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Mechanical Properties of the Enhanced with Nanodiamond and Tungsten Strengthened Aluminium Alloy Being Exposed in the Outer Space

Anna BOUZEKOVA-PENKOVA[1], Maria DATCHEVA[2], Roumen IANKOV[2]

[1] Space Research and Technology Institute, Bulgarian Academy of Sciences, Sofia, Bulgaria,
e-mail: a_bouzekova@space.bas.bg

[2] Institute of Mechanics, Bulgarian Academy of Sciences, Sofia, Bulgaria,
e-mails: datcheva@imbm.bas.bg, iankovr@yahoo.com

Abstract
In the present work, a series of nanoindentation tests were conducted on two samples of the same material (nanodiamond enhanced tungsten strengthened aluminum alloy) stored for two years and four months under different conditions. One of the samples was stored in ambient terrestrial conditions and the other sample was mounted on the outside of the International Space Station for a period over two years. In the Outer space the specimen has been exposed to radiation and two-hours cyclic temperature variation in the range of ~ 300° C. The purpose of the nanoindentation experiments is to determine two basic mechanical characteristics - indentation hardness (H_{IT}) and indentation modulus (E_{IT}) and this way to reveal the influence of the Outer space environment on the mechanical characteristics of the investigated nanodiamond enhanced tungsten strengthened aluminum alloy.

Keywords: aluminum alloy (7075), gamma-radiation, indentation hardness and indentation modulus, nanodiamond

1. Introduction

For space applications, modern alloys are required to work in extreme conditions and to possess a number of specific physical and mechanical characteristics. Due to the unique combination of properties, the aluminum and its alloys are one of the most important materials of today's industry where a high strength to weight ratio is required, e.g. in aviation, aerospace and missile/rocket industry [1].
These aluminum alloys have a complex chemical composition and the main alloying elements are magnesium, copper, manganese and zinc [2-5].
For the purposes of this study we used aluminum alloy 7075 AL. The aluminum alloy 7075 AL is the most widely used alloy for the production of high strength structures operating in extreme conditions.
Due to the fact that the alloy 7075 AL operates under extreme conditions and is used in modern aircraft constructions and space techniques [6,7], it is particularly promising its further strengthening with nanodiamond particles and other alloying additives to improve the properties of the alloy.
The proposed work has been studied a new aluminum-based matrix composite material enhanced with ultradispersed diamond powder / UDDP / and tungsten. The new material is expected to combine the high strength with high modulus of elasticity, good resistance to sudden temperature changes ranging between -150°C + and 150°C and to wearing and radiation as well as to have at the same time low weight.

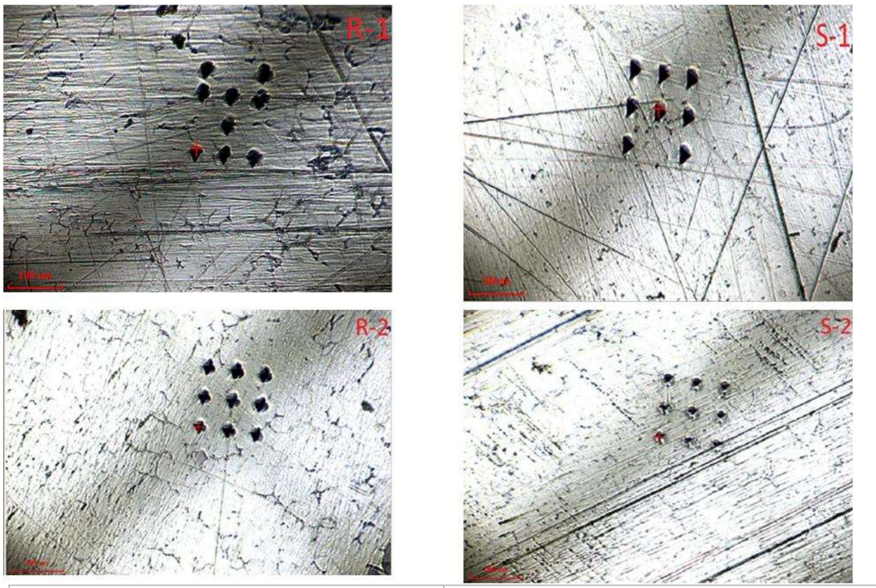
2. Materials and Methods

In the present study, nanoindentation experiments were performed on two types of specimens of the same material stored for two years and four months under different conditions. The first type of specimens, referred to as “Reference samples"(R), were stored in natural terrestrial conditions and the second type specimens, referred as "Space samples"(S), were mount on the outside of the International Space Station (ISS) and thus were exposed in the outer space in periods 2013-2015. After being return to Earth, space sample were kept under regular ambient conditions.

