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New testing techniques to obtain tensile stress-strain curves for a wide range of strain rates

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Abstract: A new method of applying a dynamic load directly to a tensile specimen was developed. By combining the new method with the testing method based on a sensing block [1-5], we improved the testing method to obtain the entire tensile stress-strain curves for a wide range of strain rates on the order of 10^{-3}~$10^{3}s^{-1}$, with remarkable accuracy, especially for the high strain rates range. Based on numerical simulations and experiments, the accuracy of the measurement of the non-coaxial Hopkinson bar method [6,7] was discussed. By performing a series of numerical simulations, the relation between the gauge length of a specimen and the testing strain rate, necessary for obtaining an accurate dynamic stress-strain curves corresponding to a testing error of approximately 2% or 4%, was also obtained for a wide range of strain rates from $10s^{-1}$ to $10^{4}s^{-1}$.

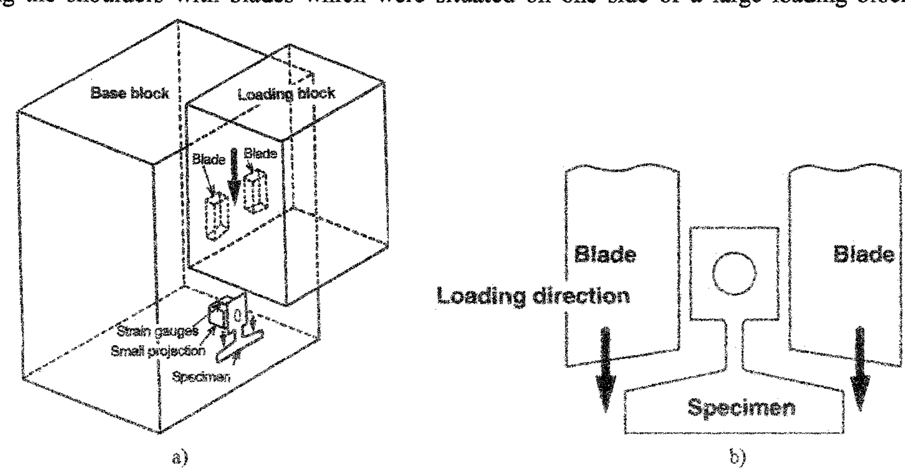
1. NEWLY IMPROVED DYNAMIC TESTING METHOD

1.1 A new method of applying a dynamic load

In many cases in which dynamic tensile tests are performed in order to obtain a tensile stress-strain curve at high strain rates on the order of 10^{3}~$10^{4}s^{-1}$, large oscillations are sometimes observed in the measured load-time records. A reduction of these oscillations is highly important in order to obtain an accurate tensile stress-strain relation at these high strain rates.

We developed a new method of applying a dynamic load directly to a very simple specimen, in combination with the sensing block method developed by Tanimura and others[1-5], as shown in Fig. 1 a and b.

As an improvement of the distinguishing feature of the sensing block method, the projection was made sufficiently small in comparison with the size of the base block, and a short cylinder at the top of the projection was connected via a circular hold in the specimen, as shown in Fig.1. The dynamic load was applied directly onto the shoulders of one side of the specimen by hitting and/or pushing the shoulders with blades which were situated on one side of a large loading block. The

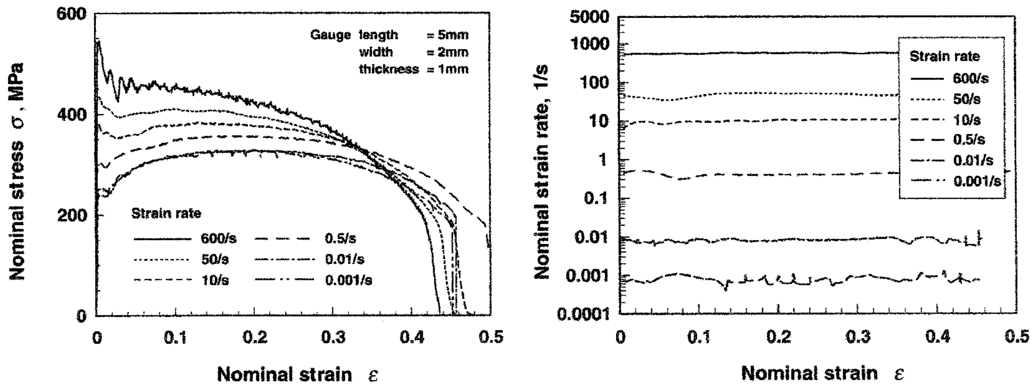


a) b)

