

Material Characterization at High Strain Rates for Optimizing Car Body Structures for Crash Events

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Abstract

The demand for increased vehicle safety has become a matter of considerable concern of users. The use of high strength steel is beneficial for the realization of a light weight body with enhanced vehicle safety. An optimum combination of body structure and material is highly required and thus an exact evaluation of high strain rate properties of materials has been also demanded. In this report, the methods for testing the high strain rate tensile properties of sheet materials were reviewed and the recent improvements made for our testing machine, one bar method, were presented. In addition, the points that should be taken into accounts in applying the experimental material data at high strain rates to FEM analysis, which is a key tool for an optimization, were discussed.

1. Introduction

Because environmental issues, beginning with the prevention of global warming, pose great tasks in the 21st century, measures are being taken in respective fields. Particularly important is the reduction of exhaust gas from automobiles that accounts for 20 to 30% of CO₂ emission. It was legislated in Europe to control CO₂ emission at below 140 g/km, a reduction of 25% over 1995, after 2008. In Japan as well, it was established by the revised energy conservation law to reduce fuel consumption by 25% over 1995. On the other hand, despite various measures taken, casualties at home due to traffic accidents amounted to 1.19 million persons in 2001, which is a serious problem to be solved. The crashworthiness measures against automobiles made a progress along the legislation and the disclosure of information (NCAP) in Japan, the U.S., and Europe before and after 1995. Crashworthiness made a great improvement during this period in Japan, as well. With the optimizing car body structures and the use of high strength steel, crashworthiness and weight reduction (reduction of exhaust gas) were rendered compatible. It is only in recent years, however, that designing has made progress on the basis

of crash FEM analysis taking into account the strain rate sensitivity of material strength. Although the foregoing are present-day problems that have been tackled, basic research dates far back to the 19th century¹⁾.

This report will summarize the high strain rate tensile testing methods of steel sheets, which are a basis of structure and material optimization, by referring to the history of their research.

2. Contribution of material to the crashworthiness of automobiles

In order to protect automobile passengers from injury during a crash, car crash experiments are carried out to simulate the actual accident and legal regulations have been established based on these experiments in Japan²⁾, the U.S.³⁾, and Europe⁴⁾. Furthermore, crashworthy performance has been opened to the public as NCAP (New Car Assessment Program) in Japan, the U.S., and Europe, which are conducted under the conditions severer than crash experiments of the legislations. Those crash experiments are intended to evaluate the degree of injuries inflicted on the head, the breast, the pelvis, and

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the legs of a human body in relation to acceleration, load, displacement, and velocity using a dummy simulating the human body aboard the car. The above parameters and the degrees of injuries comply with the data of the accident research. Those injuries of human bodies can be moderated to a great extent by using the constrainer of a human body or a buffer, such as a seat belt or an air bag. Studies have been made, however, as to how the injuries of passengers can be lessened by optimizing car body structures on the assumption that passengers wear restraining equipment.

The following measures are mainly taken for lessening the injuries of passengers by the optimizing of car body structures:

Frontal crash: To have the front part of a car crushed so that its plastic deformation can absorb crash energy. The compartment of a car should be made rigid to avoid the influence of deformation on it.

Side crash: To avoid a thrust into a compartment as much as possible by holding down the deformation of the side of a car.

In the international project, ULSAB-AVC (Ultra Light Steel Auto Body-Advanced Vehicle Concept), in which crashworthiness and weight reduction are made compatible, designing was entrusted to Porsche Engineering Service, which has succeeded in optimizing car body structure under the conditions of US-NCAP (Full-width frontal crash tests), Euro-NCAP (Frontal offset crash tests), and SINCAP (Side crash tests) as the indices of deformation of auto body structure for crashworthiness⁵⁾.

Although the above-described studies are necessary so that crashworthiness is made compatible in terms of car body structure, it is generally considered acceptable to absorb crash energy roughly by having the front-side member axially crushed to absorb crash energy in the frontal crash, by reinforcing the center-pillar not to break due to bending in the side crash, and by having the locker bend-crushed. To enhance the strength of material against these fundamental deformation on crash, that is, to replace material to higher strength, is advantageous to holding down plastic yielding against bending. This makes it possible to increase the amount of energy to be absorbed on axial crush⁶⁾.

