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3D FEM MODEL FOR HOPKINSON SPLIT TORSIONAL (KOLSKY) BAR EXPERIMENTAL TECHNIQUE

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Abstract: In this paper, a 3D FEM model for Hopkinson Split Torsional (Kolsky) Bar experimental technique was made, in order to study the mechanical behavior of some high entropy alloys (HEA). A virtual model of the TSHB system, composed of two collinear bars of 2 m length and 25 mm diameter, one incident and the other transmitted was made, between which the cylindrical, short, thin-walled test specimen is arranged, having hexagonal ends for clamping in the practiced recesses in the two bars. The incident bar is uniformly loaded over a length of 600 mm by rotating its free end and applying a clamp in the section of the bar that delimits the loading zone from the free one. Shear stress values are recorded using virtual sensors placed on the incident and receiver bars, symmetrical to the specimen. The simulation was performed using the Ls-Dyna program.
Key words: numerical simulation, TSHB, high strain rates, torsion, Ls-Dyna, HEA.

1. INTRODUCTION

With the challenges posed by the development of science and technology in the last century, there arose a need to evaluate existing materials under dynamic conditions at high strain rates, as well as a desire to improve existing materials or discover and obtain new materials. The field that has driven this evolution is primarily the military, but not only, as fields such as machine construction, aircraft and spacecraft construction have also driven a leap in materials engineering.

Depending on the strain rate of materials, mechanical tests can be classified into three categories [1]: static tests, with strain rates ranging from $10^{-8} – 10^{-6}$ s^{-1}, quasi-static tests in which the strain rate is between $10^{-5} – 10^{-1}$ s^{-1}, and dynamic tests in which the strain rate varies in the range of $10^{-1} – 10^{4}$ s^{-1}.

The dynamic characterization of materials is carried out using a series of experimental techniques that involve tensile, compression, and torsion tests. For the characterization of materials subjected at high strain rates by compression, there are three types of tests used: impact test, Split Hopkinson Pressure Bars, and gas guns. In the case of tensile testing, equipment such as expanding rings and Split Hopkinson Tensile Bar (SHTB) are used. As for high strain rates shear testing, two experimental techniques are used: compression-shear and torsion [1].

From a historical perspective, the first dynamic material characterization test using an SHPB-type equipment was carried out in 1949, using a device created by Herbert Kolsky and based on the theory of John Hopkinson, Bertram Hopkinson, and Davies [2]. In 1966, Baker and Yew, based on the SHPB technique, introduced the concept of TSHB [3], based on the generation of a torsional wave, which was later developed by other researchers. As a result, 50 years later, this experimental technique is used on a wide range of materials such as steel, lead, copper, aluminum, and titanium [1]. Compared to SHPB, TSHB has the main advantage of precision, avoiding certain phenomena observed in SHPB, such as dispersion effects in bars and the inertial effect of the sample. In this paper, a numerical simulation approach using the Ls-Dyna program is proposed for the dynamic characterization process of high-entropy alloys using the TSHB technique. Thus, a 3D model was created for the TSHB system, which was discretized using hexahedral elements. Using virtual transducers, the variation of stress and strain on the incident and receiver bars, symmetric to the specimen, was recorded. For the high-entropy alloy probe, a previously determined material model was used [4] using a methodology described in the literature [5]. Also, the distribution of stress and strain in the specimen was analyzed. Numerical simulation proves to be an extremely efficient means of scientific research, as in this case it substitutes for costly experiments, and due to the fact that the equipment involved in the tests must first be developed.

2. SIMULATED MODEL

Over time, a series of TSHB systems have been designed and built, based on several operating principles, as previously shown. Figure 1 shows the diagram of the first TSHB system proposed by Baker and Yew.

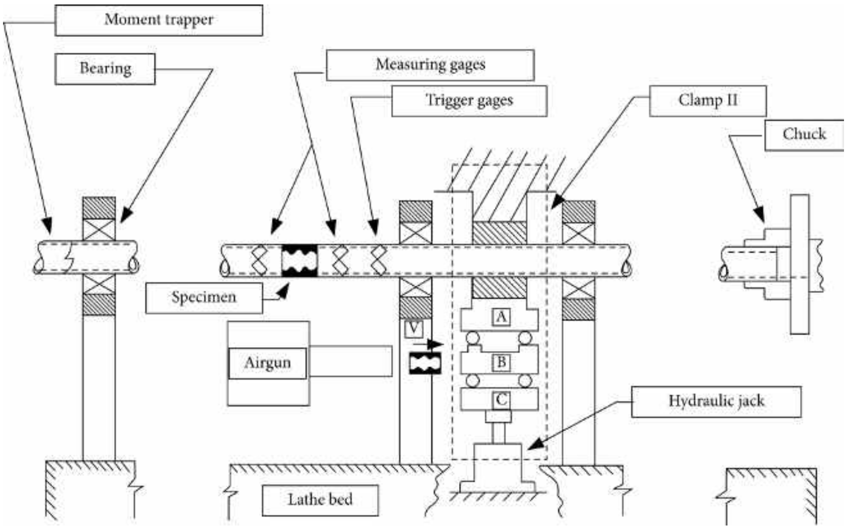

Fig. 1. The first TSHB system designed by Baker and Yew, [3]

