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Ramzi Othman, Gérard Gary

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# Testing Aluminum Alloy from Quasi-static to Dynamic Strain-rates with a Modified Split Hopkinson Bar Method

R. Othman · G. Gary

**Abstract** An aluminum alloy<sup>1</sup> was tested at quasi-static to dynamic strain-rates (from  $10^{-1}$  to  $5 \cdot 10^3 \text{ s}^{-1}$ ), using a single measuring device, a modified Split Hopkinson Bar. A wave separation technique [Bussac et al., J Mech Phys Solids 50:321–350, 2002] based on the maximum likelihood method was applied to process the strain and velocity measurements recorded at various points on each bar. With this method, it is possible to compute the stress, strain, displacement and velocity at any point on the bar. Since the measurement time is unlimited, the maximum strain measured in a given specimen no longer decreases with the strain-rate, as occurs with the classical Split Hopkinson Bar method.

**Keywords** Split Hopkinson Bar · Medium strain-rates · Wave separation · Aluminum

## Introduction

The Split Hopkinson Bar method involves the use of two bars to measure the force and the velocity at the interfaces between the ends of the bars and the specimen tested. For

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<sup>1</sup>The authors wish to thank the automobile manufacturer who provided samples of the alloy used in this study. For reasons of commercial and industrial confidentiality, we were not informed about the composition of this alloy.

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R. Othman (✉) · G. Gary  
Laboratoire de Mécanique des Solides, Ecole Polytechnique,  
91128 Palaiseau, France  
e-mail: ramzi.othman@ec-nantes.fr

R. Othman  
Institut de Recherche en Génie Civil, Ecole Centrale de Nantes,  
1 Rue de la Noë BP 92101,  
44321 Nantes Cedex 3, France

this purpose, it is necessary to assess the two elementary waves propagating in opposite directions, at the ends of the bars. In the classical configuration, which was developed by Kolsky [1], a gauge is cemented in the middle of the incident bar and the maximum length ( $l$ ) of the striker is limited to half the length of the bar so that the incident wave is recorded before the reflected wave reaches the gauge. The loading time is equal to the time required by the wave to do a return trip in the striker. The problem is simpler in the case of the second bar (the output bar), as one only has to deal with one wave. The gauge is cemented closer to the bar/specimen interface. The remaining distance, which is equal to half the length of the input bar ( $=l$ ), is long enough to delay the return of the output wave until after the end of the recording in the input bar.

The loading time  $\Delta t$  (the pulse duration) is equal to the time required by the wave to do a return trip in the striker. The maximum strain measured in the specimen is proportional to the pulse duration and to the average strain-rate occurring during the test:  $\epsilon^{\max} = \dot{\epsilon}_m \Delta t$ . The maximum strain measured in the specimen therefore decreases with the strain-rate. In the case of a conventional 3 m-aluminum input bar such as that used in this study, the duration of the test is approximately 500  $\mu\text{s}$ . When tests are carried out at medium strain-rates, the maximum strain measured in the specimen amounts to only a few percent and can be less than 1%, which means that it is impossible in most cases to investigate the non-elastic behavior of the materials of interest. There is therefore no point in carrying out tests with a Split Hopkinson Bar apparatus at medium strain-rates (1–100/s).

To perform medium strain-rate tests using a Split Hopkinson Bar, it is necessary to increase the useful measuring time (and hence the loading time). The main problem which arises is how to separate the two elementary