3. Measurement of at high strain rates deformation characteristics of steel sheets

It is effective to enhance the strength of material for crashworthiness against a car crash and it is known that deformation resistance increases when strain rate is increased because steel has rather high strain rate sensitivity. This makes it necessary to evaluate high strain rate characteristics corresponding to those of a crash when we consider materials substitution. According to FEM analysis, when a square tube, 70 mm square and 2.0 mm thick, simulating the front-side member of a car, crushes against a rigid wall at a speed of 55 km/h, a strain rate exceeds 1000/s at the corner where deformation is concentrated, one million times as great as the strain rate in conventional material testing⁶⁾. Because a conventional test method is not applicable to the evaluation of the deformation characteristics at such a high strain rate, another test method is required at a high strain rate.

At a conventional strain rate, a load cell is considered to deform homogeneously and the loading force is measured by a strain gauge attached to it. As the strain rate increases, the time needed to attain the homogeneity of elastic deformation within the load cell approaches that of the testing time, which leads to the necessity of considering the wave propagation within the load cell. At strain rates higher than about 10 to 100 /s, the signal of the loading force is greatly perturbed by multiple passages of waves reflected within the load cell in a usual configuration.

Thus, a special technique is required for the load measurement. This may be accomplished in two opposite ways. One is to shorten the load cell in the loading direction, thus reducing the time needed to homogenize the elastic deformation within the cell.

The other way is to lengthen the load cell, in order to finish the measurement before the coming back of the elastic wave reflected at the other end. The former type of the load cell is actually used for car crash experiments. However, it is inevitable to be affected by the waves reflected at places other than the load cell.

Thus, for a precise measurement, as required for determining the material stress-strain behavior, the latter approach is usually applied and it is called as a split Hopkinson pressure bar method. B. Hopkinson proposed a principle of the Split-Hopkinson Pressure Bar Method⁷⁾. Later on, H. Kolsky established a compression test method at a high strain rate in 1949 in such a manner that a small cylindrical test piece is placed between two long bars to give compression waves from one end⁸⁾. Although split-Hopkinson bar method enables to measure material behavior up to a high strain rate, it is in principle a compression test method. A car body is mostly composed of thin sheets, making it difficult to apply the compression method in terms of buckling. A tensile test method was therefore developed, as an improvement of split-Hopkinson bar method. Recently, a committee was organized mainly by New Material Center, one division of Osaka Science & Technology Center, for the research and development of a method of evaluating the high strain rate deformation behavior of metals to realize better crashworthiness design of automobiles, and carried out a systematic study, including the comparison of various high rate test methods as shown in Fig. 1⁹⁾. Furthermore, in cooperation with this movement, The Iron and Steel Institute of Japan organized a committee for the study of the high strain rate deformation of materials for auto bodies, and continued the study for four years from 1997¹⁰⁾.

D) in Fig. 1 is called a servo-hydraulic method, a method to carry out a tensile test by running a chuck up to a given velocity, and load measurement is made with the strain gage attached to the load cell or the grip part. It is claimed that this method has a limit of measurement for a strain rate above 200 to 300/s because of a large noise caused by the reflected waves from the chuck part.

A) indicates the original split-Hopkinson pressure bar method, a method to measure the stress and strain of a test specimen from the stress waves appearing in the output bar after passing through the test piece and from the stress waves of the input bar, with stress pulses given to the input bar with the striker. B) is a method arranged so that a tensile test can be carried out with the split-Hopkinson bar method. Like in the original method, that is a coaxial Hopkinson bar method with both of the input and output bars arranged on a common axis. A yoke is attached to the input bar, and a tensile test is

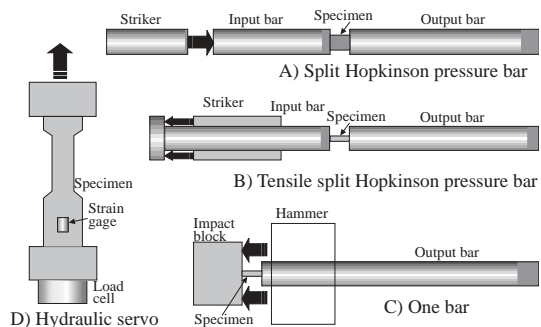


Fig. 1 Various high strain rate deformation test methods

carried out by striking this yoke part with the striker. This method enables to measure up to a high strain rate because it is a coaxial Hopkinson bar method. However, it is usually difficult for this method to measure stress-strain characteristics until materials rupture.