Performing an analysis of the structure of multiple systems reveals that there are five basic components [1]:

➢two long bars, one incident and one transmission, with constant cross-sectional area, whose contact surfaces with the sample must be accurately machined;

➢the specimen to be tested, placed between the two long bars in contact with them, usually through cylindrical or hexagonal flanges;

➢a system for loading the incident bar with torsional waves;

➢a system of guidance and alignment of the bars, necessary to ensure coaxial adjustment of the incident bar, the specimen, and the transmission bar to maintain 1D wave propagation conditions;

➢a data acquisition system consisting of strain gauges mounted on both bars, a Wheatstone bridge, signal amplifier, and oscilloscope.

Such a system is schematically presented in Figure 2, as shown in [2].

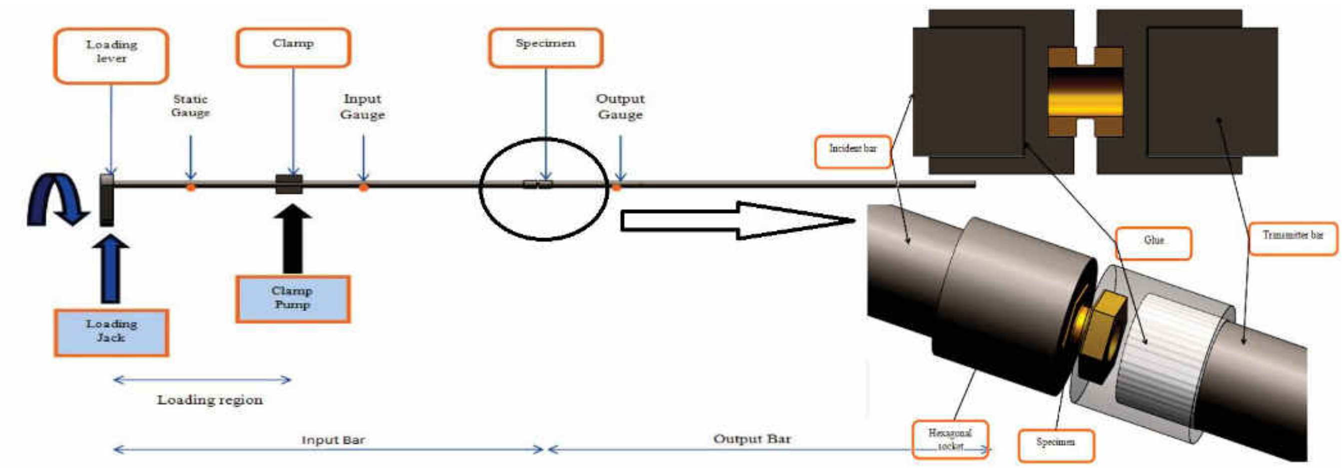

Fig. 2. General presentation of a TSHB system, [2]

A torsional wave is generated in the incident bar by releasing a clamp that delimits the 600 mm initial load zone. This torsional wave will propagate towards the specimen and at the interface between the incident bar and the specimen, part of the wave is reflected back into the incident bar, while another part continues through the specimen and then into the transmitted bar. Thus, during the time the wave travels through the specimen, it undergoes a load at high strain rate. By placing transducers in the incident and transmitted bars, variations in strain over time can be recorded, and the specimen can be dynamically characterized.

According to Kolsky's theory, the values of stress, strain, and strain rate in the specimen can be obtained by measuring the shear strain on the incident and transmitted bars. Thus, the strain rate of the sample can be expressed as a function of time as [6]:

$$\gamma_s(t) = \frac{2 \cdot C_s \cdot D_s}{L_s \cdot D} \cdot \gamma_R(t), \tag{1}$$

in which,

$C_s = \sqrt{\frac{G}{\rho}}$ is shear velocity in the transmitted bar, D_s is the average diameter of the thin wall of the specimen, [mm]; L_s is the gage length of the specimen, [mm]; D is the diameter of the transmitted bar, [mm]; γ_R is the transmitted shear strain at the surface of the transmitted bar; and G, and ρ, are shear modulus and the density of the transmitted bar, respectively.

By integrating relation (1), we obtain the shear strain of the sample:

$$\gamma_s(t) = \frac{2 \cdot C_s \cdot D_s}{L_s \cdot D} \cdot \int_0^t \gamma_R(t) \cdot dt, \tag{2}$$

while the shear stress has the expression:

$$\tau_s(t) = \frac{2 \cdot T_s}{\pi \cdot D_s^2 \cdot t_s}, \tag{3}$$

where t_s is the thickness of the sample wall, [mm]; and T_s is the average torque applied to the sample.

Starting from these considerations, a virtual model of the system was built, as shown in Fig. 3. In the created model, the bars have a diameter of 25mm and a length of 2m, while the HEA material sample is placed between them, in two hexahedral flanges, as presented in the figure below.