Figure 1. New method of applying a dynamic load directly to a specimen, combined with the sensing block method.

dynamic load generated on the specimen could be measured by using strain gauges cemented on the outer surfaces of the small projection. This could be done with sufficient accuracy and for a sufficiently long measuring time, independent of the waves reflected from the boundaries of the blocks and interference from the bodies outside of the blocks. Elongation of the specimen was evaluated by measuring the displacement of the loading block using the magnetic reluctance method.

Examples of the tensile stress-strain curves of SPCC steel at various strain rates, obtained by using the improved High Speed Material Testing System based on the newly developed testing method, are shown in Fig.2 a and b. The specimens used are SPCC steel as received, which corresponds to ISO 3574; a cold-reduced carbon steel sheet of commercial and drawing qualities, having a 5 mm gauge length, 2 mm width, and 1 mm thickness (Fig.1b). A wide range of testing strain rates on the order of 10^{-3}~10^{3} s^{-1} is attained by selecting the speed of the loading block, whose speed is controlled by using an electron-hydraulic servo system. It may be recognized in Fig.2 that the newly developed testing method can be used to obtain the entire tensile stress-strain curves for a wide range of strain rates, with sufficient accuracy.

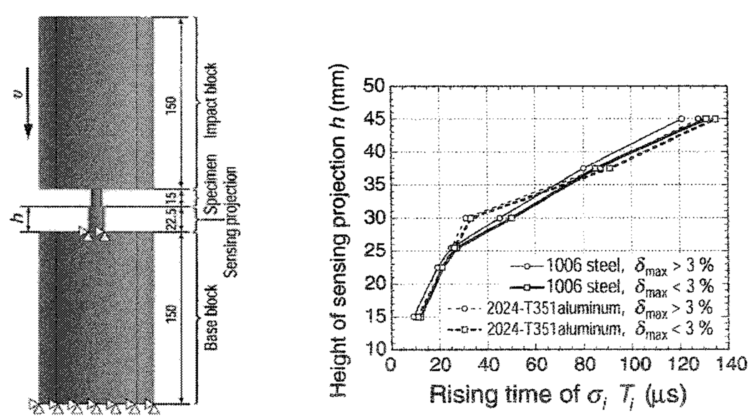


a) b)

Figure 2. Stress-strain curves of SPCC steel at various strain rates.

1.2 Discussions about the size of the projection.

In order to establish the conditions necessary to achieve a high accuracy of measurement based on the sensing block method, e.g., in the case of a compression test, a series of analyses for various sizes of sensing projections, base blocks, loading blocks and specimens, and for a variety of rising times of the



a) b)

Figure 3. a) Model of analyses and b) relation between the height of projection, h, and the rising time, T_i, crresponds to a maximum measuring error of about 3%.

load applied to the specimen, as shown in Fig.3a, was performed [8] by using the code LS-DYNA [9]. The material properties of the specimens of 1006 steel and 2024-T351 aluminum were modeled by means of the Johnson-Cook model. Figure 3b provides a summary of the established conditions between the height of the sensing projection, h, and the rising time, T_i, in order to keep the maximum measuring error of the stress value, in a measured stress-strain curve, below 3%, δ_{max}<3%, and over, δ_{max}>3%.

We can use the results given in Fig.3b in the following manner: When the height of sensing projection h is 22.5mm, for instance, the load generated in a specimen can be measured by means of the sensing block at a measurement error of below about 3%, in a case in which the rising time (T_i) of the load applied onto the specimen is longer than approximately 20 μs. The relation given in Fig.3b can also be used in the case of a tension test, as shown in Fig.1a, where h is the length of the small projection, and T_i is the rising time of the applied load. Relations such as these results may also be useful in the measurement of a dynamic load generated at the impact end, when a comparatively large structure or a car collides with an elastic body.