C) is One Bar Method proposed by Kawada¹¹⁾, a method adopted by the authors. This method enables to measure material behavior until a fracture of materials without any limits for material strength, since a tensile test is carried out by striking with a hammer the impact block ahead of a test specimen attached to the top of the output bar. Because the one bar method uses only one bar, a long output bar can be applied in the same installation space. Measurement can be made until reflected waves coming back from the other bar end. Since the longitudinal elastic wave velocity in steel, $C_0 = \sqrt{E/\rho} = 5,100$ m/s, time to the extent of 2 ms can be secured with a 5 meter long bar.

The nominal stress ($\sigma_n(t)$) and nominal strain ($e(t)$) of steel can be given as follows:

$$e(t) = \frac{1}{L_0} \int_0^t [V(\tau) - c\varepsilon_g(\tau + a/c)] d\tau$$

$$\sigma_n(t) = \left(\frac{A_{bar}}{A_0} \right) E_{bar} \varepsilon_g(t + a/c)$$

Here, $V(\tau)$ is a velocity of the block, $\varepsilon_g(t)$, a strain of the output bar at a distance a from the output bar end by A_0 and L_0 , a cross sectional area and the length of a reduced section of a specimen, and A_{bar} and E_{bar} are a cross-sectional area, Young's modulus, and an elastic wave velocity of the output bar.

In the course of the study for the standardization of the test methods, it was pointed out that the one bar method tends to have a larger stress peak in the initial stage of deformation than the other methods. It is possible to construe that a yield stress becomes higher because sufficient mobile dislocations are unable to be produced in the initial stage of deformation at high strain rates. On the other hand, it can be considered as a phenomenon peculiar to this test method, for a direct impact is applied in the one bar method, and the coaxiality of a specimen and the output bar tends to be affected by testing conditions.

This led to the study of the influence of the layout of the test machine using FEM on this initial stress peak¹²⁾. The findings of the FEM analysis, in which the self-weight deflection of the output bar in the initial stage was considered, revealed that micro-vibrations in a very small amount of several tens of μm occur at the output bar end at the moment a hammer strikes the impact block. An apparent initial stress peak is generated because elastic waves, resulting from the expansion and contraction in the direction of the axis, produced by these vibrations at the bar end, propagate to the position where the load is measured and they are superimposed on true measurement signals. Therefore, it stands to reason to consider that a large initial peak results from the oscillation at the output bar end due to divergence of the test piece and the output bar in coaxially. To prevent this, fixing jigs were attached to the output bar end to secure the coaxially of the output bar and the impact block, and an actual test was carried out.

As a result, it was rendered possible to eliminate an apparent peak as Fig. 2 shows, enabling to obtain precise measured waves in combination with the fact that no reflected noise was present from the beginning¹²⁾. It was also rendered possible to compare precisely static deformation characteristics with dynamic ones as Fig. 3 shows. Fig. 4 gives the finding of the high rate tensile test of steel sheets at some strength levels, carried out again in the state in which the peak induced by the test machine was removed. Whereas a large peak can