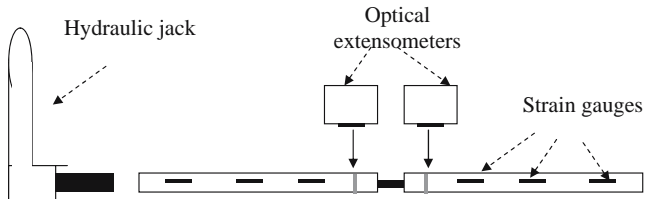


Fig. 1 Simplified scheme of the *slow bar* set-up

waves without giving rise to any time constraints. Some authors [2–10] have carried out two measurements on each bar. The pioneers in this respect were Lundberg & Henchoz [2] and Yanagihara [3], who independently developed a wave separation technique based on one-dimensional wave propagation theory. This method did not take the wave dispersion into account, and many attempts have since been made to develop methods also accounting for this parameter [4–10]. However, most of the solutions proposed so far require two measurements to be performed on each bar. Jacquelin and Hamelin [7] and Bussac et al. [12] investigated the effects of the noise recorded on the reconstituted force and velocity. They showed that two-measurement wave separation methods are sensitive to the noise. A wave separation technique based on redundant measurements (more than two) has been proposed by Othman et al. [11] and Bussac et al. [12]. In line with Jacquelin and Hamelin [13], this method will be subsequently called the BCGO method. It is based on the Maximum Likelihood approach. This method is highly insensitive to noise. Jacquelin & Hamelin [13] have developed an alternative three-point wave separation technique which is also insensitive to noise. In the latter method, the gauges were cemented to specific points and the force was calculated at one bar end (which is the only point where it can be calculated).

Jacquelin & Hamelin [13] have also stated that the BCGO method is less sensitive to noise [13] than their own method.

In the present study, the BCGO method was applied to the analysis of Split Hopkinson Bar tests, and the rate sensitivity of the aluminum was assessed in a wide range of strain-rates (from  $10^{-1}$  to  $5 \cdot 10^3 \text{ s}^{-1}$ ).

### Wave Separation: The BCGO Method

In this section, the BCGO method is briefly presented. For a more detailed description of the method, readers can refer to Bussac et al. 2002 [12].

Let us consider an elastic or viscoelastic bar. In the case of single-mode propagating longitudinal waves, the Fourier transforms of the stress, strain, displacement and velocity are expressed in terms of four functions : the forward wave  $A(\omega)$ , the downward wave  $B(\omega)$ , the complex wave number  $\xi(\omega) = k(\omega) + i\alpha(\omega)$  and the complex Young's modulus  $E^*(\omega)$ . Therefore, strain, stress, displacement and particle velocity can be obtained at any point on the bar if the following four parameters are known:  $\xi(\omega)$ ,  $E^*(\omega)$ ,  $A(\omega)$  and  $B(\omega)$ .

The two parameters  $E^*(\omega)$  and  $\xi(\omega)$  depend only on the bar characteristics (its geometry and material). They only need to be determined once. Here we used the method previously developed by Othman et al. [14, 15]. With this method, the wave dispersion is deduced directly from the spectral resonances of the strain recorded in the middle of a free-ended bar. The complex Young's modulus is deduced from the dispersion relation by inverting the Pochhammer [16]-Chree [17] equation, which was extended by Zhao & Gary [18] for dealing with the linear viscoelastic case.