The aim of the nanoindentation testing is to determine the influence of the cosmic radiation and the abrupt temperature changes on the mechanical characteristics of the investigated composite material - indentation hardness (H_{IT}) and indentation modulus (E_{IT}) [8]. For this purpose, we used Nano Indenter Agilent G200 (Agilent Technologies), equipped with a standard XP head, which allows measurements to be made with a penetration accuracy of up to 0.01 nm and an accuracy of the applied loading up to 50 nN. The head tip used in this study is a sharp Berkovich triangular pyramid with tip rounding of 20 nm [9-10].

The indentation program includes the built-in load-control operating method of indentation named “Series Hardness and Modulus via Cycles Load Control” (for details see in “Nano Indenter G200 manual”). Within this indentation method we set the time for penetration of the tip 10 seconds and maximum applied load P_{max} = 300 mN. In order to collect a preliminary information about the hardness of the tested material a series of indents were done under displacement control up to maximum penetration (indentation) depth h_{max} = 50 nm.

The predefined maximum load P_{max} = 300 mN was achieved by five indentation cycles with gradually increasing loading and unloading up to 90% of the corresponding maximum applied force. For better statistics, each indentation tests consists of nine individual indents that are in most of the cases located at a distance of 30 to 50 um of each other.



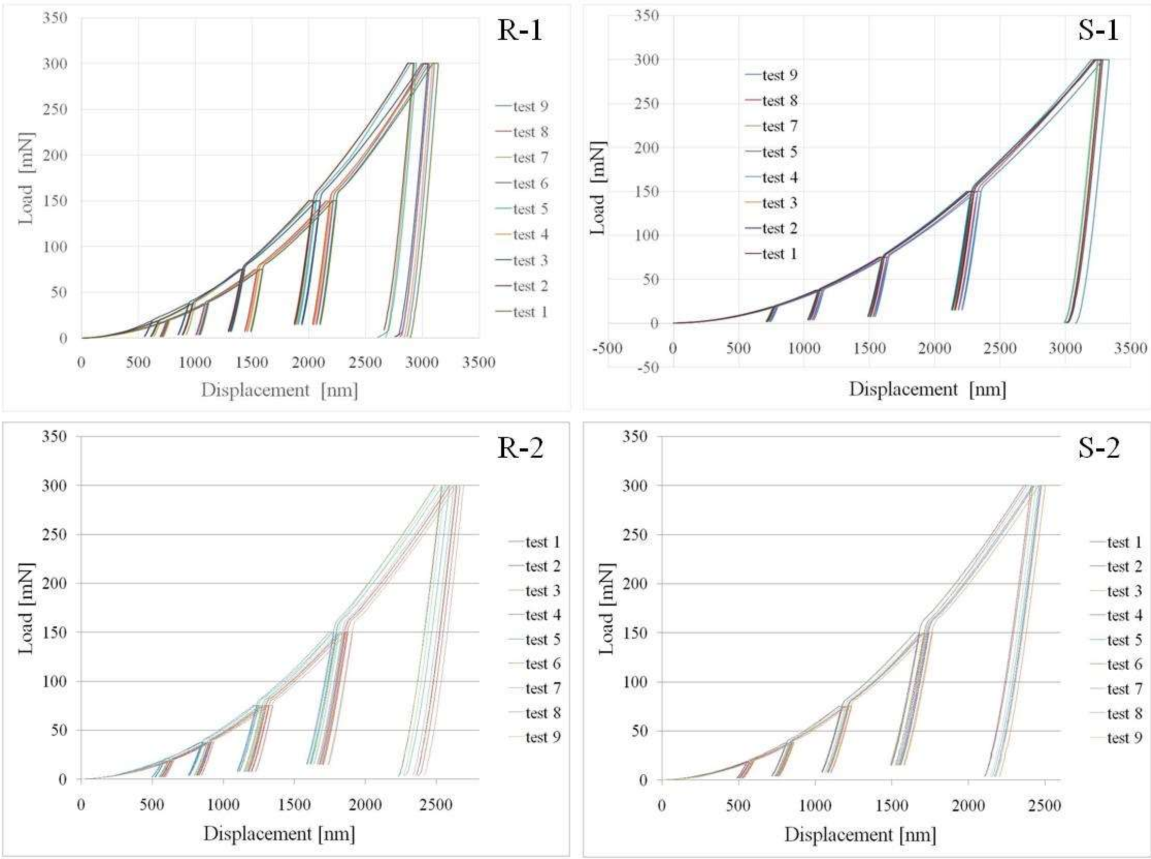
a	b

Fig. 1. Imprints left by the Berkovich pyramid after nanoindentation onto the reference samples R-1 and R-2 (a), the space samples S-1 and S-2 (b)

3. Results and Discussion

For presenting the results we use the following nomenclature. The “Reference” type specimens that were stored solely in ambient for the Earth conditions are R-1 and R-2, while those being exposed to conditions in the outer space (“Space” samples) are S-1 and S-2. Samples R-1 and S-1 were examined after the return of the “Space” specimens from the ISS. Samples R-2 and S-2 were tested 3 years after the testing of samples S1 and R1 took place.

