Torsion ratchet associated with mechanical hysteresis

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1 INTRODUCTION

The experimental determination of behavior of material like metals, is often obtained with a tube shape sample. For the traction-compression and internal pressure test the direction of the solicitation principal axes is maintened constant. On the contrary the torsion test is a rotational solicitation and thus is accompagnied by secondary effects, like the well-known Poynting effect (Poynting 1909 ; Foux 1962). Further more during a cyclic solicitation some secondary effects may accumulate and give rise to a ratchet phenomenon (Swift 1947 ; Ronay 1967). Thus it seems to be worthwhile, from an engineer's point of view, to consider these effects more in detail.

On the other hand it seems that these effects are material dependent. Indeed the results of cyclic torsion obtained by Poynting (1909) and Foux (1962) with steel piano wires do not show any noticeable ratchet ; this is probably due to the particular state of this metalic material which contains a very high dislocation density and thus behaves almost elastically since it is quite impossible for a dislocation to unpin. On the contrary, for ordinary metals, the deformations are irreversible from the beginning (Han, Wack 1986), since dislocations can unpin at a very low stress level. In that case this hysteresis behavior is accompagnied by second order effects which give a ratchet phenomenon with cyclic solicitation. The amount of ratchet seems to be related to the material type. Thus it is possible that the informations obtained are of importance for the scientist to dissipate the uncertainty concerning the possible choices in the modelization of material behavior.

For these reasons we conduct some cyclic torsion tests, with or without axial force, and attempt to measure as precisely as possible the axial deformation. The tests are run at a low strain rate and at room temperature so as to reduce as much as possible the influence of the viscosity phenomena and consequently to obtain results whose interpretation may be less complex. Most of the tests concern an austenitic stainless steel and two tests were obtained with a superalloy and an engineering steel (Han 1985) ; these results complement partial results already published concerning the ratchet (Elleuch, Han, Wack 1983) and the behavior (Han, Wack 1986 and 1987).

2 THE EXPERIMENTAL CONDITIONS

Most of the tests are run on a servo-controlled hydraulic machine and a

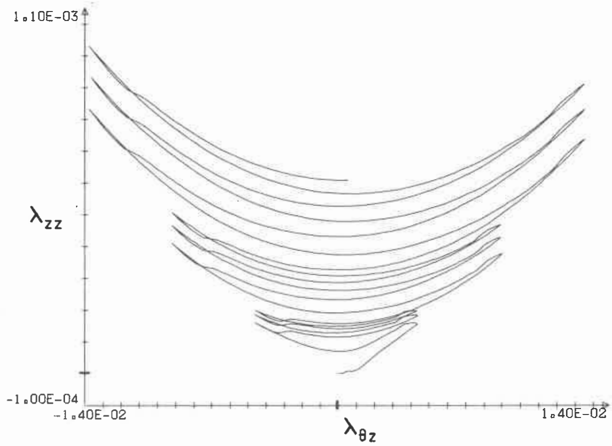

Figure 1.
Torsion ratchet with no axial force.
Stainless steel.
Test n° 206

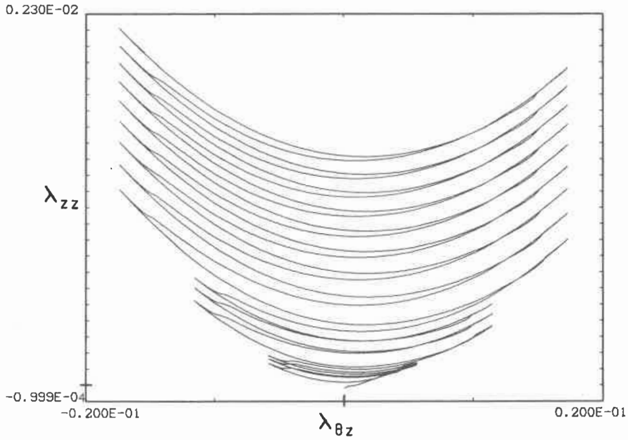

Figure 2.
Torsion ratchet with no axial force.
Stainless steel.
Test n° 208.

few of them on a special torsion device. The sample is a tube with the following internal and external radii : 12 - 14 mm (stainless steel and engineering steel), 8 - 9.3 mm (superalloy) ; the gage length is 30 mm. The strains are measured with a set of three strain gages glued on the outside cylindrical surface.