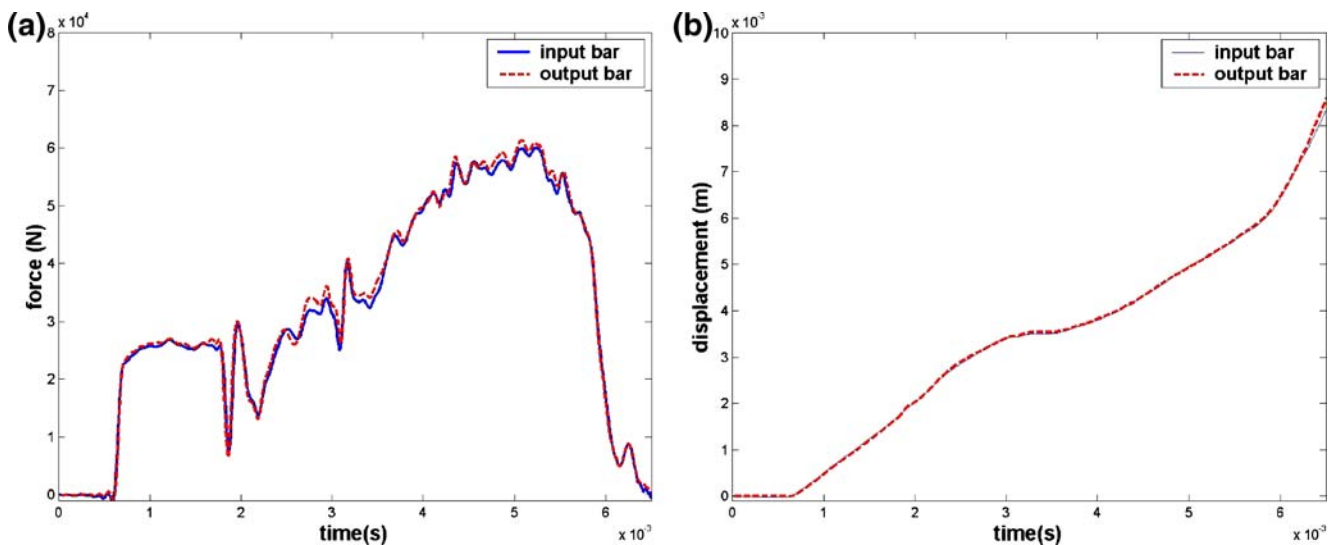


Fig. 2 (a) Forces calculated at the bar/bar interface. (b) Displacements calculated at the bar/bar interface

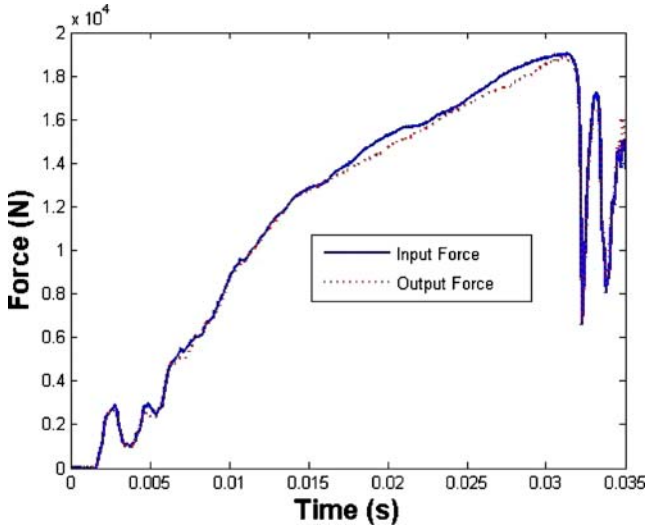


Fig. 3 Force equilibrium

In what follows,  $\xi(\omega)$  and  $E^*(\omega)$  are therefore assumed to be known.  $A(\omega)$  and  $B(\omega)$  are calculated based on the data obtained by performing three strain measurements and one velocity measurement. We express the fact that the signals recorded are noisy by writing that they are the sum of the exact value of the strain (or the velocity) and an unknown noise. The statistical distribution of the noise is assumed to be Gaussian. Consequently, the Maximum Likelihood Method can be used to estimate the two functions  $A(\omega)$  and  $B(\omega)$ . This consists in writing that the signals measured correspond to the most probable event. Our problem is therefore equivalent to the minimization of a functional: this minimization yields an explicit formula for  $A(\omega)$  and  $B(\omega)$ . By applying the BCGO method to each of the bars, it is then possible to assess the force and the velocity at the two bar/specimen interfaces.

