539.4.019 : 534.2

Torsional Impact Loading of the Thin-Walled Aluminum Statically Pre-Tensioned*

By Hidekazu FUKUOKA**
Takuo HAYASHI**
Noboru TANIMOTO***
Toshimitu TANAKA****

One of the authors formerly performed the experimental studies on the dynamic behavior of a bar under impulsive forces and reported that a decrease of the shear strain was observed when the bar was pre-stressed to the plastic range by pure torsion and an impulsive incremental axial stress was applied on it.

In the present paper, the experimental studies are reported on the dynamic behavior of a bar pre-stressed axially to the plastic range and then submitted to the impulsive torsional stresses. In this case, a decrease of the axial strain, as is the torsional strain in the previous work, was observed apparently. The theoretical calculations are also worked out based on the isotropic work hardening assumption and Mises' yield condition. Theoretical results are in relatively good agreement with the experimental ones.

1. Introduction

One of the authors formerly performed the experimental studies of the incremental combined impact loading⁽¹⁾ and examined the effectiveness of the theoretical solution obtained by Clifton⁽²⁾, and he observed the initial decrease in shear strain in a thin walled-tube statically pre-torsioned to the plastic range, as a theoretical solution predicted, when a longitudinal impact was applied on it. But a decrease in axial strain in the case where torsional impact was applied to a thin walled-tube statically pre-tensioned to the plastic range was not observed in spite of the theoretical prediction. After that, authors made a new impact testing machine and testing the performance of this equipment, they confirmed that with this new impact testing machine, pure torsional impact loading could be applied to a specimen without bending or longitudinal stress. Utilizing this new impact testing machine, an incremental torsional impact experiment was performed again and the decrease in axial strain was noted apparently. And the theoretical calculation was carried out with the impact load measured at the end face of the specimen as the boundary condition. As the result, considerably good agreement between the theoretical and experimental results was found. The principle

of the new impact testing machine is the same as that of the torsional impact machine used by Baker and Yew⁽³⁾, Campbell and Dowling⁽⁴⁾, and a static axial load applying apparatus was attached to the new testing machine so that the experiment of the incremental impact loading could be carried out.

2. Torsional impact testing machine

2.1 Principle

The principle of the torsional impact testing machine used in the present experiments is as follows. An illustration is shown in Fig.1. First, a thin walled-tube specimen is connected to an elastic solid

Fig.1 Principle of torsional impact testing machine

* Received 5th November, 1974.

** Professor, Faculty of Engineering Science, Osaka University.

*** Graduate student, Faculty of Engineering Science, Osaka University.

**** Engineer, Kobe Steel, Ltd.

bar (Fig.1 (a)), which is statically subjected to tension load. In this state, the part AD of the whole specimen is submitted to the axial force, therefore the thin walled-tube specimen is in tension state (Fig.1 (b)). Fix the center part B of the elastic solid bar by a clamping apparatus, and statically rotate the one end A of elastic solid bar to a certain rotating angle. In this state there is a difference in torque between AB and BD (Fig.1 (c)). Then, releasing the clamp rapidly causes the loading wave of torsional shear stress to propagate along BD and the unloading wave along BA (Fig.1 (d)). In this way, torsional impact load to the thin walled-tube statically pre-tensioned can be applied. Clamp mechanism, a schematic view of which is shown in Fig.2, is as follows. The blocks ③ and ⑩ make a rest stand to support the specimen and the equipment. If we rotate the bolt ① to the right, the block ④ moves in the left direction along the axis of the bolt and tension force acts on the metal band ⑦ through the tension bar ⑤ and the cutting bar ⑥, and so, the sector plate ③ clamps the elastic solid bar. This clamping force can hold the elastic solid bar ⑨ against the torque T. The tensile force of the metal band ⑦ is released in an instant by cutting a notch in the bar ⑥ with a chisel or by a brittle fracture of the notch. The amount of the torque can be controlled by measuring the tensile force from the output of the strain gage bonded on the tension bar ⑤ so that the clamping torque will be sufficient without a failure of the cutting bar.

The method of static tension loading is as follows. Fig.3 shows an illustration. If we rotate the block ⑥, the block ⑦ moves in the right direction through the right angle block ⑦, and the bogie moves in the axial direction of the specimen.

2.2 Performance of the testing machine

An experiment was carried out to examine the performance of the testing machine especially about whether torsional shear wave obtained by the equipment is pure plane wave without bending and axial stresses or not. For the performance test, comparisons of the outputs from strain gages mounted in the direction parallel to its axis with those from strain gages mounted in the direction inclined to the axis by 45° were made.

