Direct impact split-Hopkinson bar experiment for compression testing at strain rate of 50,000 s^{-1}

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Abstract

A direct impact Hopkinson compression bar experiment is used for compression testing at strain rates in the order of 50,000 s^{-1}. A short specimen mounted on the cross-section surface of a transmitter bar is impacted directly by a projectile (the incident bar in the classical split Hopkinson bar is eliminated). The quantities measured in the test are the projectile impact velocity, the force in the transmitter bar and the strain on the surface of the specimen, which is measured using the digital image correlation method with high-speed cameras. The deformation measurements show a nonuniform deformation in the specimen. To study the strain rate sensitivity properties of the specimen's material, the experiment is simulated using an assumed material model properties which is validated by comparing the calculated and measured quantities. For aluminum 2024-T351 the results show a small strain rate sensitivity (increase of stress with strain rate) at strain rates above 10,000 s^{-1}.

1. Background

The deformation and fracture properties of materials depend on the rates at which they are loaded and deform. Testing of small coupon materials specimens at different strain rates is usually used to study the rate sensitivity. In compression at high strain rates, the Split Hopkinson Pressure Bar (SHPB) technique is most commonly used for testing materials in the strain rate range of 500 s^{-1} to about 5,000 s^{-1}, and the plate impact experiment is typically used for testing at strain rates of 10^5 s^{-1} and higher. In the SHPB test a short material specimen is placed between two bars (incident and transmitter), Kolsky (1949), Gray (2000). A compression wave is generated in the incident bar by impacting the free end of the incident bar with another bar. The incident wave propagates toward the specimen, and once the specimen is loaded a small part of the wave is transmitted through the specimen to the transmitter bar and a large part reflects back to the incident bar. The stress and strain in the bars remain within the elastic limit of the bars' material throughout the test. Using elastic waves theory, the force applied to the specimen and the velocity of cross sections of the incident and transmitter bars that are in contact with the ends of the specimen can be determined from the measured incident, reflected and transmitted stress waves. The engineering strain rate in the specimen is determined by dividing the difference in the particle velocity between the incident and transmitter bars' interfaces that are in contact with the specimen by the initial length of the specimen. The strain is calculated by integration of the strain rate. The engineering strain rate and strain that are determined by the waves analysis are average values based on the assumption of uniform deformation along the specimen. The deformation of the specimen can also be measured directly on the specimen's surface using the Digital Image Correlation (DIC) technique with high-speed cameras. The assumption of uniform deformation in the specimen during a SHPB test have been studied extensively over the years. In tests with ductile materials, that typically last a few hundreds of microseconds, the specimen deforms under a nearly uniform uniaxial state of stress and deformation except for the first few microseconds. This means that the measured stress and strain can be directly used for plotting the stress strain curve that characterizes the material response of the specimen. The strain rate in the specimen depends on the specimen length, the force required to deform the specimen, the properties of the bars, and the amplitude of the incident wave. For a given setup (specimen and bars properties and dimensions), the maximum possible strain rate is limited by the elastic properties of the incident bar, since the amplitude of the stress waves in the incident bar cannot exceed the yield stress of the bar's material. The maximum strain rate in a typical SHPB setup is in the range of 7,000 s^{-1}, Couque (2014).

To achieve higher strain rates, the standard SHPB setup has been modified by removing the incident bar and impacting the specimen directly by the projectile. This eliminates the restriction imposed on the stain rate by the limit on the amplitude of the wave in the incident bar. Dharan and Hauser (1970) used a large diameter projectile to directly impact specimens with different lengths mounted on a much smaller diameter transmitter bar at velocities ranging from 100 to 1,000 ft/s. Their results are presented in plots of stress versus strain rates, in the range of 10^4 s^{-1} to 10^5 s^{-1}, at different strains. With a similar setup Couque (2014) used a projectile with the same diameter as the transmitter bat to impact specimens at a speed of 50 m/s. Results are presented in the form of a stress strain curve at strain rate of the order of 2×10^4 s^{-1}. In both references uniform deformation in the specimen is assumed, and the engineering strain rate and strain are calculated from the difference between the projectile velocity and the particle velocity at the contact surface of the specimen and the transmitter bar. A direct impact of a specimen mounted on a bar at a velocity of 100 m/s was also used by Gorham (1979). In this project an optical system with a high-speed visual camera was used to record the deformation. The stress was determined from the transmitted wave and strain was determined from measuring the radial expansion in the recorded optical images. The images also showed that the specimen deformation is not uniform. A stress strain curve at a strain rate of 4×10^4 s^{-1} is presented. Theoretically, there is no limit to the strain rate in the direct impact test, since the projectile can be shot at any speed. However, it cannot be expected that the specimen will deform under a uniform state of uniaxial stress during tests when the strain rates exceed 10^4 s^{-1}. At these high strain rates, the duration of the test is of the same order of magnitude as the time that it take for the waves to traverse the specimen. (e.g., at strain rate of 5×10^4 s^{-1} is takes 4 μs for 20% deformation.) This means that a stress strain curve that is obtained from the force measure in the transmitter bar and the average engineering strain does not represent the specimen material properties accurately, and a more advanced analysis of the experiment is required in order to obtain the correct material properties.