## Measurement of the Material Behavior

### Experimental Set-up

In this section, it is proposed to explore the strain-rate sensitivity of aluminum. The behavior of this material is explored under a large range of strain-rate conditions, namely under quasi-static, medium and high strain-rates. In the high strain-rate tests, the classical time domain approach corresponding to the Split Hopkinson Bar (also called the Kolsky bar) method was used. In the quasi-static and medium strain-rate tests, the new method involving the use of extra sensors on the SHPB was adopted, as explained above. In this range of strain-rate tests, low velocity loading was required. The kinetic energy of a striker would not suffice to induce large strains in the specimen, and longer loading durations were required. The bar system was therefore loaded using a hydraulic actuator of the kind first introduced by Zhao & Gary [4]. Low loading speeds (of less than 0.1 m/s) can be monitored and automatically kept constant throughout the test. At higher speeds of up to 5 m/s, the requisite value is maintained approximately constant during the test. The new apparatus is called the “slow bar” apparatus. In the present case, three strain gauges and an optical displacement extensometer were used on each bar. The derivative of the displacement was then calculated numerically to obtain the velocity. A simplified scheme is presented in Fig. 1. Aluminum bars 40 mm in diameter and 3 m in length were used in these tests on the strain-sensitivity of the aluminum. Visco-elastic bars can also be used to carry out tests on low-impedance materials.

Both the Hopkinson bar and “slow bar” apparatus give force and displacement measurements at the two bar/specimen interfaces. To determine the behavior of the material, we assume the stress to be homogeneous in the specimens. This

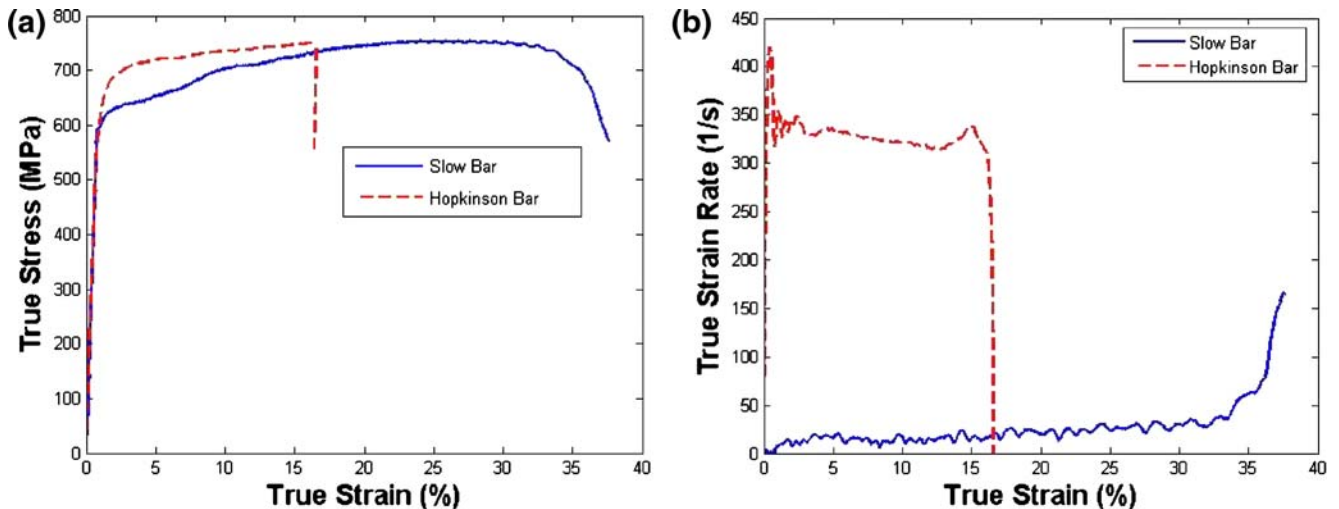


Fig. 4 (a) True stress/true strain relations. (b) True strain-rate/true strain relations