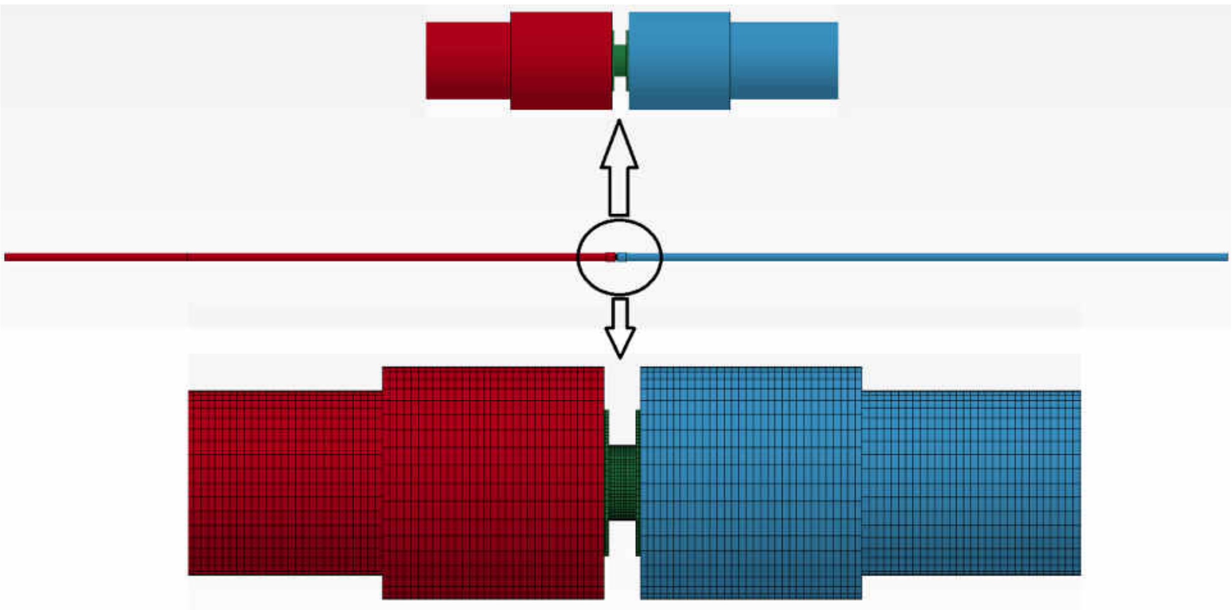

Fig. 3. TSHB virtual model used in numerical simulation

The sample used in the numerical simulation, as shown in Fig. 4, is a cylindrical one with an inner diameter of 9.5 mm and a wall thickness of 0.45 mm. It has two hexagonal flanges with a thickness of 4 mm at each end.

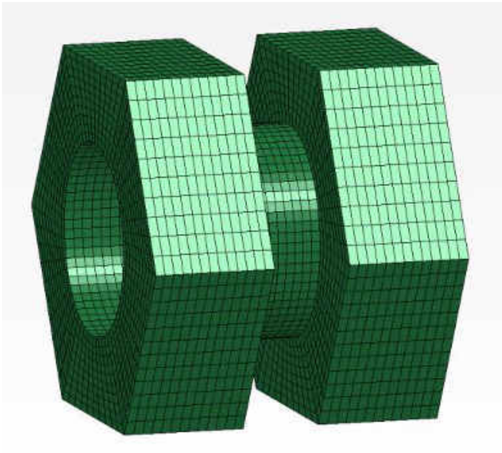

Fig. 4. Sample discretization

The domain discretization was achieved using a structured grid, using a number of 1228152 SOLID type hexahedral elements with 8 nodes, which allow nodal rotations, resulting in a number of 1317100 nodes. Additionally, in order to achieve the torsional loading of the incident bar, two new parts were defined as two sections in the incident bar, which were discretized with a number of 600 Belytschko-Tsay SHELL elements, whose nodes were connected to the corresponding ones of the incident bar. The distance between these two sections is 600 mm, as shown in Fig. 5, and represents the distance over which the bar is torsionally loaded.