The present paper takes advantage of the availability nowadays of high quality high-speed digital cameras and the DIC technique for measuring the deformation directly on the surface of the specimen. This provides new means for analyzing the Direct Impact Hopkinson Pressure Bar (DIHPB) experiment. In the current paper it is done by impacting a 10 mm long specimen attached to a transmitter bar with a projectile at an impact velocity of about 200 m/s, which corresponds to an average engineering stain rate of 2×10^4 s^{-1}. High-speed DIC strain measurements at a rate of two million frame per second (a frame every 0.5 μs) show non-uniform deformation along the specimen throughout the test. To study the strain rate sensitivity properties of the specimen material, the experiment is simulated by assuming a strain rate sensitive material model. The assumed constitutive equations are validated by comparing the measured and calculated strain distribution and force in the specimen.

2. Experimental setup

A schematic of the experimental setup is shown in Figure 1. It consists of a small specimen positioned on the cross-sectional surface of a short transmitter bar that is placed inside a vacuum chamber. The specimen is impacted directly by a projectile that is shot from a gun at velocity of 200-300 m/s. The experiment resembles the compression split Hopkinson bar (SHB) technique, except that the incident bar of the traditional SHB technique is eliminated and the specimen is impacted directly by the projectile. This provides means for deforming the specimen at strain rates that are one-order of magnitude higher than the highest typical strain rate in a traditional SHB test. The quantities measured during a test are the impact velocity, the force on the specimen at the contact surface with the transmitter bar (measured by strain gages that are placed on the transmitter bar), and full field deformation on the specimen's surface using the Digital Image Correlation (DIC) technique with high-speed cameras. The actual setup of the experiment, that were carried out at NASA Glenn Ballistic Impacts Laboratory, is shown in Figure 2. The 304.8 mm long transmitter bar and a 50.8 mm long projectile (not shown in the photos) are both 12.5 mm diameter round titanium 6Al-4V bars. Tungsten carbide inserts are placed on the ends of the projectile and transmitter bar that are in contact with the specimen to prevent localized plastic deformation of the titanium at these interfaces during the test. The force that the specimen applies to the transmitter bar is measured by two strain gages that are placed on the transmitter bar on opposite sides. The transmitter bar remains within the elastic limit during the test. The strain gages are placed at a distance of 100 mm from the specimen. This provides a duration of about 80 μs during which the force can be measured (before the arrival of the reflected wave from the free end of the transmitter bar). The projectile is placed inside a sabot that is shot with a 50.8 mm diameter gun toward the specimen.

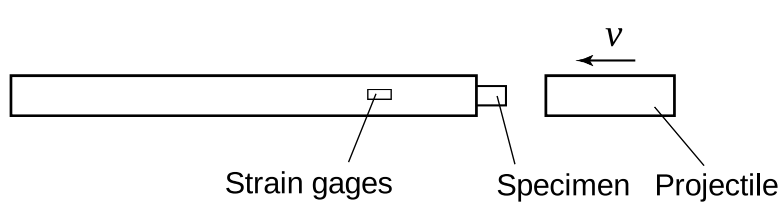

Figure 1: Schematic of the experimental setup.