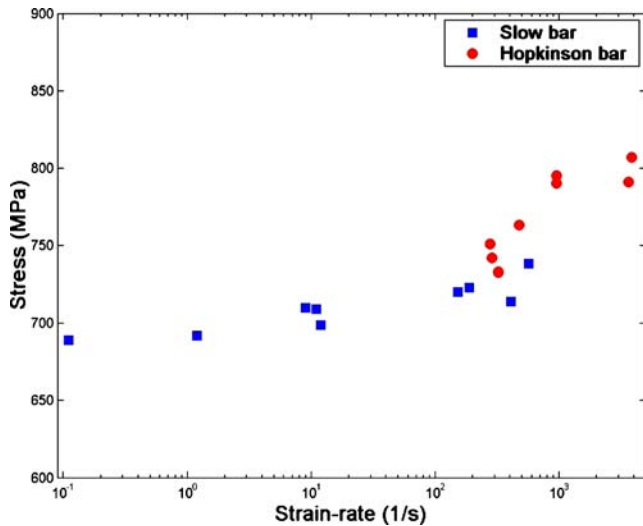


Fig. 5 Strain-rate sensitivity of aluminum

assumption was systematically checked in the case of the “slow bar” technique and SHPB by making sure that the forces measured in the bars on each side of the specimen were practically equal. As was to be expected, it was observed that the smaller the loading rate, the more exactly this condition (called equilibrium) was fulfilled.

#### A Bar/Bar Test Check

To check the consistency of the complete system (as well as testing the accuracy of the BCGO method), a bar/bar test was carried out, in which the two bars were put in contact without placing a specimen between them. The force and the displacement were computed at the bar/bar interface in two independent ways, using the measurements obtained on each bar separately and checking whether the two results obtained were equal. The forces and displacements calculated at bar ends are compared in Figs. 2(a) and (b), respectively. In the present example, the velocity of the hydraulic jack was set at 1.5 m/s. The results of computations made on each bar were almost equal, as was to be expected (with the bars in contact).

#### Aluminum Characterization

In the “slow bar” tests, the specimens used were 6 mm in length and 6 mm in diameter. The velocity of the hydraulic jack ranged from  $2 \cdot 10^{-4}$  to 2.5 m/s. The strain-rate ranged approximately from  $10^{-1}$  on to 400/s. In Hopkinson bar tests, the specimen geometry and the striker impact velocity have to be adapted to the strain-rates, which range approximately from 150 to 5,000/s. In each test, the assumption that the force equilibrium conditions were satisfied between the two bar/specimen interfaces was

checked. An example of a force equilibrium check is given in Fig. 3 in the case of a slow bars test. The forces dropped suddenly at approximately 0.032 s because the specimen failed at that point.

Assuming (as well as checking) that the equilibrium conditions were satisfied, the stresses, strains and strain-rates were obtained from these measurements. True stress-strain and strain-rate relations are given in Figs. 4a, b. It can also be noted that the duration of the tests increased considerably when using “slow bar” apparatus, reaching several seconds, in comparison with the usual duration of 500  $\mu$ s in the case of the classical Hopkinson bar tests carried out on the same bars.

The results of the aluminum test show that this material is only slightly sensitive to the strain-rate. In Fig. 5, the changes in the stress corresponding to a 10% strain level were plotted versus the strain-rate corresponding to the same strain level. The stress increased by approximately 15% when the strain-rate increased from  $10^{-1}$  to 5000/s. Slow bar tests and Hopkinson bar tests were both carried out at strain-rates in the 150–400/s range. The mean difference between the results obtained with these two methods was less than 20 MPa (less than 3% relative error). This difference can be attributed, in our case, to the fact that the two systems were not perfectly calibrated: upon shifting from a striker to an actuator, it was not possible in our case to use the same bars.

#### Conclusion

Based on the results published in a recent paper [12], a multi-point method (giving multi-strain and/or multi-velocity measurements) was developed for reconstructing one-dimensional waves in bars. This method is highly accurate when used with the single-mode dispersive propagation model commonly applied to Hopkinson bars. It significantly increases the observation time available when measuring techniques based on the use of bars such as SHPB set-ups are used. The present method yields accurate measurements whatever the strain-rate, especially at medium strain-rates between those generally tested with classical hydraulic machines and Hopkinson bar methods. The method described here, which was applied to testing aluminum samples at average strain-rates ranging from  $10^{-1}$  to  $5 \cdot 10^3$   $s^{-1}$ , involves no maximum strain limitations.

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