STRENGTH OF A SMOOTH SHELL IN THE PRESENCE OF RESIDUAL STRESSES

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A shell made from a plate by shock loading has variable residual stresses and strains, which influence the strength and the distribution of the working stresses.

Figure 1 shows an end cover made by pulse stamping from 08KP sheet steel 1 mm thick and 330 x 135 mm with a drawing depth of 25 mm.

The residual strains were recorded at various points on the inside and outside surfaces with strain gages placed in pairs along the directions of principal curvature at each point.

The residual stresses were calculated via the theory of elasticity [1]. Figure 2, a and c, shows the distribution of the residual stresses on the outer surface with transverse sections shown on the left and longitudinal ones on the right. The sign of the stress changes in regions where the curvature changes. The ribs (with frequent sign change in the curvature) complicate the distribution of the residual stresses.

The residual stresses are calculated from the measured residual elastic strains and are sums of the residual stresses arising from the normal forces and the bending moments, so they may be distinguished via the following relations:

\[ \sigma_1 = \sigma_1^{\text{NI}} + \sigma_1^{\text{MI}}, \quad \sigma_1 = \sigma_1^{\text{NI}} - \sigma_1^{\text{MI}}; \]

\[ \sigma_1^{\text{NI}} = \frac{1}{2} (\sigma_1 + \sigma_1^r); \quad \sigma_1^{\text{MI}} = \frac{1}{2} (\sigma_1 - \sigma_1^r). \]

Here \( \sigma_1 \) and \( \sigma_1^r \) are the residual stresses on the outside and inside surfaces, while \( \sigma_1^{\text{NI}} \) and \( \sigma_1^{\text{MI}} \) are the residual stresses arising from the normal forces and bending moments.

Figure 3, a and c, shows the residual stresses in transverse sections: on the left, those due to the normal forces; on the right, those due to the bending moment. Figure 3, b and d, shows the residual stresses in longitudinal sections in the same way.

Residual stresses produced by pulse stamping in the transverse section are caused primarily by bending moments and in the longitudinal section by normal forces.

The ribs reduce the resultant residual stresses from the bending moment, while in the middle of the shell they produce ones of reverse sign. The various radii of curvature and the ribs are responsible for the changes in sign and numerical value. The residual stresses in a transverse section exceed those in a longitudinal one because of flexure and drawing, which result in large plastic deformations.

The two widely separated transverse sections differ in the distribution of the residual stresses due to the normal forces on account of the transition to the narrow end.
The effects on the strength were evaluated from tests on the yield point and plastic deformation in stretching specimens with \( \ell_0 = 50 \text{ mm} \) cut transversely from a sheet of 08KP.

Table 1 gives the yield point \( \sigma_y \) as a function of the plastic strain \( \varepsilon \) for 08KP, as well as the working stresses \( \sigma_1^W \) and \( \sigma_2^W \) together with the residual ones \( \sigma_1^R \) and \( \sigma_2^R \), the reserve strengths \( n^r \) and \( n \) with and without allowance for the residual stresses, and the parameter \( k \) for the effects of work hardening and residual stress.

The yield point is dependent on the work hardening relative to the annealed state and at first increases considerably, with the largest value for \( \varepsilon \) of 20-25%. This is followed by a fall. The numerical value for the nominal yield point has been calculated with a tolerance corresponding to the residual strain.

The residual plastic strain after drawing was deduced from the parameters of a rectangular network of lines on the outside of the original plate.

The residual and working stresses add within the limits of elastic strain exactly as for stresses due to external loads, i.e., the forces act independently, so the safety factor can be deduced from the following relation [2] for a two-dimensional state of stress:

\[
n = \frac{V^2 \sigma_y}{V^2 (\sigma_1^r - \sigma_2^r + \sigma_2^r) + \eta_u (\sigma_1^r + \sigma_2^r)}
\]

where \( \sigma_1 = \sigma_1^W + \sigma_1^r; \sigma_2 = \sigma_2^W + \sigma_2^r; \sigma_1^W \) and \( \sigma_2^W \) are the principal working stresses, \( \sigma_1^r \) and \( \sigma_2^r \) are the principal residual stresses, and \( \eta_u \) is the factor for unequal strength, which was taken as 0.12 for 08KP steel.