Specimen bar used is medium carbon steel S45C. Its dimension is 2100 mm long with circular cross section of 10 mm diameter. Strain gages mounted in the direction parallel to its axis and in the direction inclined to the axis by 45° were cemented at the points respectively 500 mm and 510 mm apart from the impact end.

An oscillogram obtained in the pure torsion impact test is shown in Fig. 4. Beams (i) and (ii) show the outputs from strain gages axially and symmetrically mounted on the output bar in the direction

Fig.2 Clamp apparatus

- ① : Specimen ② : Chuck
- ③ : Bogie ④ : Bed
- ⑤ : Block fixed to ④
- ⑥ : Bar pinned to ③
- ⑦ : Block pinned to ⑤
- ⑧ : Turn buckle
- ⑨ : Block fixed to ⑩
- ⑩ : Foundation frame

Fig.3 Static tension loading apparatus

Fig.4 Oscillogram of impulsive test under pure torsion in elastic range

Horizontal scale : $100 \mu\text{sec./div.}$
Vertical scale : 0.5 mvolt/div.

parallel to its axis. Beams (iii) and (iv) are the outputs from strain gages axially and symmetrically mounted on the output bar in the direction inclined to the axis by 45° . Comparing beam (i) or beam (ii) with beam (iii) or (iv), we find that the ratio between the former and the latter is about 10^{-2} . We also find that beams (iii) and (iv) are in good agreement with each other. They show that the testing machine can apply almost pure torsional impact to the specimen. Rising time of pulse in Fig. 4 is about $120 \mu\text{sec}$. Maximum torque of this testing machine is 2100 kg mm . The length of the pulse can be changed at longest to $450 \mu\text{sec}$ by moving the position of the clamping apparatus in the axial direction of the specimen bar. The value of the torque obtained from beam (iii) is about one-half of the torque statically loaded in AB.

3. Experiments

3.1 Experimental method

A schematic view of the test equipment is shown in Fig. 5. A test bar is composed of medium carbon steel S45C and commercially available aluminum. They are pasted face to face collinearly by the cement Bond E39Y6. The dimension of the former is 1460 mm long with circular cross section of 10 mm diameter and the latter 760 mm in length, 10 mm in outside diameter and 1 mm in wall thickness.

Static tension force is applied on the specimen by statically pulling the one end D of the aluminum tube by using the lever as mentioned in section 2-1 (Fig. 5). In order to avoid the unloading of the axial force by creep deformation of aluminum specimen, the applied axial force continues to be increased a little during the impact torsion test. Impulsive torque is loaded as follows. Clamp the center part B of the elastic solid bar (Fig. 5) and rotate statically one end A of it. Then torque is stored in the elastic solid bar AB and impulsive torque is loaded on the thin-walled aluminum specimen CD through the elastic solid bar BC by releasing the clamp rapidly.

The aluminum specimen was annealed by heating it gradually to 673°K in one hour, keeping the temperature constant in half and one hours and then cooling it in the furnace.

Simple tension stress-strain curve used for numerical calculation was obtained by static tension test of a piece cut out from the same specimen with the same heat treatment condition as in dynamic test. Experimental formula for the stress-strain curve of the specimen was obtained by least square method from the experimental results.

Strains were measured by strain gages mounted on the test bar. A pair of strain gages was mounted axially and symmetrically at every measuring point and connected in series. Strain gages for shear strain were mounted in the direction inclined to the axis by 45° and strain gages for axial

strain in the direction parallel to its axis. The outputs from strain gages were displaced on the oscilloscope through the voltage dividing circuit and photographed by a camera. Strain gages mounted on the elastic solid bar near the clamping apparatus were used for trigger of the oscilloscope.

3.2 Experimental results and considerations

Figure 7 (a) is an oscillogram of strain-time relation in elastic solid bar. Beam (i) shows an incident wave of torsional shear stress, beam (ii) shows a composite wave of incident and reflected waves of torsional shear stress. As the stress in the solid bar is so controlled as not to exceed its elastic range, applied shear stress at the face of the aluminum specimen can be obtained from strain-time histories. Figure 8 shows the stress-time history at the struck end thus obtained.

Figure 7 (b) and (c) are oscillograms of strain-time relation in aluminum tube specimen. In this case, the gain of the vertical scale was large enough to observe the initial behavior of the axial strain and the shear strain, so that the increasing process of the axial strain is out of scale. Figure 7 (b) shows the experimental results at the point 2.5 mm far from

Fig. 5 Schematic view of the experimental apparatus

Fig. 6 Static simple tensile stress-strain relation of aluminum

the impact face. Symbols I and II in Fig.7 (c) show the experimental results at the points respectively 80 mm and 160 mm apart from the impact face. Symbols α and s denote the axial and the shear strain respectively.

