Dynamic behavior of zirconium alloy E110 under submicrosecond shock-wave loading

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Abstract. Stress waves have been measured under shock wave loading of zirconium alloy E110 samples with the 0.5 – 8 mm thickness at normal and elevated temperatures. Duration of shock loading pulses varied from ~0.05 up to 1 µs with the amplitude varying from 3.4 up to 23 GPa. Free-surface velocity profiles have been registered using VISAR and PDV interferometers with nanosecond resolution. Attenuation of the elastic precursor has been measured to determine plastic strain rate behind the elastic precursor front. The plastic strain rate was observed to decrease with propagation from 10⁶ s⁻¹ at the 0.46-mm distance down to 2 · 10⁵ s⁻¹ at the 8-mm distance. Spall strength has been measured under normal and elevated temperatures. Spall strength versus strain rate relationships have been constructed in the 10⁶ s⁻¹ – 10¹⁰ s⁻¹ range. Under shock compression higher than 10.6 GPa, the three-wave configuration of the shock wave has been registered and the polymorphous α → ω transition is considered to be the reason of this phenomenon.

This work was supported by State Atomic Energy Corporation “Rosatom” within State Contract # H.4x.44.90.13.1111

1. Introduction

Investigation into processes of elastic-viscous-plastic deformation of metals and alloys under shock-wave loading [1] allows us to measure velocity-temperature relationships how these materials resist to deformation and fracture. In shock waves, a wide range of strain rates of solid bodies can be covered and thus we can accumulate experimental data that can serve as the basis for construction of defining relationships needed to predict materials behavior under high-intensity shock loads [2].

The structure of shock waves in solid bodies depends on processes of their elastic-viscous-plastic deformation, possible phase transformations, as well as on kinetics of fracture incipience and development [3–5]. In recent years, shock-wave methods were used for [6–9] systematic investigations into the velocity-temperature relationships for yield stresses and fracture of pure metals with face-centered and body-centered cubic structures. These data are practically absent for metals with hexagonal close-packed structure.

Interest to zirconium and alloys on its basis is inspired by a wide application of this material in nuclear power engineering due to happy combination of its nuclear physical (small thermal-neutron capture cross-section), physical-and-mechanical characteristics, processing behavior and also resistance to corrosion. Zirconium — is a polymorphous metal that has a hexagonal close-packed lattice under normal conditions and belong to transition metals. Zirconium alloy E110 (Zr – 1.0% Nb) — is one of the main commercial alloys for nuclear power engineering. Experimental data on dynamic properties of zirconium alloys in the area of high-strain rate deformation are practically unavailable. The considered experimental investigation results for zirconium alloy E110 samples loaded in well-controlled conditions is an attempt to fill this gap.

2. Material and experimental setup

Zirconium alloy E110 contains niobium (Nb 1%) as an alloying component; principal impurities — are iron and oxygen (O and Fe less than 0.1%), the rest admixtures (tin, hafnium, nickel, chromium, carbon, silicon, etc.) in the aggregate do not exceed 0.25%. The alloy has 6.5 g/cm³ density, 160 MPa yield strength, and 270–310 MPa ultimate strength.

The material was studied in the as-received condition. The rod with the 35-mm diameter was sliced into disks with the thickness of 0.5, 1.0, 2, 4, and 8 mm to serve as zirconium alloy E110 samples for tests. Unevenness of the sample surface after processing was within 2.5–6 µm. The ultrasonic technique and samples with the 8-mm thickness were used to determine longitudinal c_l and shear c_s sound velocities: c_l = 4700 ± 15 m/s and c_s = 2262 ± 5 m/s. Volume sound velocity was estimated to be c_v = 3.91 km/s. In order to estimate stresses arising in the samples, we used Hugoniot adiabat of zirconium D = 3.91 + 0.91u (km/s), where D — is shock wave velocity, u—is mass velocity [10] with a correction for sound velocity data obtained for alloy E110.

Our experiments used a 44-mm bore one-stage gun [11] and the “symmetric” impact approach when strikers and samples are made of the same material apart from experiments with 0.5-mm thick samples, wherein strikers were cut out from the zirconium foil having 0.1-mm thickness. Shock waves in samples with 1; 2; 4; and 4-mm
Table 1. Setting Data on experimental setups and measured strength characteristics of zirconium alloy E110.

<table>
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<th>$V_{hi}, m/s$</th>
<th>$h_{hi}, mm$</th>
<th>$h_{si}, mm$</th>
<th>$W_{hi}, m/s$</th>
<th>$\sigma_{h0}, \sigma_{cl}, \sigma_{sp}, \sigma_{sp}$</th>
<th>$SR_{w}, m/s^{-1}$</th>
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<td>53</td>
<td>0.82</td>
<td>0.38</td>
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Figure 1. Free-surface velocity profiles for Zirconium alloy E110 samples.

