$), the formation of defects accelerates, and the concentration of point-like defects increases to such a degree that they become to interact with one another, and their aggregates, i.e. small clusters, are formed. Then the initial effect of a stretching of specimens becomes less pronounced, and the modulus of longitudinal elasticity increases (the second region in the Figure). This effect holds up to the third region ($D_3$), where the sizes of small clusters attain the critical one. The number of clusters is great, and they overlap. In this case, the system is characterized by "the shaking," and the anomaly in the form of a "plateau" appears on the curve $E(D)$ in the range of absorbed doses $(8 \times 10^6 - 1.6 \times 10^7)$ Gy. In this case, we may expect the condensation of the excess of vacancies (interstitial atoms) on dislocations, the accumulation of dislocations from aggregates of vacancies, the formation of clear interfaces, and the separation of phases [9–11], which is apparently accompanied by the strengthening of the material, an increase in $E$, and the saturation of the dependence of the elasticity parameter on the dose.

On the basis of the above-presented analysis of available experimental data on the change of mechanical properties of the processed alloy SAV-1 with regard for both the literature data and the process of radiation-induced formation of defects, we advance the conception of the cluster (vacancy) mechanism of radiation-induced modification of the modulus of normal elasticity of the alloy which is based on the continual model of accumulation of defects and on the known theoretical ideas [12, 13]. According to these ideas, defects of a lattice in solids reveal the tendency to the formation of small aggregates. In the course of irradiation, the size of aggregates and the energy needed for their formation increase. This proceeds up to the attainment of the critical size of clusters at great doses, and then the process is accelerated. We assume that these aggregates of defects lead, in turn, to a deformation of the lattice due to the stresses arising at the irradiation of the material, can be disorder formation centers, and facilitate the appearance of interfaces and intrusion zones or phases. This representation is supported by the data [10] on the presence of intrusion phases on registered images, their decay in the neutron-irradiated alloy, and the appearance of an oxide film on the surface.

The measurement of the resistance [2] during the deformation of irradiated Al indicated the appearance of a great number of vacancies. This fact together with data on the presence of an oxide film on the surface of the irradiated alloy [10], the extreme decrease of electron conductance $\sigma(D)$ of aluminum oxide up to $10^5$ Gy [14, 15], its growth at $D \geq 10^6$ Gy, and the appearance of peaks of TSC (thermostimulated current) and TL (thermoluminescence) ($F$- and $V$-centers) testify to the similarity of the curves $\sigma(D)$ and $E(D)$ for the alloy and support the assumption about both the acceleration of the process of formation of defects in the course of its irradiation and the generation of defects of the vacancy type in preference. The last fact serves an additional argument to the favor of the above-advanced vacancy-involved mechanism of the radiation-induced modification of elastic properties of the Al-based alloy under study. In the frame of this mechanism in view of the above-performed detailed analysis of specific features of the formation of defects, the appearance of clusters of point-like defects, and their variation with increase in the radiation dose, we may suppose that, indeed, the beginning of the irradiation of the alloy is characterized by the processes of a gradual generation of point-like defects (vacancies) and swelling of specimens, which causes the relaxation of the main modulus of elasticity. The number of vacancies increases with the radiation dose, and they begin to interact with one another, by forming small clusters. This is accompanied by the compression of specimens, i.e. the modulus of elasticity begins to increase, and we observe the second stage where the sizes of clusters grow. This process proceeds till the time moment when the critical size is attained (the third stage). Then the attachment of new vacancies leads to "the shaking", the curve $E(D)$ becomes a "plateau", i.e. we deal with the third stage where the normal elasticity of the alloy is stabilized. We do not exclude the possibility that the redistribution of point-like defects (vacancies, impurities) at a deformation of the alloy as a result of the irradiation will act jointly with the processes of ionization and formation of defects.

We performed the quantitative evaluation of the degree of a radiation-induced variation of the elasticity modulus of alloy SAV-1. Table 4 illustrates the relative variation of the main modulus of elasticity ($E$) of the alloy as a function of the radiation dose in the form $\Delta E/E = (E_{\text{init}} - E_{\text{irr}})/E_{\text{init}}$. It is seen that, at the dose $D = 5 \times 10^6$ Gy, the radiation-induced effect is highest (about 10%), whereas it is less by a factor of 1.5 at the dose $D = 8 \times 10^6$ Gy. On the whole, the radiation-induced variation of the elasticity modulus is small and does not leave the admissible limits, which testifies to the perspective to use this alloy as a constructional material.

**T a b l e 4. Relative variation of the Young modulus $E$**

| Specimen | Dose, Gy | $\Delta E/E$, rel. un. |
|---|---|---|
| 1 | $3 \times 10^6$ | 0.108 |
| 2 | $5 \times 10^6$ | 0.112 |
| 3 | $8 \times 10^6$ | 0.096 |

## 4. Conclusion

Within the method of ultrasound resonance, we have studied a complex of mechanical properties of the input and processed alloys SAV-1. We have traced the effect of ionizing radiation in a wide range of absorbed doses ($10^3 - 3 \times 10^7$) Gy on their elasticity characteristics. The regularities of variation of a number of mechanical properties of the alloy as a resul of the action of various radiation doses are established. We have revealed the extreme radiative kinetics which is accompanied by a nonlinear modification of the modulus of normal elasticity of alloy SAV-1.

We have advanced the conception of the cluster (vacancy) mechanism of modification of the elasticity modulus of the alloy. In the frame of this conception, the phenomenological description of the initial decrease in the elasticity, its subsequent recovery, and the final stabilization of the mechanical parameter at great radiation doses is presented. The degree of a radiation-induced variation of the Young modulus of the alloy is quantitatively evaluated.

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## УЛЬТРАЗВУКОВЕ ДОСЛІДЖЕННЯ КОНСТРУКЦІЙНОГО СПЛАВУ НА ОСНОВІ АЛЮМІНІЮ ТИПУ САВ-1

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Р е з ю м е

У роботі проведено дослідження механічних властивостей деяких конструкційних матеріалів із залученням акустичних методів. Отримано дані про набір пружних властивостей, дисперсійні залежності основних модулів алюмінієвих сплавів типу САВ-1 до і після дії іонізованого випромінювання на основі відзнятих спектрів згинальних коливань. Установлено значну стійкість модулів пружності сплавів за звичайних умов зберігання, відстежено нелінійну дозову залежність пружних параметрів зразків у широких межах поглинальних доз. Проаналізовано можливі причини виявлених ефектів модифікування механічних властивостей радіаційно оброблених сплавів САВ-1.