2. ACCURACY OF THE NON-COAXIAL HOPKINSON BAR METHOD MEASUREMENT AND ITS APPLICATION

A detailed view of how a specimen is set up for testing using the non-coaxial Hopkinson bar method, developed by Tanimura and Kuriu[6], is shown in Fig.4. The tensile stress-strain curve of a sheet material set in non-coaxial bars can be obtained by an analysis of the following conventional Hopkinson bar methodology. Typical time-records of input, reflected, and transmitted longitudinal waves, in the case of a mild steel sheet of 1 mm thickness, are illustrated in Fig.5. In this figure, the vertical values of a transmitted wave (axial force in the output bar) is shown by magnifying the original values ten times because the magnitude of the transmitted wave is very small as compared with that of the input wave (axial force in the input bar). Flexural waves shown by the dotted curve as "bending moment" was detected by the two strain gauges symmetrically cemented on the surface of the output bar with respect to the neutral axis (or plane). The distance from the impact end of the output bar to these two gauges is the same as that to the gauges for detecting the "axial force (output bar)" shown in the figure.

In order to estimate the influence of these flexural waves on the measurement of the stress-strain curve, we analyzed the dynamic behaviors of the output bar by using the MSC/DYTRAN code (MSC.Software, 1999, Fig.6). In the analysis, the recorded axial force, denoted as "output bar" in Fig.5, was applied on the top of a small pin in the axial direction of the output bar model, as shown by the arrow in Fig.6. We confirmed that the analyzed bending moments at each point B ~ F on the output bar (Fig.6) coincided fairly well with the recorded bending moments of the experiments at each

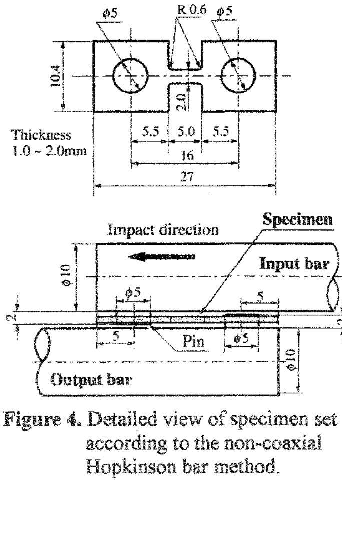


Figure 4. Detailed view of specimen set up according to the non-coaxial Hopkinson bar method.

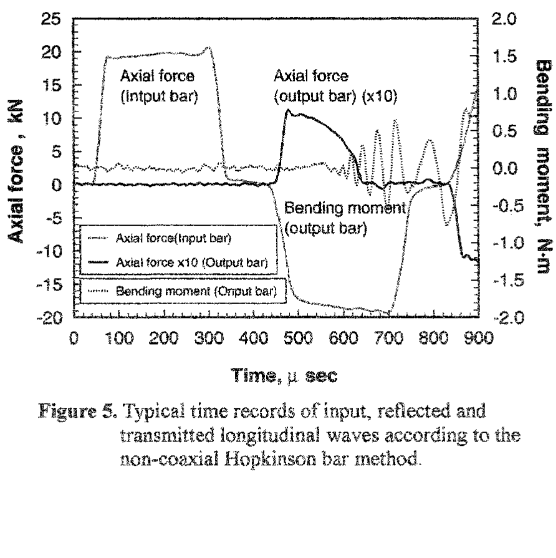


Figure 5. Typical time records of input, reflected and transmitted longitudinal waves according to the non-coaxial Hopkinson bar method.