$\sigma_{h0}$—dynamic elastic limit, $\sigma_{cl}$—dynamic yield stress, $\sigma_{sp}$—spall strength, $SR_{w}$—strain rate in a rarefaction wave ($V'/V_0$).

The value of the dynamic elastic limit $\sigma_{HEL} = \rho_0 c_l W_0/2$ agrees with conditions of uniaxial deformation; this value is converted to the yield strength in standard conditions of uniaxial stressed state $\sigma_{cl}$, using a simple relationship $\sigma_{cl} = 3/2\sigma_{HEL}(1-(c_l/c_t)^2)$.

Figure 1 shows free-surface velocity profiles $W(t)$ for Zirconium alloy E110 samples having 0.5-; 1-; 2-; 4- and 8-mm thickness under different-intensity impacts.

Each profile has designated velocity of the striker. The two-stage elastic-plastic compression wave is registered when the impact velocity is up to 0.6 km/s. When shock compression pressure goes higher than 10.6 GPa, the plastic shock wave looses its steadiness and splits due to the known polymorphous transformation $\alpha \rightarrow \omega$ with the decrease of the specific volume. When shock compression
pressure is higher than 16 GPa, the two-wave configuration “closes” due to the fact that the velocity of the wave with phase transformation becomes equal to or higher than the plastic shock wave velocity. When impact velocity varies, the compression stress on the elastic precursor remains practically unchanged. It follows that in this range of parameters, attenuation of the elastic precursor is practically independent of the final shock compression pressure.

All sample free-surface velocity profiles demonstrate decrease of parameters in the rarefaction wave behind the area of steady-state flow. Interaction of the incident and reflected rarefaction waves leads to generation of tensile stresses inside the sample and to its spall fracturing. Relaxation of tensile stresses due to fracturing causes initiation of the compression wave in the stretched material and arrival of this wave at the surface is accompanied by the repeated increase of its velocity, which is called spall pulse. The subsequent periodic fluctuations of the free-surface velocity are conditioned by waves reverberation, i.e. reflection of rarefaction and compression waves from the surface on the separated layer of the material.

Spall strength was estimated based on measured free-surface velocity decrease under unloading from the shock-compressed state taking into account correction for the velocity of spall pulse and plastic wave propagation in the unloading area [4].

Elastic precursor and plastic flow behind its front. Figure 2 gives measured profiles for the free surface velocity of zirconium alloy E110 samples having different thickness. Each profile has designated thickness of samples and velocity of the striker that has generated the compression wave in the sample. Amplitude of the elastic precursor decreases with its propagation. Elastic precursor attenuation is conditioned by relaxation of stresses due to plastic deformation development.

Measurement results for the elastic precursor attenuation are given in Fig. 3. Similar to previous studies [6–9, 14–16], attenuation measurement results are approximated by the following empirical relation:

\[ \sigma_b = S(h/h_0)^{-a} \]  

where \( S = 0.87 \) GPa, \( a = 0.138 \), and \( h_0 = 1 \) mm. The elastic precursor attenuation is related to the plastic deformation rate \( \gamma'_{pl} \) just behind its front by the relationship [15,17]:

\[ d\sigma_s/db|_{HEL} = -4/3G\gamma'_{pl}/c_1, \]  

where \( G \) is shear modulus, \( \sigma_s \) – is compression stress in the direction of wave propagation, \( h \) – is distance covered by the wave. Taking into account relationship (1), the plastic deformation rate can be expressed as:

\[ \gamma'_{pl} = -3/4(S\alpha c_1(h/h_0))^{-(\alpha+1)}/(h_0 G). \]  

After the wave-covered distance \( h \) from relationship (1) is substituted into (3), we have the initial velocity of the "plastic shear deformation versus shear stress behind the precursor front" relationship:

\[ \gamma'_{pl} = 3/4(\tau E/(SG))^{(\alpha+1)/\alpha} S\alpha c_1/(h_0 G). \]  

Figure 3 shows data on the dynamic elastic limit attenuation, empirical relationship (1), and appropriate plastic deformation rate.

Plastic deformation rate behind the elastic precursor front changes from \( 10^6 \) s\(^{-1} \) at the 0.46-mm thickness of samples up to \( 2 \cdot 10^4 \) s\(^{-1} \) at the 8-mm thickness of samples and this is almost one order of magnitude higher than the plastic deformation rate in magnesium alloy Ma-2 [15].