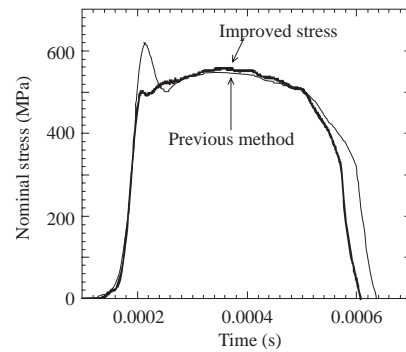


Fig. 2 Comparison of initial stress peaks before and after the improvement

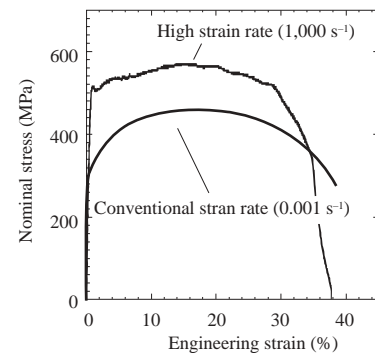


Fig. 3 Comparison between static and dynamic characteristics

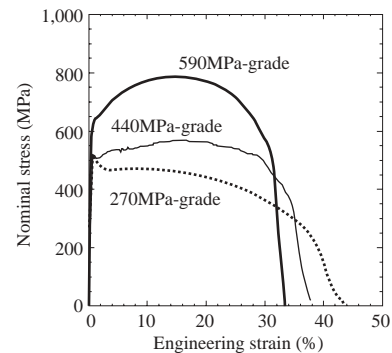


Fig. 4 Stress-strain curves measured by the improved method

be observed in mild steel even after the improvement, it is scarcely observed in DP steel at a level of 590 MPa¹²⁾. This is closely related with the density of initial mobile dislocations. It is therefore easy to understand that a large peak is produced in the material in which mobile dislocations are hard to be produced and that a peak is hard to be produced in the material with high mobile dislocation density, which is a case for DP steel, or with many sources of dislocations inside materials.

4. Material excellent in energy absorbing characteristics

As described in the previous chapter, the deformation characteristics of sheet materials can be measured precisely to an order of 1000/s, a strain rate to be attained in a car crash owing to the high rate tensile tests with the coaxial Hopkinson bar method. Fig. 3 shows the stress-strain curve measured by this method together with that

obtained by the conventional tensile test method. As the Figure shows, the strength of steels depends on a strain rate. This characterizes bcc metals, which corresponds to the fact that frictional stress against dislocation movements increases with strain rate due to Peierls-Nabarro mechanism. It is known that the extent of contribution of Peierls-Nabarro mechanism depends on crystal structure. In fcc metals, the absolute value of this stress is much small, and no large strain rate sensitivity of flow stress is observed. This means that steel material in which deformation resistance increases at a strain rate in a car crash is superior to fcc metals like aluminum.

As described above, it is known that enhancing the strength of material is advantageous for crash energy absorbing characteristics, but decreases the strain rate sensitivity of flow stress¹³⁾. However, even with the material at the same strength level (tensile strength) the strain rate sensitivity of its flow stress differs according to a strengthening mechanism. Although Fig. 5 shows the flow stresses of several steels, there are some which show a large increase in the flow stress depending on the kinds of steel^{6,14,15)}. Furthermore, since steel sheets for automobiles are usually press-formed and bake-finished, the evaluations of car crash performance should be made in terms of the high strain rate deformation characteristics in a pre-strained + baking-hardened (BH) state.

Fig. 5 also shows the results of steel sheets heat-treated at 170°C for 20 minutes same as in baking finish with a pre-strain of 5% added, which is an average amount of strain to be added during press-forming. In comparison with mild steel, deformation resistance due to strain rate effects becomes smaller in 440-MPa steel, and further smaller in 590-MPa precipitation hardened steel. However, an increase in the flow stress due to strain rate effects in TRIP and DP

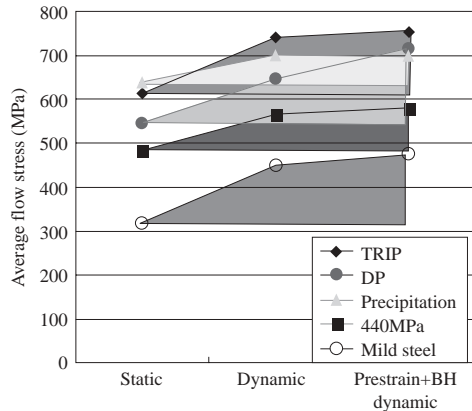


Fig. 5 Dynamic characteristics of each steel sheet and effects of pre-strain and bake hardening

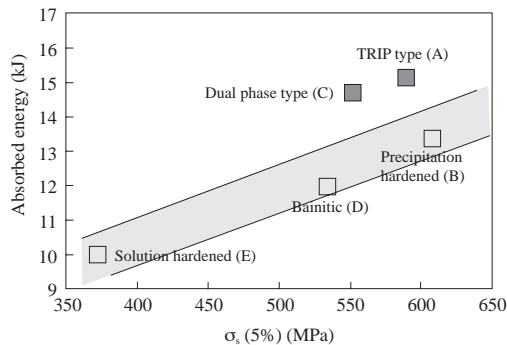


Fig. 6 Formability and crash characteristics of various kinds of steels

steels even at a 590 MPa level is almost the same with that of mild steel. Fig. 6 shows the average flow stress at a strain of 5% as an index for press formability, and the absorbed energy when the square tube was axially crushed for absorbed energy in a car crash as practical evaluation indices used for automobiles. It is easy to understand that TRIP and DP steels, generally called multi-phase steel, are more suitable in crashworthiness performance than the conventional steel¹⁵⁾. Those characteristics can be considered attributable to a relatively clean ferrite phase contained commonly in those steels.