point B ~ E, respectively. The maximum value, 0.14mm, of the lateral deflection at position A of the output bar caused by the bending moment was also evaluated during the testing period. The value of the deflection at position A was small as compared to the distance of 16 mm between the two holes in the specimen (Fig.4). This result shows that the angle between the direction of the load applied to the specimen through the two holes (which are connected with the two small pins of the input and the output bars) and the direction of the axis of the output bar (by which the applied load is measured) is sufficiently small (see Fig.4). This evidence indicates that the bar's deflection at position A caused by the bending moment may not have substantially affected the measured value of the axial force applied to the specimen. The value of axial forces calculated based on the axial strains by analysis of the output bar at each position B ~ F (Fig.6) are shown in Fig.7; they also coincided with each other and with the input axial force at position A (shown by solid curve denoted as "output bar" seen in Fig.5). These results show that the measurement of the axial force applied to the specimen by the non-coaxial Hopkinson bar method is of sufficient accuracy, independent of the mixture of bending moments. In an actual measurement of axial force, the influence of the flexural waves is more negligible, because the strain gauges are cemented onto the bar along the neutral axis, and the bridge circuit is constructed so that the disturbance due to the bending moment is canceled.

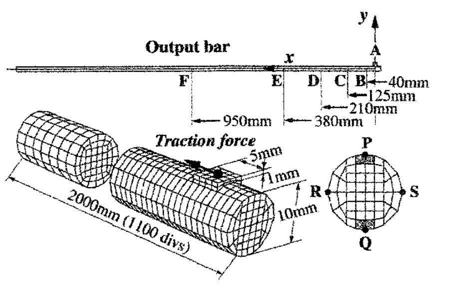


Figure 6. Evaluation points and finite element discretization of the output bar model.

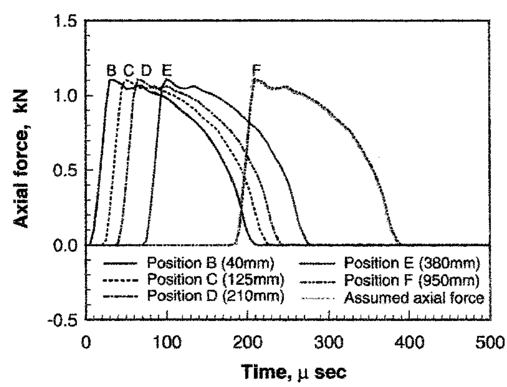


Figure 7. Comparison of transmitted axial forces at points B to F.

3. SPECIMEN SIZE TO BE USED IN THE DYNAMIC TENSILE TEST

In order to perform dynamic testing with sufficient accuracy for a wide range of strain rates, it is also important to choose a specimen size which can be adapted for the test of strain rate[10]. In order to study the specimen size, the dynamic behavior of a cylindrical specimen with diameter D and length L was analyzed by using LS-DYNA code[9], when the displacement, in the axial direction, of the end surface of the specimen was fixed and the other end was pulled with ramp-like velocity v of 20 μs rising time in the axial direction (Fig.8). The ratio $L/D = 5$ was chosen and the Johnson-Cook model for mild steel and copper was assumed for the analysis as follows:

$$\sigma_y = \left(\sigma_0 + B\varepsilon_{eq}^{p\,n}\right)\left(1 + C\ln\frac{\dot{\varepsilon}_{eq}^{p}}{\dot{\varepsilon}_0}\right) \tag{1}$$

assuming the values of parameters listed in Table1, where σ_0, ε_{eq}^p, $\dot{\varepsilon}_{eq}^p$, and $\dot{\varepsilon}_0$ are the initial yield stress, the equivalent plastic strain, the equivalent plastic strain rate, and unit strain rate (= 1 s^{-1}), respectively. B and n are the material parameters related to the strain hardening, and C is the parameter of the strain rate dependence.

The mean stress was evaluated on the surfaces of both specimen ends, and the mean displacement between both end surfaces was obtained by analysis of a specimen of length L and

Table 1 Values of the parameters for mild steel and copper

Material	σ_0(MPa)	B(MPa)	n	C
Mild steel	250	275	0.36	0.079
Copper	90	292	0.31	0.025

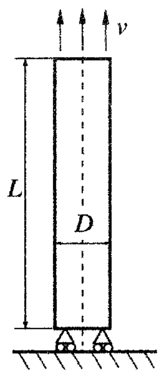


Figure 8. Model of specimen.