(a) Oscillogram of strain in elastic bar

(b) Oscillogram of strain in aluminum specimen at $x = 2.5$ mm

(c) Oscillogram of strain in aluminum specimen at $x = 80, 160$ mm

Fig.7 Example of oscillogram of torsional impact

Horizontal scale : $100 \mu\text{sec./div.}$
Vertical scale : $77 \times 10^{-6} \text{ mm/mm/div.}$

Fig.8 Shear stress-strain relation at impact face of aluminum

Fig.9 Incremental strain-time relation of aluminum at $x = 2.5$ mm

Fig.10 Incremental strain-time relation of aluminum at $x = 80$ mm

Fig.11 Incremental strain-time relation of aluminum at $x = 160$ mm

Fig.12 Incremental axial strain-shear strain relation of aluminum at $x = 2.5$ mm

Fig.13 Incremental axial strain-shear strain relation of aluminum at $x = 80$ mm

Fig.14 Incremental axial strain-shear strain relation of aluminum at $x = 160$ mm

Fig.15 Stress path from numerical calculation

Fig.16 Stress path from numerical calculation

Figures 9~14 show the comparison of numerical solution with experimental results. Impact stress at the impact face used for calculation is shown in Fig.8. Numerical calculation was carried out by replacing Clifton's fundamental equation by the finite difference equation along the characteristic curve in reference (1). Figures 9~11 show the strain-time relation at the points $x = 2.5$ mm, 80 mm and 160 mm respectively. $\Delta\epsilon$ and $\Delta\gamma$ show the incremental components of the axial strain and shear strain respectively from the initial state.

Figures 12~14 show the relations between incremental axial strain and shear strain at the points $x = 2.5$ mm, 80 mm and 160 mm respectively. The following is considered from Fig.9~14. Numerical solution is in considerably good agreement with experimental results till the axial strain reaches its minimum value except in the neighbourhood of the impact face ($x = 2.5$ mm). Perhaps, this is because the behavior of the specimen in the strain decreasing process is elastic. Numerical solution of the maximum decrease quantity of axial strain is also in good agreement with experimental results, and the farther the measuring point is, the larger it is.

As known from Figs. 15 and 16, the difference of arrival time between the longitudinal wave and the transverse wave is larger as the measuring point is farther, and the phenomenon approaches to that of the step loading relatively because the rise time of the pulse becomes negligible to the difference of arrival time of both waves. In the increasing process of the axial strain, experiments show smaller values than the calculation. Concerning the shear strain, calculated values are in fairly good agreement with experimental ones in the initial increasing process. After the process, strain rate decreases in numerical solution but such a phenomenon can not be observed in the present experiments. This is, perhaps, because of the viscosity of the material. Near the impact end ($x = 2.5$ mm), initial decrease in axial strain can not be observed. The change in axial strain and shear strain with time in experiment has the same tendency as that in calculated one, but experimental value is smaller quantitatively.

4. Conclusions

The main results of the present investigation are as follows:

(1) A testing machine was designed such as to apply the torsional impact loading to a long tube specimen statically pre-tensioned. Its loading device utilized the unloading wave of an elastic bar and the performance was good enough for the present experiment.

The experiments were carried out by the testing machine to apply a torsional impact loading to a long thin walled-tube

of aluminum statically pre-tensioned. On the other hand, a numerical calculation was performed based on the strain rate-independent and isotropic work-hardening theory with Mises's yield condition. Comparing the calculated values with the experimental ones, the following results were obtained.

(2) Except in the neighbourhood of the impact end ($x = 2.5$ mm), initial decrease of axial strain was observed and the decrease of the strain became larger with the distance from the impact end. The experimental and the theoretical results are in considerably good agreement.

(3) In the whole process, including near the impact end, the theoretical and experimental results coincide qualitatively well with each other, but in the process after the initial decrease of the axial strain, both are not in good agreement quantitatively. This might be especially because of the viscosity of metal.

References

- (1) Fukuoka, H. and Masui, H., Trans. Japan Soc. Mech. Engrs. (in Japanese), Vol. 40, No. 334 (1974-6), 1544.
- (2) Clifton, R.J., Proc. 5th U.S. Congr. Appl. Mech., (1966), 465.
- (3) Baker, W.E. and Yew, C.H., Trans. ASME, Ser. E, 33-4 (1966-12), 917.
- (4) Campbell, J.D. and Dowling, A.R., J. Mech. Phys. Solids, 18 (1970), 43.
- (5) Courant, R., et al., Communications on Pure and Applied Mathematics, 5 (1952), 243.