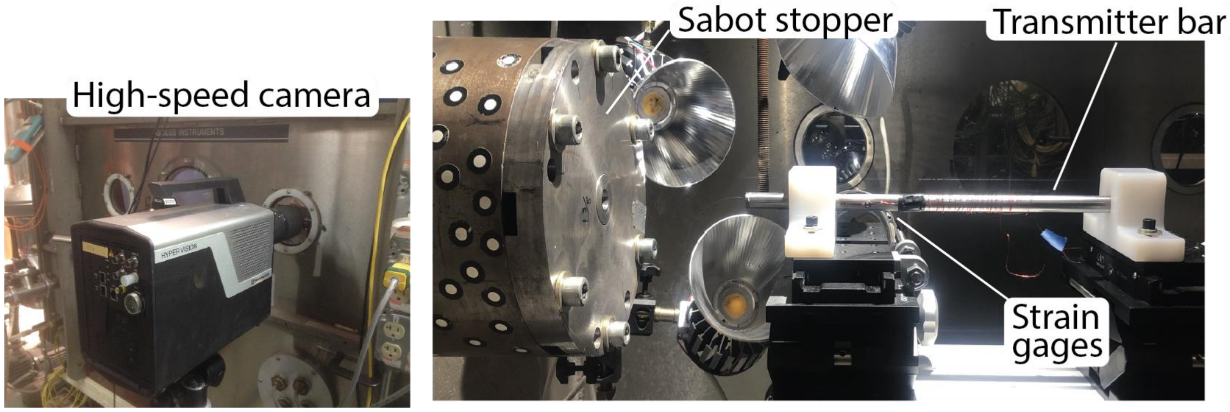

Figure 2: Experimental setup.

3. Results

Tests have been performed with specimens made of 2024-T351 aluminum. The specimens are 5.08 mm diameter cylinders, 10.16 mm long, machined from a 12.7 mm thick plate stock. The projectile impact velocity is 220 m/s. A series of five DIC images of the axial strain recorded in a test are displayed in Figure 3. The images, recorded at a rate of two million frames per second, show the arrival of the compression wave at the impact face on the right, and propagation of the wave toward the transmitter bar on the left during the first 2 μs. In the first image at $t = 0$ μs the strain is zero. At 1 μs the front of the wave is at the midpoint of the specimen, and at $t = 2$ μs the front of the wave is near the end of the specimen that is in contact with the transmitter bar. This corresponds well with the elastic bar wave speed of about 5,000 m/s. The DIC image at $t = 2$ μs shows a non-uniform strain distribution along the specimen length where the strain near the transmitter bar end is about zero and near the impact face (up to where a valid DIC measurement is available) is about 5%. Larger strain can be visually observed very close to the impact face where DIC data is not available. The average engineering strain rate in the specimen throughout the test is about 20,000 s^{-1}. A local strain rate of 50,000 s^{-1} can be estimated from the DIC image at $t = 1$ μs at points where 5% strain is accumulated during the first 1 μs. The nonuniform deformation in the specimen continues throughout the test. Figure 4 shows six additional images from the same test. The time interval between the images is 4 μs with the last image at $t = 20$ μs. Starting at $t = 8$ μs (or possibly even at $t = 4$ μs) the images show that the specimen fractures near the impact end. As the test continues, at $t = 12$ μs, the strain over a large area at the left half of the specimen is 0.2 and a large area at the right half of the specimen is fractured. The next two frames at $t = 16$ μs and $t = 20$ μs show progression of the fracture and no DIC data since the paint speckle detaches from the surface. The nonuniform deformation and fracture that is observed in the images in Figures 3 and 4 indicate that, from a continuum point of view, the experiment cannot be analyzed in the same way as a standard split Hopkinson bar test. A standard split Hopkinson bar test typically lasts 100-200 μs and, except for the first few microseconds, the deformation in the specimen is uniform. In the current direct impact test useful information about the plasticity and fracture properties of the material tested can, however, be obtained by numerically simulating the experiment. Material properties (strain rate sensitivity, strain hardening, thermal softening, etc.)

are assumed in the material model of the numerical code, and then can be validated by comparing the calculated and measured data.