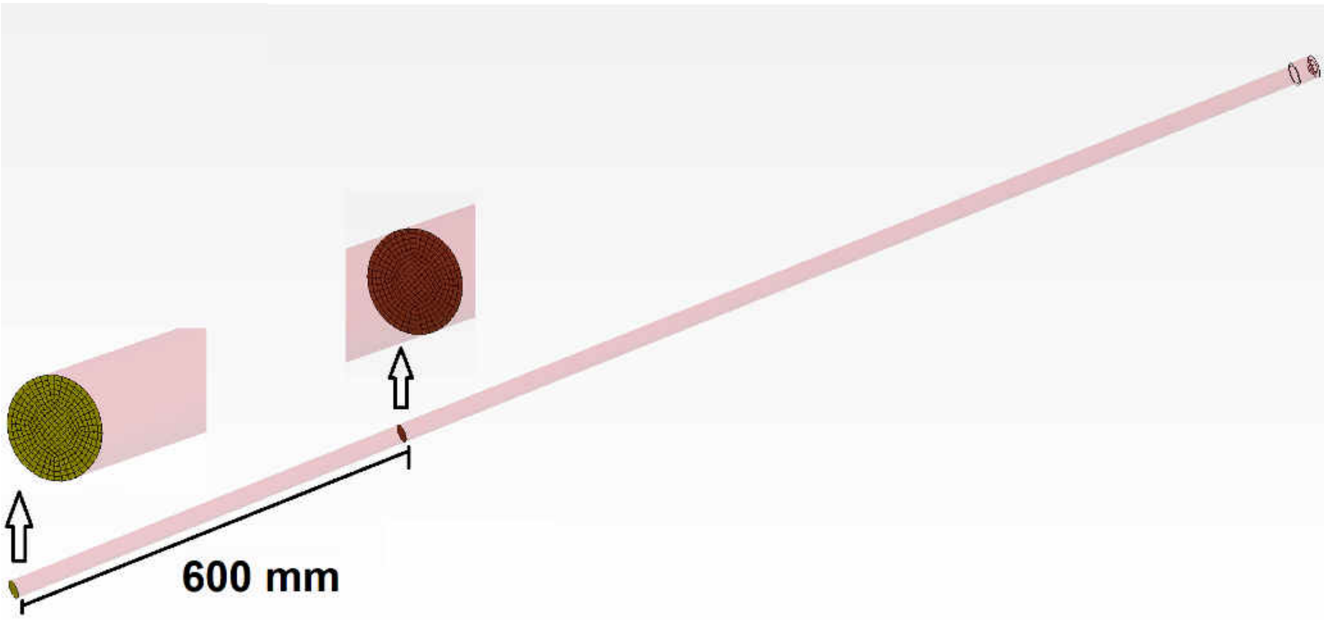

Fig. 5. The arrangement of the two discretized sections using SHELL-type elements

The first defined section plays the role of the loading system for the incident bar, while the second section serves as a fixing clamp.

3. MATERIAL MODELS AND INPUT DATA

The constitutive material models used in the numerical simulation are *MAT_RIGID for the two sections, *MAT_ELASTIC and *MAT_PLASTIC_KINEMATIC for the incident and transmitted bars, respectively. The material constants used for the bars, sample, and the two sections are presented in the table below.

Table 1. Material constants used in numerical simulation

Part	ρ o [kg/m^3]	Young Modulus [MPa]	Poisson's Ratio	Yield Stress [MPa]	Tangent Modulus [MPa]
2 section	7.8500E+3	2.0000E+5	0.30		
2 bars	7.8500E+3	2.0000E+5	0.30		
probe	7.6500E+3	1.9000E+5	0.30	1470	3030

The incident bar is loaded over a distance of 600 mm using the *BOUNDARY_PRESCRIBED_MOTION_RIGID command applied to the first section, for a time interval of 3.5 ms, according to the curve shown in Fig. 6. During this time, the second section is held in place and thus the load is applied to the incident bar only on the region between the two sections. After the loading time, the "clamp" is released by canceling the imposed condition on the second section.

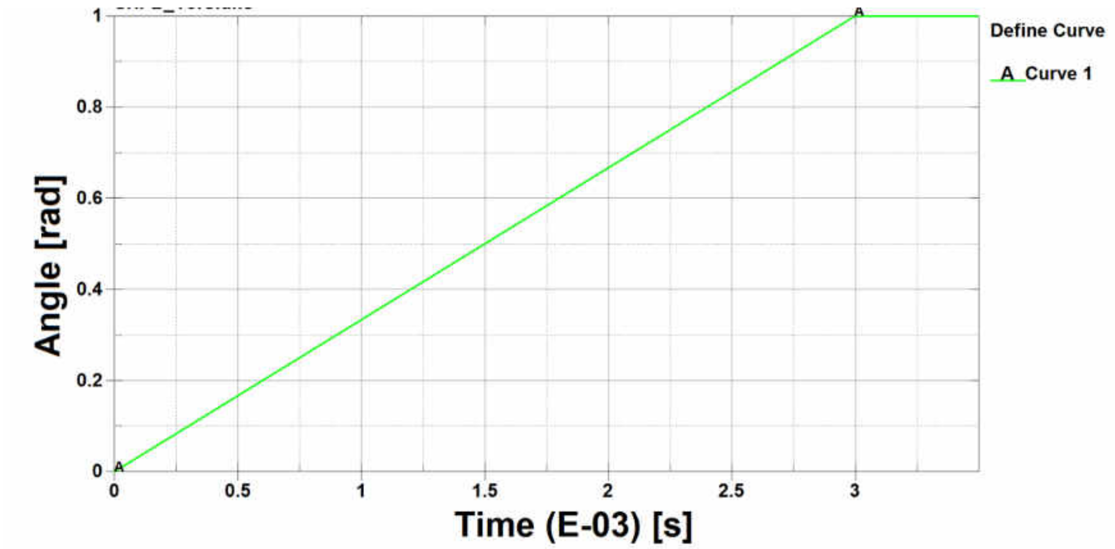

Fig. 6. The torsion loading curve of the delimited portion of the incident bar

As can be seen in the previous figure, after a 3.0 ms load, there is a 0.5 ms period in which the maximum torsion amplitude of the bar is maintained. This was done in order to uniformize the load along the entire length between the two sections.