Analysis of elastic precursor attenuation provides information on the initial plastic deformation rate directly after the elastic limit is attained. Measurements of compression velocity in the plastic shock wave provide data on the material behavior at the follow-on stages and usually at higher deformation rates. The maximum plastic deformation rate of alloy E110 in the plastic shock wave is \( 5 \cdot 10^5 \) s\(^{-1} \) at the impact velocity of 254 m/s (compression stress behind the plastic shock wave is 3.4 GPa) and \( 1.3 \cdot 10^7 \) s\(^{-1} \) at the impact velocity of 577 m/s (compression stress – is 7.8 GPa). The maximum shear stresses in the plastic shock wave were 173 GPa and 284 GPa, respectively.

Phase transformation. Splitting of the plastic shock wave (Fig. 2) indicates polymorphous transformation,
Figure 4. Measured spall strength of zirconium alloy samples versus deformation rate under expansion.

probably a well-known transformation $\alpha \rightarrow \omega$ [18]. As the first plastic shock wave propagates, pressure at its front, which corresponds to transformation onset, decreases from 11.2 GPa for the sample having 0.46-mm thickness down to 10.6 GPa when this wave leaves the sample having 4-mm thickness. Pressure decrease in the first plastic shock wave as it is propagating is indicative of the final velocity of phase transformation. When striker velocity is 1181 m/s, loading amplitude becomes sufficient for the principal wave to begin to “close” the first plastic shock wave.

Spall strength. Figure 4 shows results of processing the stress wave profiles as the “spall strength versus the material expansion rate in the unloading part of the incident compression pulse” relationship.

Measurement results for the elastic precursor attenuation are given in Fig. 3. Similar to previous studies [6–9, 14–16], attenuation measurement results are approximated by the following empirical relation:

$$\sigma_{sp} = 0.402 \left( \frac{V'}{V_0} \right)^{0.164} \text{GPa.}$$ (5)

Relationship (5) also determines how the initial rate of discontinuities growth depends on stresses and can be used to construct a macrokinetic model of fracturing.

Experimental data given in Fig. 4 cover the impact load duration range from $\sim 0.05 \mu s$ up to 1 $\mu s$ and, respectively, spall thicknesses – from 0.08 mm up to 2 mm.

Figure 5 illustrates how the dynamic elastic limit and spall strength of zirconium alloy E110 depend on temperature. We were forced to limit experiments to the temperature of 370°C as zirconium loses its reflectivity even if its surface is protected by deposited gold. In the meantime, zirconium alloy members are usually in service just in this temperature range.

Wave profiles were processed taking into account temperature relationships of elastic moduli given in [19]. Particularly in this temperature range, shear modulus of zirconium decreases by 20% and the longitudinal sound velocity –by 3.2%.

Comparison of wave profiles in Fig. 5 shows 10% growth in the dynamic elastic limit of zirconium, i.e. from 640 MPa at room temperature up to 710 MPa at 315°C. Calculation of the appropriate yield strength

$$\sigma_t = 1.5 \sigma_{HEL} \left( 1 - \left( \frac{c_b}{c_l} \right)^2 \right)$$

taking into account the time-dependent longitudinal sound velocity demonstrated that yield strength decreases from 300 MPa at room temperature down to 280 MPa at 315°C. Spall was measured at normal and elevated temperatures in very similar loading conditions taking into account measurement errors and it proved to remain unchanged and to be equal to 2.7 GPa.

4. Conclusion

The paper presents measurement results for dynamic characteristics of zirconium alloy E110 in the range of loading duration from $\sim 0.05 \mu s$ up to 1 $\mu s$ when the pressure amplitude in the shock wave varies from 3.5 up to 23 GPa. Measured dependences of elastic precursor attenuation allowed us to estimate the plastic deformation rate that changes from $10^6 \text{ s}^{-1}$ at the 0.46-mm thickness of samples to $2 \times 10^4 \text{ s}^{-1}$ at the 8-mm thickness and this practically one order of magnitude higher than the plastic deformation rate in zirconium alloy E635, VT1-0 titanium and magnesium alloy Ma-2.

The reason why the compression wave is split into the three-wave configuration under pressure higher than 10.6 GPa (striker velocity is higher than 780 m/s) is the polymorphous $\alpha \rightarrow \omega$ transformation. Attenuation of the first plastic shock wave indicates the final rate of phase transformation. Splitting of the plastic shock wave “closes” when the impact velocity is more than 1.2 km/s.

Spall strength of zirconium alloy increases with the deformation rate according to $\sigma_{sp} = 0.402 \left( \frac{V'}{V_0} \right)^{0.164}$. Spall strength of the material is practically independent of heating up to 315°C.

Authors express their sincere gratitude to G.I. Kanel for problem statement and useful discussions during this work implementation.

Very helpful in experiments were E.I. Karnaukhov, M.I. Serkov, M.F. Geraschenko, S.Yu. Filatov.
References