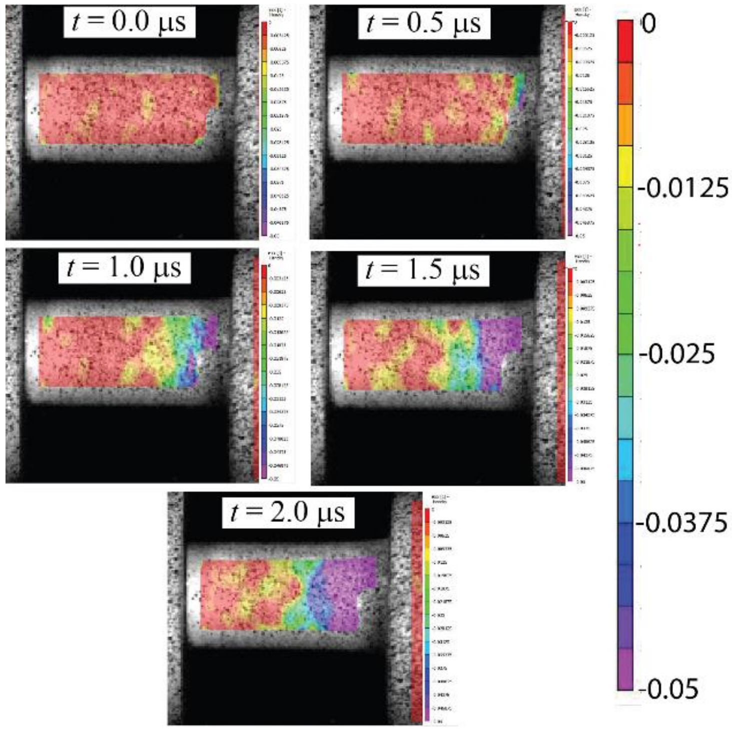

Figure 3: Compressive strain in a 10.16 mm long aluminum specimen during the first 2 μs of the test.

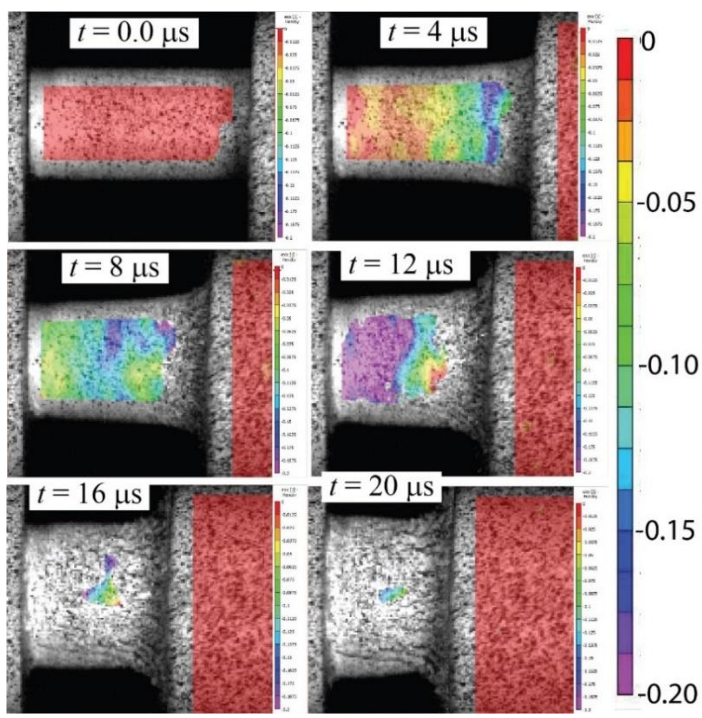

Figure 4: Compressive strain in a 10.16 mm long aluminum specimen during the first 20 μs of the test.

Finite Element Analysis (FEA) of the experiments is done using the software LS-DYNA. All the components, shown in Figure 5, are meshed using 0.25mm cubic solid elements. The impactor and associated end cap are given an initial velocity matching the velocity measured in the experiments. Friction is not considered, as the specimen contact interfaces are lubricated during the experiments. The projectile and transmitter bar, which are made of titanium 6Al-4V, and the tungsten-carbide end caps affixed to the end of the impactor and transmitter bar are modeled as elastic-perfectly plastic materials since their stresses do not exceed the yield stress until after the test has been completed. The elastic modulus and yield stress for the titanium and tungsten carbide are E =110 GPa, $\sigma_y = 980$ MPa and $E = 670$ GPa, $\sigma_y = 4$ GPa, respectively. The specimen is modeled using LS-DYNA material model MAT224, a tabulated plasticity and fracture model that allows for direct entry of true stress vs true plastic strain curves at various strain rates and temperatures [LS-DYNA, 2021]. The stress strain curves, at different strain rates, that are entered for the 2024 aluminum are displayed in Figure 6. The curves up to a strain rate of 5,000 s^{-1} are from uniaxial testing. The curves at higher strain rates are assumed and calibrated such that simulations of projectile impact on aluminum pates with the model agreed with experimental measurements. The assumed strain rate sensitivity of the aluminum in the simulation is also shown in Figure 7 where the stress at 10% strain versus strain rate is displayed. The fracture proces is not included in the simulation.