5. Important points in crash analysis and coupling analysis

Car crash analysis has improved in accuracy because of the precise understanding of material characteristics at high strain rates. Not only because of the difference in reaction force of member element in a car crash, but also because of the changes in collapse mode of the whole car body¹⁶⁾, it is necessary to consider precisely the strain rate sensitivity of materials. The results of finite element analysis for parts by using the precise strain rate sensitivity agree well with those of experiments¹⁵⁾.

When the actual car crash was further considered, it is impossible to neglect not only the pre-deformation due to press-forming but also the influences of baking finish (BH). As reported previously, the flow stress of material increases with pre-deformation and BH⁶⁾. To grasp the precise behavior on crash, an analysis is necessary with the changes in sheet thickness due to press-forming and the amount of pre-deformation considered. Recently, a trial has been started to solve the above problem by coupling analysis for pre-forming and crash.

What is important in this case is to incorporate material behavior at high strain rate after pre-deformation into an analysis. Actually, it is complicated to do so because of the differences in pre-deformation mode or direction for every member¹⁷⁾. However, on the assumption that the direction of deformation changes at 90° as seen typically in members, a high strain rate tensile test was carried out after the application of pre-tension perpendicular to the direction of rolling and the heat treatment equivalent to BH. Fig. 7 shows the findings of the test. It can be seen that the application of pre-deformation increases the stress immediately after the start of deformation and that the amount of this increase changes along the stress-strain relationship of material with 0% pre-deformation. Accordingly, it is possible to carry out a coupling analysis as the primary approximation by allowing the stress-strain relationship of a raw material to shift according to the amount of prestrain¹⁸⁾ (see Fig. 8). However, since the actual material differs respectively in work hardening and bak-

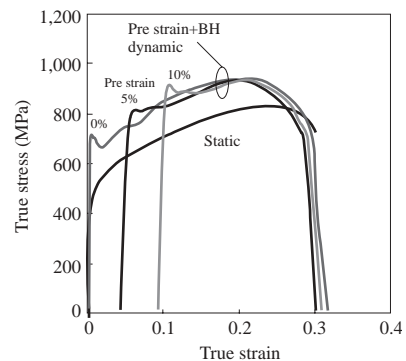


Fig. 7 Characteristic curves after pre-deformation + bake hardening (BH)

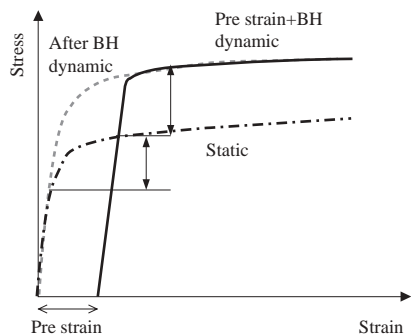


Fig. 8 Material characteristics for coupling analysis of forming and crash

ing hardening, it is important to make an analysis by grasping the characteristics of every material using the proper database of the material.

6. Conclusions

For the achievement at a high level of targets conflicting with each other, that is, the improvement of crashworthiness and the reduction in weight of a car body, it has become necessary to develop excellent materials and use them properly. In around the middle of the 1980's when the application of the finite element analysis of a car crash started, a car model was composed of some 7,000 elements. Recent rapid progress in both computer capability and computing technology has led to the rapid elaboration of a model with the number of elements approaching some one million at present. Highly precise technology as described herein is essential for material evaluation to support increasingly progressing digital development. It is all the more important to incorporate the technology into the analysis.

It is important to develop more excellent materials so that highly

growing demands can be complied with in the future in line with the development of technology to apply those materials. It is expected that a car body light in weight and excellent in crashworthiness can be realized in the pursuit of the capability of steel.

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