4. RESULTS AND DISCUSSION

Using virtual transducers placed on the two bars, symmetrically to the specimen, at the middle of two bars, the time variation curves of the shear strain on the incident and transmitted bars were recorded. These are presented in Fig. 7.

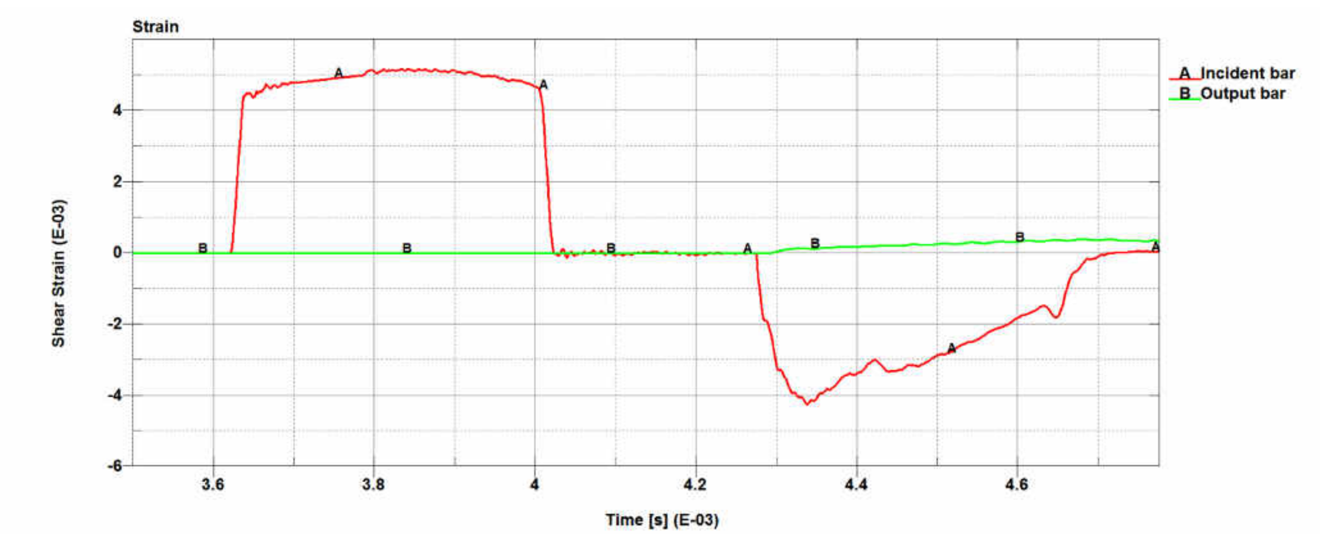

Fig. 7. Shear strain variation curves function of time on two bars

For evaluating the distribution of stress and strain produced during testing, Fig. 8 – 9 present two outlines of the analyzed parameters of the sample at the moment of loading.
Also, as a result of numerical simulation, the variations over time of shear stress and shear strain, as well as the shear stress – shear strain curve in the specimen were obtained, as shown in Fig. 10 – 12.