As a result of the nanoindentation testing, the load-displacement curves *P-h* were first obtained (Figure 2). Using the unloading part of the *P-h* curves and applying the Oliver and Pharr method, the indentation hardness and indentation modules were determined [11].



a	b

Fig. 2 Indentation load-displacement curves for the reference samples R-1 and R-2 (a), the space samples S-1 and S-2 (b)

Figure 3 shows the mean value of the indentation hardness and the standard deviation for each sample type and applied load, while in Table 1 the average indentation values over the five loading cycles are given with the calculated standard deviation.

The hardness of the space sample S-1 is lower than the hardness of the reference sample R-1. The sample hold in the outer space was subjected for two hours to high temperature amplitude when the temperature varied from -150° C to + 120°C. Thus the material of S-1 underwent partial recrystallization and its structure is crushed showing distinct boundaries between the grains compared to the structure of the reference sample that has been not exposed to the influence of the outer space environment. The cosmic radiation and the intense temperature cycling induce in the material internal stresses resulting in changes in the crystal lattice, and these changes apply especially to the surface layer of the sample leading to a decrease in the hardness of the material. The hardness of sample S-2 that spent three years at Earth after returning back from the space is the highest compared with the hardness of the other three samples. The material over time has become stronger and has the highest values. Being on Earth, the two reference samples R-1 and R-2 have undergone inhomogeneity in depth and volume due to the conditions of the Earth.

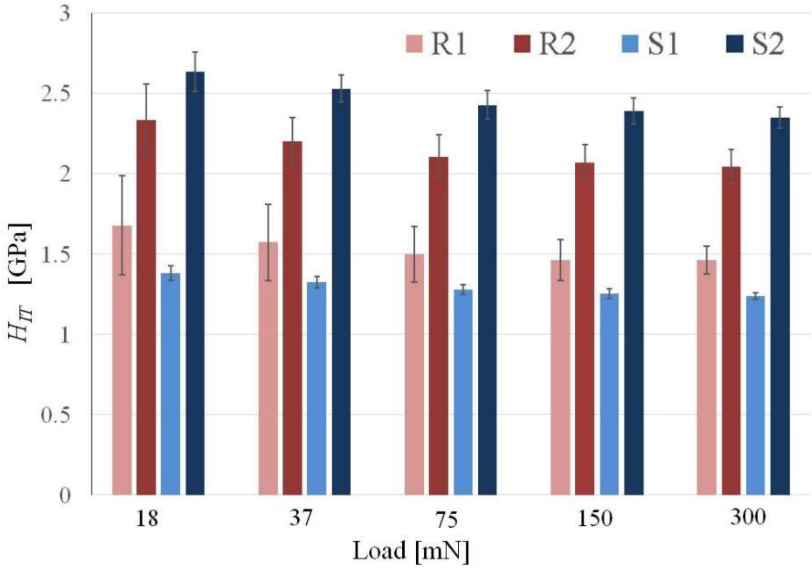


Fig. 3. Indentation hardness vs. applied load onto the reference samples R-1 and R-2 and the space samples S-1 and S-2