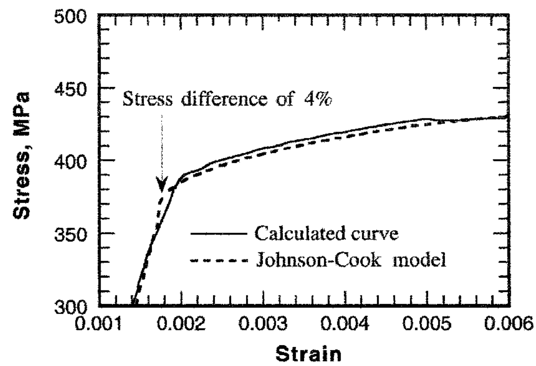


Figure 9. Stress difference between the calculated curve and the assumed curve based on the Johnson-Cook model for mild steel.

pulling velocity v, at each elapsed time during the deformation period. The solid curve in Fig.9 shows, as an example, the calculated stress-strain curve of mild steel at mean plastic strain rate v/L = 495 s^{-1}, obtained using the mean stresses and the mean displacement in the case of analysis for length L = 20 mm and velocity v . The broken curve in Fig.9 shows the stress-strain curve at a plastic strain rate of 495 s^{-1} as determined by the Johnson-Cook model. As the conditions of the analysis shown above we can observe that the value of the gauge length is 20 mm at the average strain rate v/L = 495 s^{-1} during the deformation of the specimen, which corresponds to a stress difference of approximately 4%, and the result corresponds to a point shown by a small-black triangle at gauge length 20 mm in Fig.10. By performing a series of analyses in this manner, i.e., by varying the specimen length L and pulling velocity v, the relation between the gauge length of the specimen (specimen length L in this model), and the testing strain rate was obtained for a wide range of testing strain rates. The relations corresponding to the case having a testing error of 2% or 4% are summarized in Fig.10.

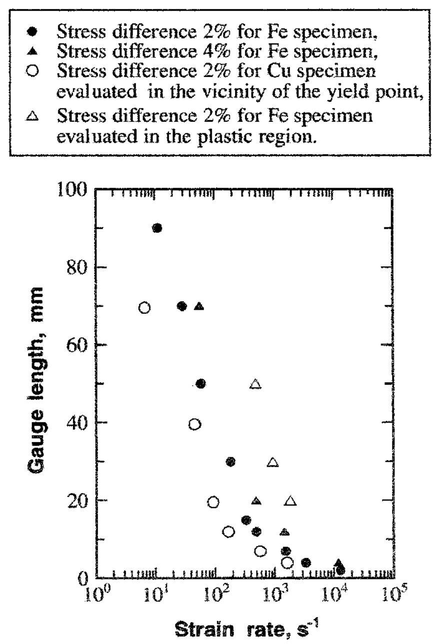


Figure 10. Relation between the gauge length of the specimen and the testing strain rate, corresponding to the case of a testing error of 2% or 4%.

The maximum stress difference occurred in the vicinity of the yield point, and the stress difference occurring in the plastic region was comparatively small, in a series of analyses shown in Fig.9. Small white-triangles show the similar results when estimating the maximum stress difference occurring only in the plastic region.

4. CONCLUSIONS

A new method of applying a dynamic load directly to a simple specimen was developed. By combining the new method with the testing method based on a sensing block, we improved the testing method to obtain the entire tensile stress-strain curves for a wide range of strain rates on the order of 10^{-3}~10^{3} s^{-1}, with remarkable accuracy, especially for the high strain rates range. Through numerical simulations and experiments, it was confirmed that the non-coaxial Hopkinson bar method is quite effective for accurately obtaining the tensile stress-strain curves for a sheet metal, independent of the disturbance of the flexural waves.

By performing numerical simulations, the relation between the gauge length of a specimen and the testing strain rate, necessary for obtaining an accurate dynamic stress-strain curve corresponding to a testing error of approximately 2% or 4%, was also obtained for a wide range of strain rates from 10 s^{-1} to 10^{4} s^{-1}.

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