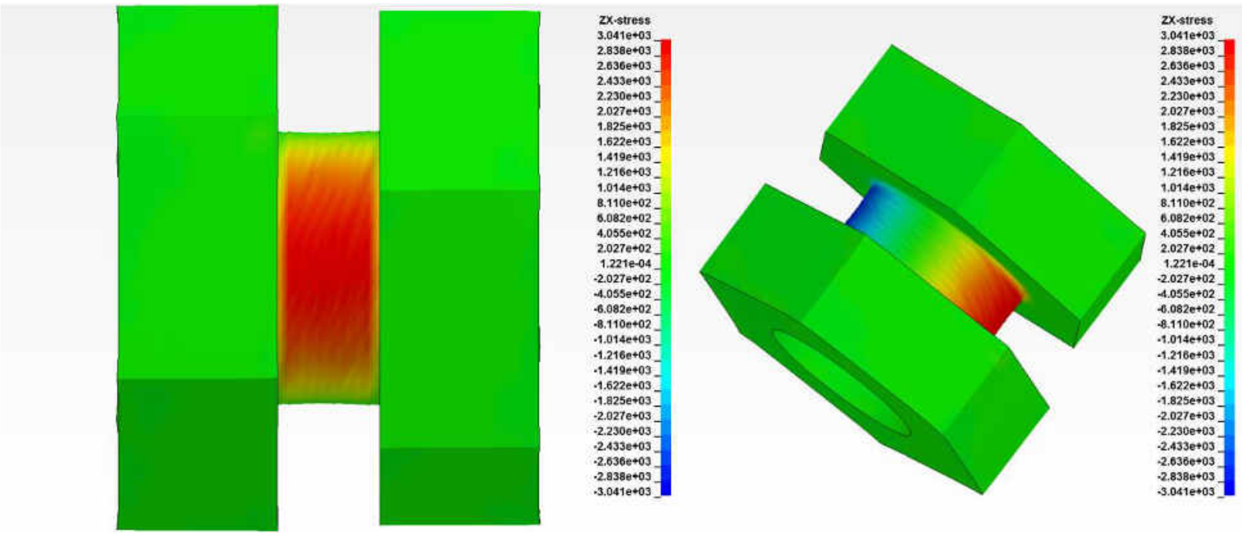

Fig. 8. Conturs of shear stress in the specimen

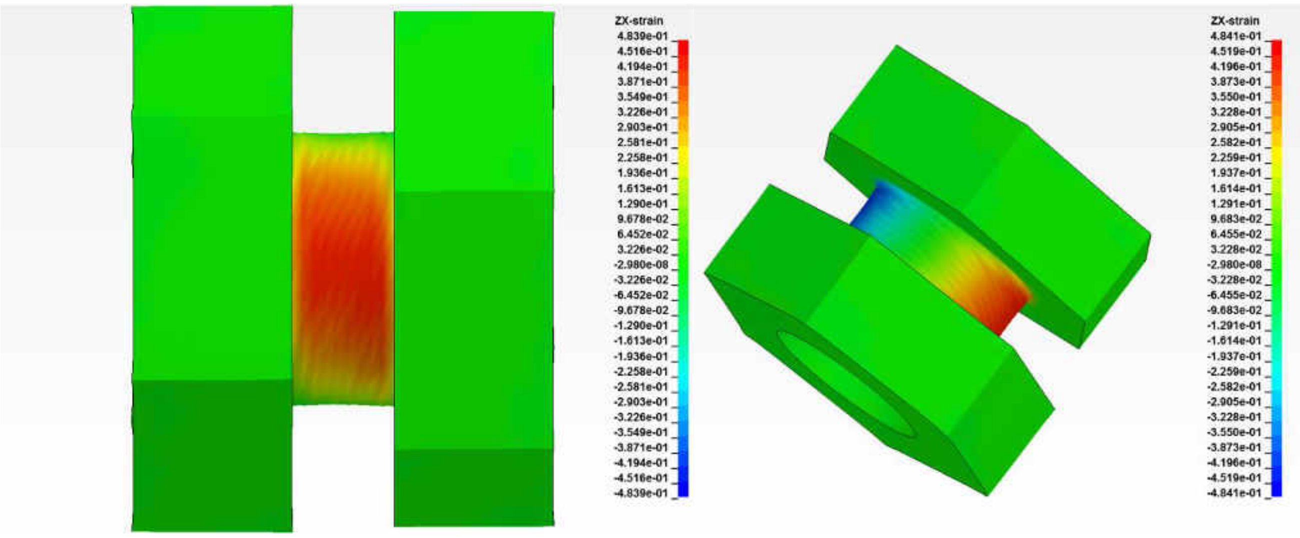

Fig. 9. Conturs of shear strain in the specimen

As can be seen from the above figures, since the specimen is subjected only to torsional loading, the ZX stresses will be one of tension and the other of compression on the two sides of the sample.

