The Effects of Explosive Loading and Neutron Irradiation on Mechanical Properties of Titanium and Copper

Nikoloz Chikhradze 1

1 LEPLG, Tsulukidze Mining Institute/Georgian Technical University. 7, E. Mindeli Str., Tbilisi, 0186, Georgia

E-mail address: chikhradze@mining.org.ge

Abstract. It is known that properties of materials sufficiently depend on their initial defect structure. One of the methods of mechanical treatment of materials is explosive working (strengthening, welding and etc.). High strain rate deformation of materials under explosive loading caused significant changes of defect structure of crystals and as a result appropriate variations of their physical and mechanical properties. Radiation effects in crystals with non-equilibrium defect structure represents great interest for scientific as well as from applied points of view. The paper describes the results of experimental investigations of strengthening processes of titanium (purity-99.5%) and copper (purity 99.98%) using axial-symmetric explosive loading. Shock loading of materials was carried out by axis-symmetric cylindrical scheme. For shock wave generation the industrial explosive substances ANFO, Ammonite and Hexogen were used. The experiments show that the intensive shift deformations caused by the explosive pressure of intensity 10-20 GPa increase the strength and flow limits approximately 2.0-2.5 times above-mentioned materials. The samples strengthened by shock waves were subjected to the neutron irradiation. Results of the interaction of structural defects induced by the explosive pressure of intensity 10-20 GPa increase the strength and flow limits approximately 2.0-2.5 times above-mentioned materials. The samples strengthened by shock waves were subjected to the neutron irradiation. Results of the interaction of structural defects induced by shock waves followed by fast neutron irradiation (exposure of irradiation 8 x 10 21 m-2; E=0.5 MeV) and its influence on strength characteristics are discusses. Samples for mechanical testing as well as for investigation of thermal stability of explosive strengthening in combination with shock and neutron action, were annealed in vacuum furnace (10^-6 torr). The temperature during annealing of samples was controlled by the thermo-regulator. Accuracy of temperature fluctuation during the sample annealing for mechanical testing was ± 3°C. It is shown that: a) shock loading of titanium and copper significantly increases strength characteristics with a simultaneous decrease (up to total disappearance) of plasticity; b) Neutron irradiation tends to partial relaxation of strength and plastic characteristics of titanium whereas in the case of copper in contrast its further strengthening is observed without an appearance of plasticity.

1. Introduction
Development of new materials for application in energy sector main strategy and big challenge for research and industry. Fabrication of structural materials for nuclear application is one of the key priority for development of the next generation nuclear reactors. Sustainable Nuclear Energy Technology Platform has developed strategic research agenda and a deployment strategy [1] in this direction. Therefore, the elaboration of new technological maps for fabrication of new energetic materials is strategic direction in materials science. Explosive working of metals and alloys is one of the attractive method for modification and synthesis of materials with desired properties. Currently the
explosive energy is successfully used for metal hardening, powder compaction, phase transformation, welding of dissimilar materials, synthesis of new materials and etc. Due to the technological peculiarity, the explosive strengthening of the materials is non alternative in some particular cases when conventional methods are inapplicable. If material is affected by high intensity explosive impulse, it rapidly generates in material shock wave and initiate high strain rate deformation. The strain rate plays key role for outcomes of materials property, including: ductility, fracture toughness, ballistic impact, adiabatic shear bending and etc. Shock wave action on the material create non-equilibrium defect structure and change physical-mechanical-chemical characteristics of crystals [2, 3, 4]. If the strain rate exceeds to the elasticity limit of the material, generation and interaction of one dimensional (vacancies and implemented atoms) defects and dislocations, tends to sufficient strengthening of metals, which may reach to total disappearance of plasticity. The investigations of explosive strengthened structures under radiation and thermal impact is important issue for determination of reliability in extreme conditions before implementation in nuclear power plants. In this connection an investigation of radiation effects in crystals with non-equilibrium defect structure is of great interest from scientific as well as from applied points of view.

In the present paper the results of investigation of mechanical properties of titanium and copper under shock loading, following neutron irradiation and thermal impact are reported.

2. Materials and Experiment Technique
The investigation was concerned with polycrystalline titanium (purity 99.5%) and oxygen-free copper. Shock loading of materials was carried out by cylindrical/axis symmetric scheme (Figure 1).