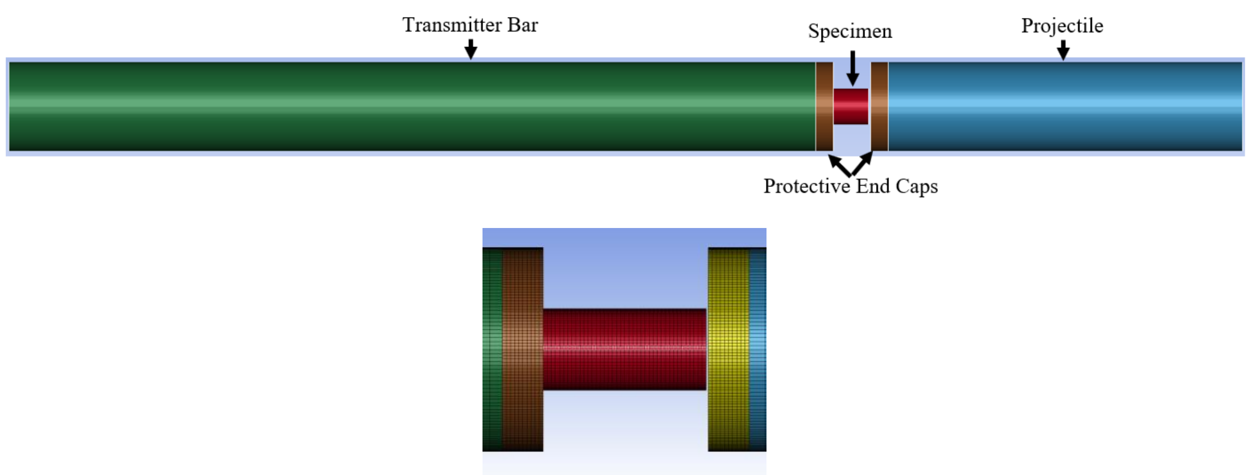

Figure 5: LS-DYNA FEA model of 220 m/s direct impact experiments.

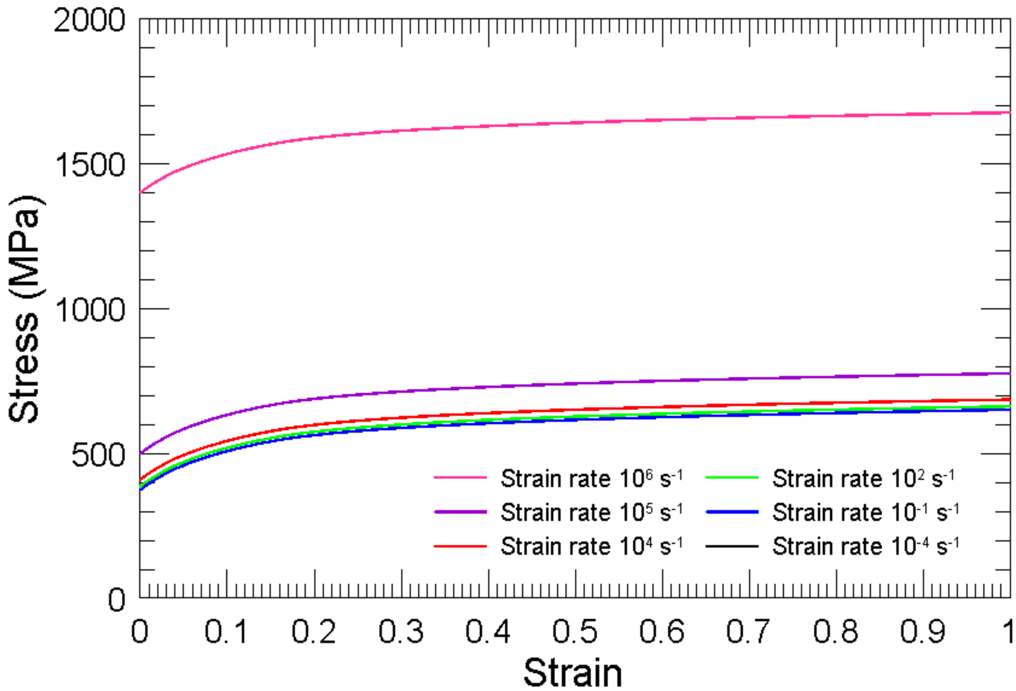

Figure 6: Numerical model stress strain curves at different strain rates, aluminum 2024-T351.