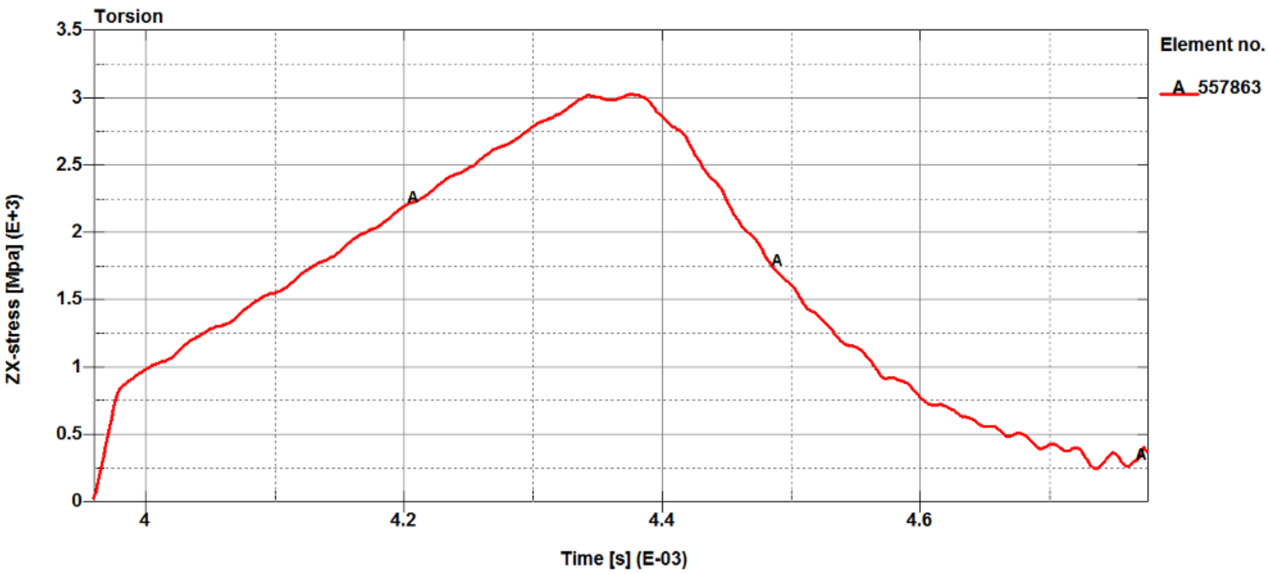

Fig. 10. Shear stress curve vs time in the sample

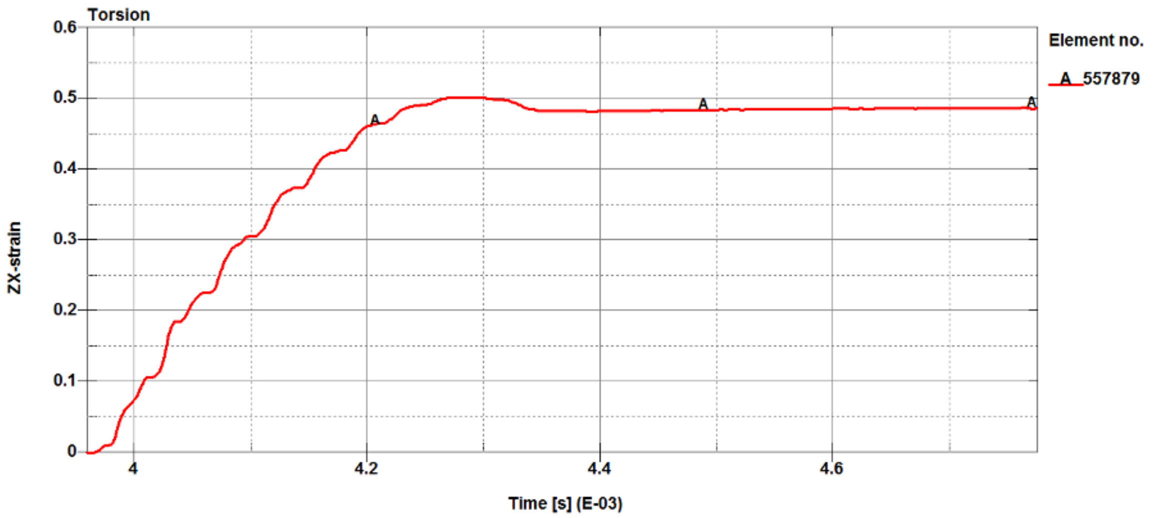

Fig. 11. Shear strain curve vs time in the sample

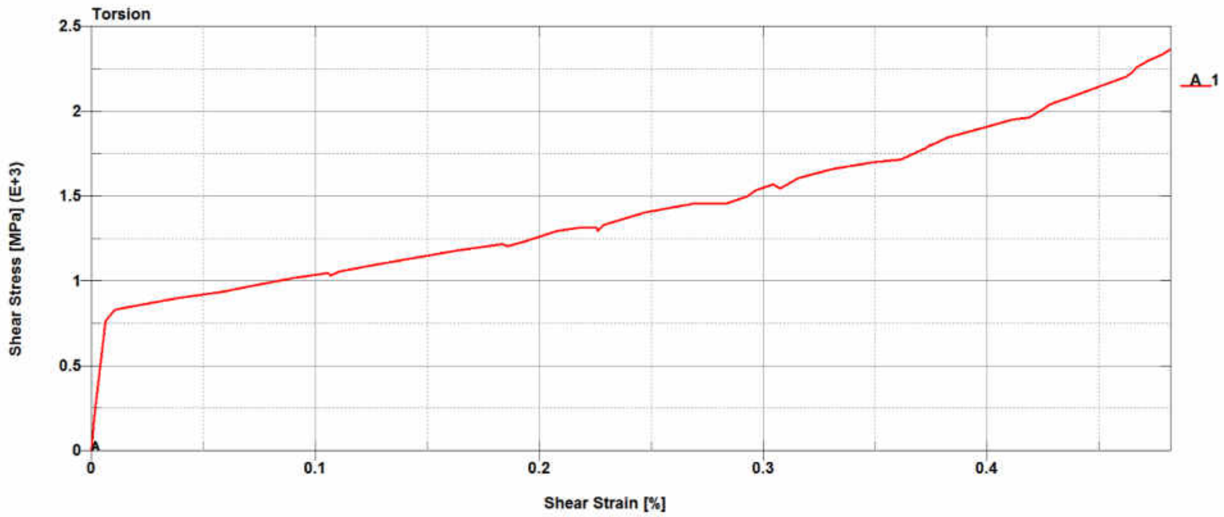

Fig. 12. Shear stress vs shear strain for sample

For comparison, in Fig. 13, the equivalent von Mises stress plots were drawn as a function of the effective strain for the specimen material, obtained one by applying the methodology presented [5] as well as the results of the numerical simulation. As can be seen, the differences are insignificant.