To minimize the viscosity effects, the tests are run at a low strain rate of $3.10^{-5} s^{-1}$, and at room temperature. All the tests are symmetrical cyclic torsion tests. The chemical composition of the engineering steal in weight percent is as follow : C (0.38), Cr (0.97), Mo (0.20), Mn (0.60), Si (0.25), Ni (0.17). The stainless steel is 17 - 12 SPH, which is of 316 L type and the superalloy is INCO 718 ; their precise metallurgical definition was given previously (Han, Wack 1987).

The strain gages do not measure exactly components of a strain tensor. The results are noted λ_{ij} and are very near the Green-Lagrange strain tensor related to the initial state. For a cylindrical tube (or rod) submitted to a solicitation having the same symmetries, one can demonstrate that the displacement field is written (Wack 1984) :

$$\rho = \rho_0 + u(\rho_0, \tau) \; ; \qquad \theta = \theta_0 + z_0 \tau \; ; \qquad z = z_0 + k z_0$$

With ρ_0, θ_0, z_0 and ρ, θ, z being the initial and actual cylindrical coordinates of a material point, and τ being the angle of torsion per unit length. By using the Pythagoras theorem one obtains :

$$\lambda_{\theta z} = \tfrac{1}{2} \rho_0 \tau + O[(\rho_0 \tau)^2] \; ; \qquad \lambda_{zz} = k + \tfrac{1}{2} (\rho_0 \tau)^2 + O[(\rho_0 \tau)^3]$$

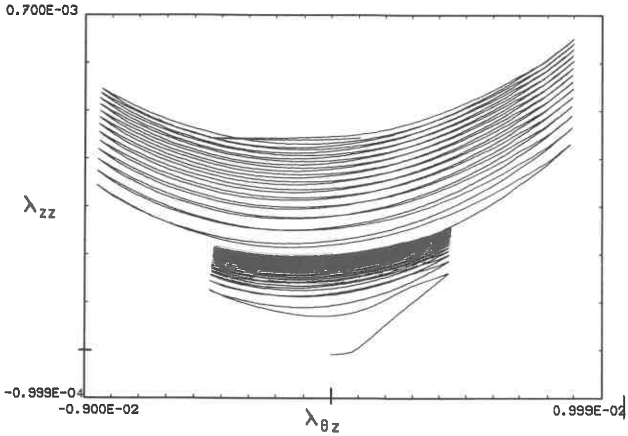

Figure 3.
Torsion ratchet with a small compression.
Stainless steel.
Test n° 214

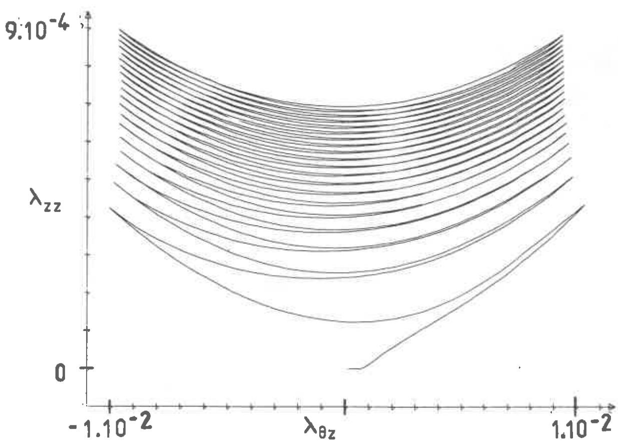

Figure 4.
Torsion ratchet with a small compression.
Stainless steel.
Test n° 217 run on a special device.

For a cyclic symmetrical torsion test the axial strain λ_{zz} can be separated into a parabolic "reversible part", and an axial elongation whose accumulation gives the ratchet phenomenon.

3 EXPERIMENTAL RESULTS

A typical result of a cyclic symmetrical torsion test with no axial force is represented on figure 1, giving the axial strain versus the shear strain : the test is a succession of three cycles of small (+ 0.45%) medium (+ 0.90%) and large amplitude (+ 1.37%). We see that the tube always elongates and the axial ratchet par cycle increases with the cycle amplitude. The parabolic geometrical effect is well reproduced. These results were confirmed by an other similar test N° 207 (Han 1985). The results of test 208, with nine large amplitude cycles seem to indicate that the rachet per cycle remains constant with the torsion cycle (fig. 2).