For shock wave generation the industrial explosives were used in the experiments. The characteristics of the explosives are presented in Table 1.

| No. | Explosive | Density ρ x10^3 [kg/m^3] | Detonation rate V, [m/s] | Pressure P, [GPa] |
|-----|-----------|--------------------------|-------------------------|------------------|
| 1   | 79%NH₄NO₃+21%C₆H₂(NO₂)₃CH₃ (ammonite) | 1.0-1.2 | 3600-4800 | 10 |
| 2   | 95%NH₄NO₃+5%C₆H₂(NO₂)₃CH₃ | 1.0 | 1700 | 5 |
| 3   | C₃H₆O₆N₆ (Hexogen) | 1.0 | 6050 | 20 |

A cardboard box was filled with the powdered explosive and placed around the cylindrical sample. The shock wave pressure (loading intensity) will be varied in range 5-20GPa. After shock loading from titanium and copper rods samples of two various forms were cut out. The shape and dimensions of samples for testing on tensile is shown on Figure 2. Determination of Rockwell hardness was conducted at room temperature on the samples of disk form (diameter 7mm and thickness 5mm).

Samples, prepared from shock wave strengthened rods were irradiated in nuclear reactor (Fluence of speed neutrons was 8 x 10^{21} m^{-2}; Energy E >0.5MeV).

Samples for mechanical testing as well as for investigation of thermal stability of explosive strengthening in combination with shock and neutron action, were annealed in piped furnace in vacuum (10^{-6} torr). The measurement and maintenance of temperature, during annealing processes were performed by the thermos-regulator. Accuracy of temperature maintenance during the sample annealing for mechanical testing was ± 3°C.

3. Experimental Results and Discussions
The results of tensile test are presented in tables #2 and #3. It is evident that the action of shock wave significantly changes strength characteristics of titanium and copper. Particularly, after shock loading at P=5GPa and P=10GPa the point of yield of titanium increases at 67% and 212%, respectively in
comparison with precursor (Table 2). It is remarkable that in the case of copper shock loading practically equalizes the values of yield point and tensile whereas in similar conditions for titanium its yield point remains lesser than point of tensile (Table 2) that is indicative of maintenance of specific but slight plasticity.

Figure 1. Explosive Loading Set-up: a) scheme of assembly; b) configuration of detonation and shock waves

Figure 2. Sample for neutron irradiation and tensile testing

Table 2. Mechanical characteristics of Titanium

| No. | Condition of Sample                | \( \sigma_{0.2} \times 10^7 \text{[Pa]} \) | \( \sigma_t \times 10^7 \text{[Pa]} \) | \( \varepsilon \% \) | HRC |
|-----|-----------------------------------|------------------------------------------|----------------------------------|----------------|-----|
| 1   | Initial                           | 24.5                                     | 39.0                             | 32.0           | 32  |
| 2   | Strengthened at P=10GPa           | 41.0                                     | 50.5                             | 5.0            | 75  |
| 3   | Strengthened at P=20GPa           | 75.5                                     | 87.5                             | 3.5            | 86  |
| 4   | Irradiated by Neutrons            | 28.0                                     | 40.5                             | 28.0           | -   |
| 5   | Strengthened at P=10GPa +         | 36.5                                     | 41.0                             | 14.5           | -   |
|     | Irradiated by Neutrons            |                                          |                                  |                |     |
| 6   | Strengthened at P=20GPa +         | 69.0                                     | 75.5                             | 4.5            | -   |
|     | Irradiated by Neutrons            |                                          |                                  |                |     |
Table 3. Mechanical characteristics of Copper

| No. | Condition of Sample                  | σ₀.₂ x 10⁷, [Pa] | σₜ x 10⁷, [Pa] | ε [%] | HRC |
|-----|--------------------------------------|------------------|----------------|-------|-----|
| 1   | Initial                              | 4.5              | 25.5           | 43    | 14  |
| 2   | Strengthened at P=10GPa              | 44.0             | 44.5           | 0.5   | 26  |
| 3   | Strengthened at P=20GPa              | 44.5             | 45.0           | 0.5   | 31  |
| 4   | Irradiated by Neutrons               | 12.5             | 26.5           | 26.0  | -   |
| 5   | Strengthened at P=10GPa + Irradiated by Neutrons | 50.0             | 50.5           | 1.0   | -   |
| 6   | Strengthened at P=20GPa + Irradiated by Neutrons | 50.5             | 51.0           | 1.0   | -   |