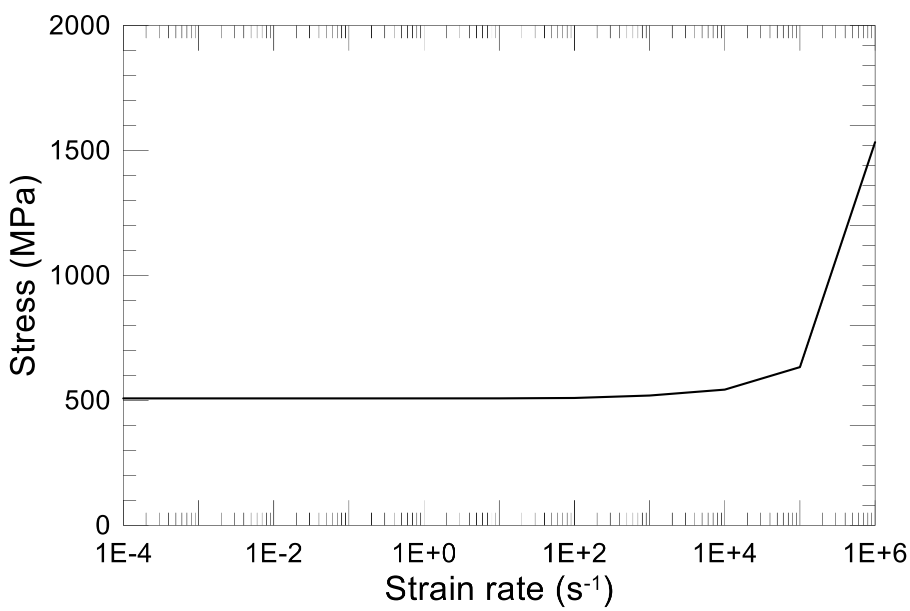

Figure 7: Numerical model stress vs strain rate at 10% strain, aluminum 2024-T351.

A comparison of the simulations with the experiment is made by examining the strain in the specimen and the force in the transmitter bar. Figure 8 shows the measured and calculated axial strains along the specimen center line at 2, 4, 6, and 5 μs. In the portion of the specimen that the DIC measurements are available there is a good agreement between the measured and calculated strains. At 2 μs there is a valid strain measurement along most of the specimen's length. As the test progresses the section that has a reliable strain measurement gets shorter since a larger portion of the specimen on the impacted right side of the specimen undergoes large deformation and fracture. Since fracture is not included in the simulations, the simulated strain curves continue into the fracture zone. The strain rate at which different point along the specimen deforms can be estimated by dividing the maximum strain measured by the time. Strain rates values of 20,000 s^{-1} to 45,000 s^{-1} are obtained.

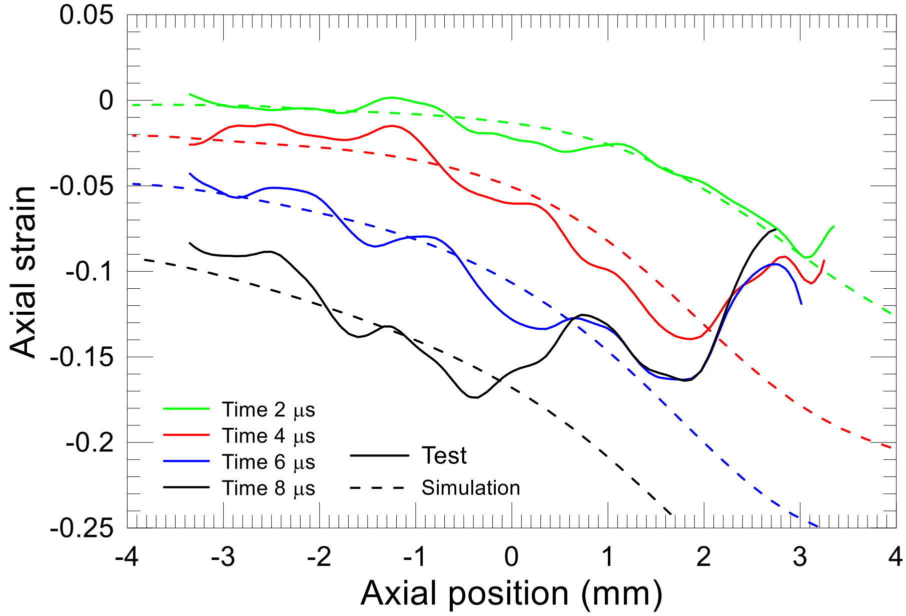

Figure 8: Measured and calculated strain along the specimen center line.