A tentative to modelize this ratchet by using the Jaumann derivative in the constitutive equation indicates that the axial elongation is proportional to the square of the shear strain for small strain and tends to be linear afterwords (Wack 1981 and 1982). Thus the results of these three tests with no axial force are summarized on figure with the mean ratchet per cycle Δk represented versus the square of the shear amplitude $\Delta\lambda_{\theta z}$. The initial parabolic evolution gives a ratio $\Delta k/\Delta\lambda_{\theta z}^2$ of

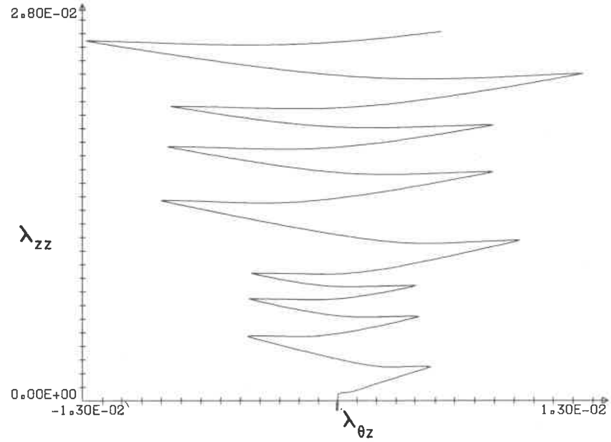

Figure 5.
Torsion ratchet with a traction of 107 MPa.
Stainless steel.
Test n° 203.

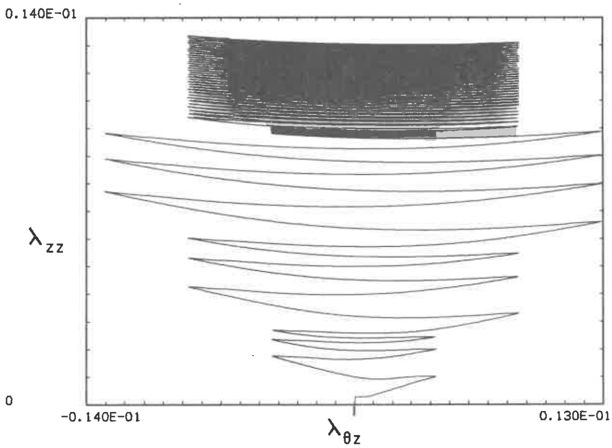

Figure 6.
Torsion ratchet with a traction of 50 MPa.
Stainless steel.
Test n° 210.

0.0133. For this shear strain amplitude interval it is possible to define a mean linear evolution with a mean ratio $\Delta k/\Delta\lambda_{\theta z}$ equal to 0.0033.

The "reversible part" of the measurements can be determined easily with the medium and large amplitude cycles : assuming a parabolic evolution of the axial ratchet we check that this part corresponds to the theoretical value within a mean relative error of $\pm$ 4 % ; this result has to be considered as verifying the correct strain measurement.

The servo-controlled hydraulic machine assures a condition of no axial force within an error of $\pm$ 10 N. Due to a poor adjustement, test 214 (fig. 3) was run with a small compression of -50 N (-0.31 MPa) and showed a reduction of the axial ratchet. This result is confirmed by test 217 (fig. 4) which was run on the special torsion device which unfortunately exerces always a small compression of about-20 N on the sample.

For the large cycles of test 214 the mean ratio $\Delta k/\Delta\lambda_{\theta z}$ is equal to 0.0009, i.e. more than three times smaller than the preceding results with no axial force. For test 217 the mean value, excluding the first cycle, is equal to 0.0012. Besides the reduction of this ratio, these two tests show that a small compression also introduces a regular reduction of the ratchet per cycle with the increase of the number of cycles. This reduction is about 1/4 between the first and the last cycle of the test 214 large cycle (fig. 3) and 1/7 between the second and last cycle of test 217. The "reversible part" of the measurement corresponds to the theoretical value within the same precision as previously. These two

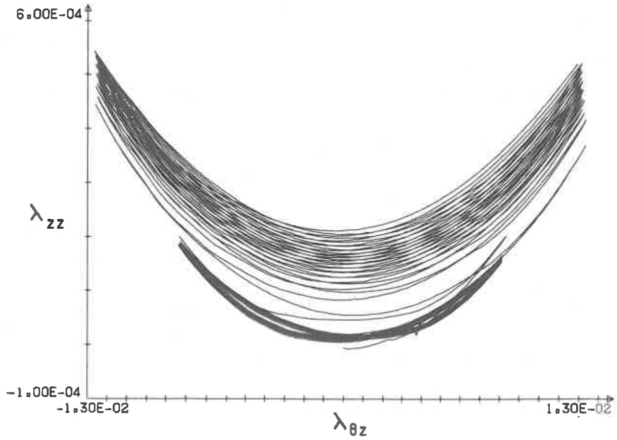

Figure 7.
Torsion ratchet with no axial force.
Superalloy.
Test n° 303.