Neutron irradiation in mentioned conditions causes various radiation effects in preliminary shock wave strengthened titanium and copper. As it is shown (Table 2), neutron irradiation of titanium causes the partially dis-strengthening and the significant increase of plasticity. This indicate to the fact that an appearance of radiation defects and their interaction with dislocations tends to significant variation of dislocation structure and by character of variation of yield and strength as well as plasticity it is thought that radiation-induced relaxation processes tend to partial decrease of dislocation density. In the case of copper an opposite picture is observed, irradiation causes a next increase of strength and yield points (Table 3). It gives an impression that generated radiation defects tend to the holding of dislocations with an appropriate increase of strength characteristics instead of relaxation processes. It can be noticed one more circumstance resulted from the comparison of obtained data. It is evident that pressure on copper samples generated by shock waves is exceeds to the value, which is necessary for total loss of plasticity. In the case of titanium, pressures generated during explosion of mentioned substances are deficient for maximal strengthening of titanium. In both cases plasticity sufficiently decreases but doesn’t disappear (Table 2) as it takes place in the case of copper (Table 3). In this regard, it is thought that during the reaching of maximal value of strength characteristics of titanium the further neutron irradiation will cause its following growth i.e. radiation relaxation of strength and plastic characteristics of metals presumably will take place only during the partial preliminary strengthening. Thermal stability of samples subjected to shock leading and neutron irradiation was investigated. For this purpose the age of their yield point was studied during an isochronal annealing in 20°C-500°C-temperature range in vacuum (5·10⁻⁶ torr) with a 30 minute holding at each fixed temperature. Results of investigations on thermal stability of strengthening effect at different conditions are shown on the Figure 3 and Figure 4.

Figure 3. Recovery of yield point of Ti at different annealing temperature
From Figure 3 it is clear, that an annealing of irradiated samples of titanium, preliminary exposed to shock loading, causes a reduction of initial value of yield point. However, at the curve of temperature, dependence of recovery of yield point an anomaly is observed—above 100°C the growth of yield point exists with a following decrease during a further increase of annealing temperature. Appearance of such maximum on the curve of recovery of yield point of titanium for the present couldn’t be explained although it is thought that this is due to the fixing of dislocations by impurity atoms of implantation (oxygen, carbon, nitrogen) that above 100°C become sufficiently mobile [5].

Figure 4. Recovery of yield point of Cu at different annealing temperature

Figure 4 illustrates a view of thermal recovery of yield point of copper strengthened during its shock loading. It is evident that by the growth of annealing temperature the yield limit of copper monotonically decreases with an appearance of marked stage of re-crystallization in 200-300°C ranges. It is clear that re-crystallization causes the total return of yield limit of copper.

4. Conclusions
Shock loading of titanium and copper significantly increases strength characteristics with decrease (up to total disappearance) of plasticity. Neutron irradiation of shock wave strengthened samples tends to partial relaxation of strength and plastic characteristics of titanium whereas in the case of copper in contrast its further strengthening is observed without an appearance of plasticity. It was established that, although during of annealing practically total reduction of initial value of its yield level is observed. An appropriate curves of temperature dependence of yield point recovery for titanium and copper are significantly differ. For titanium the dependence has non monotonic character, whereas in the case of copper return proceeds monotonically with a sharply marked re-crystallization stage.

References
[1] https://ec.europa.eu/jrc/en/research-topic
[2] Murr, L. E., Staudhammer K. P. Meyers M. A. 1986. Metallurgical Application of Shock Wave and High-Strain-Rate Phenomena”, Marcel Dekker Inc., p. 1120.
[3] Meyers M. A., Murr L. E., Staudhammer K.P., 1992. Shock-Wave and High-Strain-Rate Phenomena in Materials, Marcel Dekker, Inc., Marcel Dekker Inc., p. 1159.
[4] Murr L. E., Staudhammer, K.P., Meyers M.A., 1995. Metallurgical and Materials Application of Shock Wave and High-Strain-Rate Phenomena”, Elsevier, p. 931.
[5] A. Gindin et al., 1978. Influence of Irradiation Defects on Processes Program Hardening Titanium, in J. “Reactornoe Materialovedenie”, M., “CNII Atominform”, v.2, p.317.