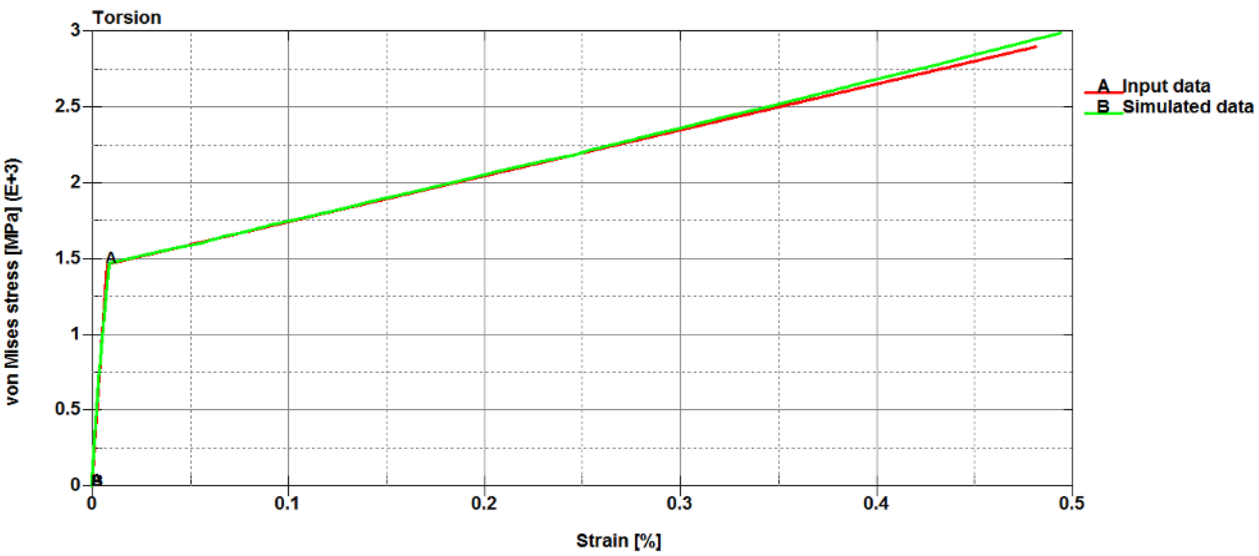

Fig. 13. Von Mises stress – effective strain comparation curves

5. CONCLUSIONS

Numerical simulation of the experimental technique for the Hopkinson Split Torsional (Kolsky) Bar system was performed in order to study the mechanical behavior at high strain rates of high-entropy alloys. For this purpose, a 3D virtual model of the TSHB was built, similar to those existing in the literature, with which a test was carried out on a sample of HEA material. Using an algorithm presented and published by the authors, the material model and constants for the high-entropy alloy from which the sample was made were determined. The shear strain variation curves over time were recorded on the incident and transmitted bars. The theoretical analytical model for obtaining strain, strain rate, and torsional stress of the sample was presented, and the variation curves of shear stress, shear strain over time and shear stress vs shear strain obtained from numerical simulation were plotted.

The model developed can be successfully applied to all materials, for which dynamic characterization is needed, in this case numerical simulation being extremely useful in the design and manufacture of materials and equipment applicable in fields such as military, automotive, machining, construction, and space.

Moreover, a comparison between the equivalent stress-strain curve (von Mises) obtained using Torsional Split Hopkinson Bars and similar results obtained, for example, using Split Hopkinson Pressure Bars under compression can be made.

REFERENCES

1. Yu, X., Chen, L., Fang, Q., Jiang X., Zhou Y., (2018). *A Review of the Torsional Split Hopkinson Bar*, Adv. in Civ. Eng., 1-17.

2. Nicolăescu, G., Ștefan, A., Enache, C., Cîrmaci M., (2015). *Torsional testing at high strain rates using a Kolsky bar*, Revista Academiei Forțelor Terestre, 2(78), 233-242.

3. Baker, W. E., Yew C. H., (1966). *Strain-rate effects in the propagation of torsional plastic waves*, Journal of Applied Mechanics, 33(4), 917.

4. Matache, L.C., Lixandru, P., Chereches, T., Mazuru A., Chereches, D., Geantă, V., Voiculescu, I., Trană E., Rotariu A.N, (2019). *Determination of material constants for high strain rate constitutivemodel of high entropy alloys*, IOP Conf. Series: Materials Science and Engineering, 591.

5. Matache, L.C., Chereches, T., Lixandru, P., Mazuru A., Mitrică D., Trană E., Șomoiag P., Rotariu A.N, (2019), *Determination of a methodology for formulating constituentmodels of high entropy alloys*, IOP Conf. Series: Materials Science and Engineering, 591.

6. Weerasooriya, T., (1990). *The MTL Torsional Split-Hopkinson Bar*, MTL TR 90-27, U.S. Army Materials Technology Laboratory, Watertown.

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