The measured and calculated force history at the strain gage location in the transmitter bar are shown in Figure 9. The calculation is limited to the first 15 μs since fracture is not included in the simulation. Good agreement is observed.

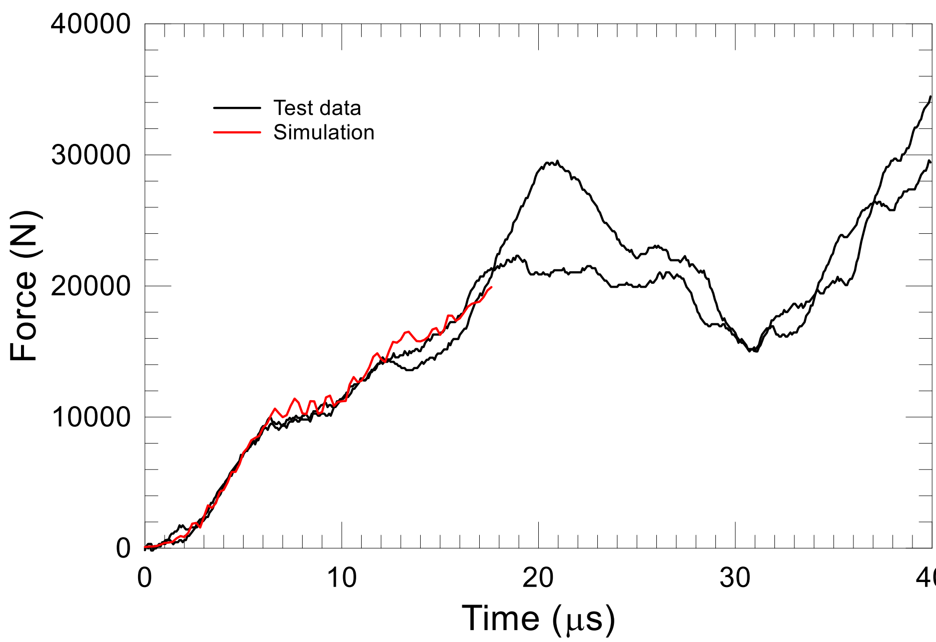

Figure 9: Measured and calculated force on the transmitter bar.

The agreement between the calculated and measured strain in the specimen and force in the transmitter bar indicates that the material model in the simulation represents well the properties of aluminum 2024-T351 in the strain rate range of 10,000 s^{-1} to 50,000 s^{-1} that the material experience in the experiment. The assumed material response in Figures 6 and 7 show essentially no strain rate sensitivity up to a strain rate of 5,000 s^{-1}, and then a small strain rate sensitivity (increase in stress with increasing strain rate) up to a strain rate of 10^5 s^{-1}. This is followed by a significant increase in strain rate sensitivity with very large increase in stress at higher strain rates. It should be pointed out that data for other materials (e.g., titanium) show that the significant increase in strain rate sensitivity starts at lower strain rates.

4. Conclusions

A modified direct split Hopkinson compression bar test in which the incident bar is removed, and the specimen is impacted directly by a projectile is used for testing at strain rates in the range of 50,000 s^{-1}. The measured quantities in the test are the projectile speed, the strain directly on the specimen surface with the DIC, and the force transmitted to the transmitter bar. Result from testing a 10 mm long aluminum 2024-T351 specimens shows that the deformation throughout the test is not uniform, and the test cannot be analyzed in the same way as a standard split Hopkison bar test. The properties of the material tested are studied by numerically simulating the experiment, assuming material properties, and comparing the simulated and measured quantities. For the 2024-T351 aluminum tested, the strain in the specimen and the force in the transmitter bar are predicted well by the simulation that uses a material model that assumes a small increase in stress at strain rates in the range of 10,000 s^{-1} to 50,000 s^{-1}, compares to the stress at quasi-static strain rates.

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6. References

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