Table 1. Indentation hardness

SAMPLE	Mean Indentation hardness ± standard deviation [GPa]
Reference R-1	1.54 ± 0.185
Reference R-2	2.15 ± 0.144
Space S-1	1.29 ± 0.032
Space S-2	2.47 ± 0.089

Figure 4 shows the average values for the indentation (elastic) modulus for the two types of specimens obtained as a result of calculations using the unloading branch of the force-displacement curve *P- h* of each of the load five load cycles [11].

Table 2 shows the average values of the indentation (elastic) modulus for the two specimens types. The sample S-1 that was tested immediately after returning back to earth from space has higher indentation modulus as compared to the indentation modulus of sample R-1. Sample S-2 has the highest indentation modulus. If we compare the values of the indentation modules of all samples, it can be concluded that material aging improves the elastic characteristics and this implies more to the “space” specimens.

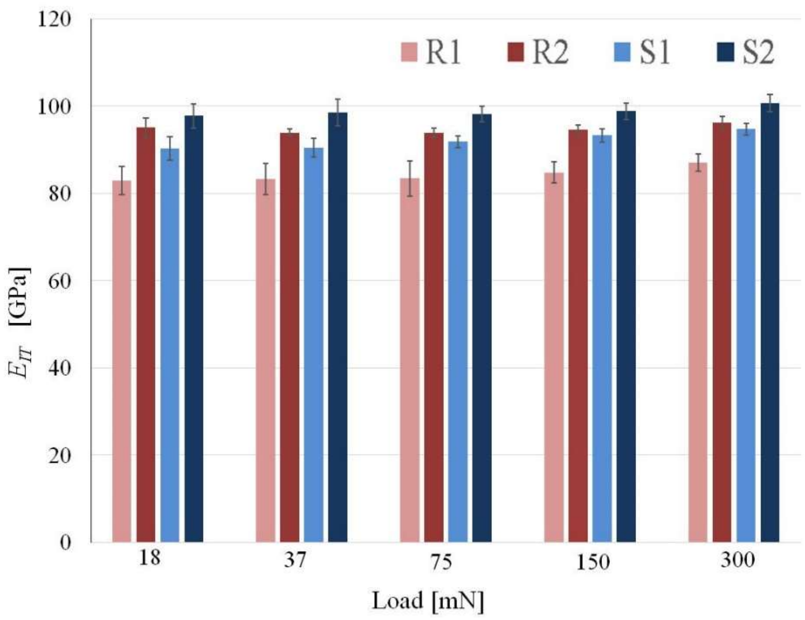


Fig. 4. Indentation modulus vs. applied load onto the reference samples R-1 and R-2 and the space samples S-1 and S-2

Table 2. Indentation modulus

SAMPLE	**Mean Indentation modulus ± standard deviation GPa**
Reference R-1	84.30 ± 3.05
Reference R-2	94.69 ± 1.37
Space S-1	92.69 ± 1.82
Space S-2	98.80 ± 2.31

4. Conclusion

The conducted nanoindentation tests showed that the absorbed radiation during the exposer of the "space" specimen in the outer space being ~ 425 kGy [12] caused changes in the crystal lattice, especially in the surface layer of the sample, which in turn reduced the material hardness. After staying on the Earth, the investigated composite hardened and its indentation hardness shows higher values. The cosmic environment has a favorable effect on the elastic properties of the material. The influence of the induced by the radiation defects in the crystalline structure exceeds significantly the effect of temperature stress and makes the material more elastic. In this sense, there is a specific elemental redistribution and the migration of the elements leads to the formation of new intermetallic phases thus changing the intrinsic properties of the investigated tungsten strengthened aluminum alloy material enhanced with nanodiamond particles.

Acknowledgements
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