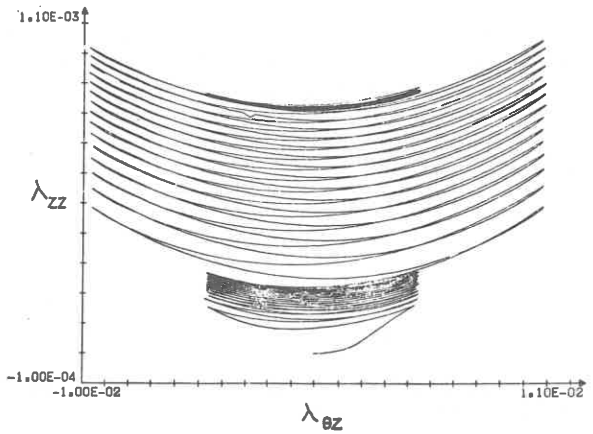

Figure 8.
Torsion ratchet with a small compression.
Engineering steel.
Test n° 405 run on a special device.

tests also show, as suggested by the first tests, that the first cycle gives a particular result : the ratchet is much larger than for the other cycles. We recall that for the principal effects the first cycle is also particular (Han, Wack 1987).

The two last test with the stainless steel were run with a constant traction : test 203 (fig. 5) and test 210 (fig. 6) with a mean traction of 107 and 50 MPa respectively ; these values represent 36% and 17% of the stress limit Y_0 before the consolidation takes place (Han, Wack 1987). The axial ratchet per cycle is much more important. With a constant axial stress of 107 MPa the mean ratio $\Delta k/\Delta\lambda_{\theta z}$ is equal to 0.29 ; in comparison the initial axial strain due to the axial load is only 0.053 % (fig. 5). With a constant stress of 50 MPa, and after excluding the ratchet of the first cycle the mean ratio $\Delta k/\Delta\lambda_{\theta z}$ is equal to 0.053 for the three sets of increasing cycle amplitude. After decreasing the amplitude of torsion the axial ratchet decreases drastically, but still remains positive for the small cycles (+ 0.42%) as for the medium cycles (+ 0.86%) : for these last cycles of shear amplitude 1.72%, the ratio $\Delta k/\Delta\lambda_{\theta z}$ is equal to 0.005, i.e. one order of magnitude smaller than initially and comparable to the ratchet with no axial force.

The two last tests concern the superalloy (fig. 7) and the engineering steel (fig. 8). Test N° 303 with the superalloy was run with no axial force : for the 22 small cycles the ratchet is almost null, and for the large cycles the mean ratio $\Delta k/\Delta\lambda_{\theta z}$ is equal to 4.5 10^{-4} , value which is one order of magnitude smaller than for the stainless steel. This result indicates that the ratchet is material dependent ; the validity of the experimental result can be checked by the axial strain "reversible part" which corresponds to the theoretical value within a relative error of 11%.

The test with the engineering steel was run on the special torsion device which gives a small compression on the sample. For the large cycles (+ 1.0%) the theoretical and experimental results of the axial strain "reversible part" correspond within a relative error of 10%. Excluding the first cycle, the ratio $\Delta k/\Delta\lambda_{\theta z}$ is equal to 0.8 and 2.1 10^{-3} for the small (± 0.5%) and the large cycles (± 1.0%) respectively. A set of small cycles run after the large cycles shows that the ratchet almost stops. An identical test (N° 219) run with a stainless steel sample gives results qualitatively similar and quantitatively with a reduction in the proportion of 1 to 0.7 (Han 1985).

SUMMARY AND CONCLUDING REMARKS

The experimental results show that the axial ratchet taking place during a torsion test with no axial force is always positive ; its amount is material dependent. A small axial force has a strong influence on it. It is not clear in which case the ratchet per cycle keeps constant or decreases to zero. The use of the Jaumann derivative in the constitutive equations does not explain all these results. This ratchet phenomenon continues to be an open problem theoretically and experimentally.

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