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# Modelling of hardening behaviour of cold expanded holes in medium-carbon steel

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**Abstract**

Cold expansion is a well-known approach for the enhancement of the fatigue life of fastener holes in structural components by introducing residual compressive circumferential stresses around them. In this work, the hardening of a medium-carbon structural steel is studied experimentally and numerically from the point of view of the material behaviour during the cold expansion process of holes in structural steel components. Six material hardening models obtained on the basis of symmetric strain-controlled experiments and half-cycle test data from unidirectional tension experiments have been used in a two-dimensional axisymmetric finite element model of the process. Parallel with this an x-ray diffraction analysis of the residual stresses at the entrance and exit faces of the structural component has been carried out to prove the finite element result's authenticity. It is established that the nonlinear kinematic hardening model obtained by a strain-controlled cyclic test to achieve a stabilized cycle for this steel secures finite element results close to the experimental ones. The constitutive hardening model obtained can be applied to a corresponding finite element model for stress analysis of steel structural component with cold expanded holes, subjected to an external load.


*Keywords:* Medium-carbon steel; Hardening; Residual stresses; Finite element analysis; Cold expansion; Fatigue life enhancement

## 1. Introduction

Stress and fatigue analysis of structural components, without taking account, the residual stresses resulting from the manufacturing process, is insufficient for reliable prediction of their behaviour in the operational process. In some cases it is possible for unexpected fatigue to be caused due to residual stresses which can seriously shorten the fatigue life of the respective component when combined with service stresses. In cases of cold expanded holes, taking into account compressive residual stresses around them inaccurately in strength estimation, also leads to inaccurate mathematical models for the prediction of fatigue life of structural components.

The cold expansion is a well-known method for the enhancement of the fatigue life of structural components with cylindrical holes by means of creating compressive tangential residual stresses around them [1–4]. These stresses are very beneficial for resisting fatigue since they reduce the resultant longitudinal stresses at the critical points around the hole when the structural component is subjected to an external tensile load. Such reduction of the resultant stresses is shown in Fig. 1. The action of the residual compressive field around the cold expanded hole (Fig. 1b) can be compared to brackets which close the existing cracks and impede the formation of new ones.

The cold hole expansion method has been invented for aerospace industry, but can be implemented in conventional machinery construction on steel components [5].

The determination of the residual stresses around cold expanded holes, and these stresses which play an important role in increasing the fatigue resistance of the material, are a subject of scientific research [6–9]. With the rapid development of the finite element method and computer technology, numerical solutions can be carried out more efficiently for the cold hole expansion process. The known numerical

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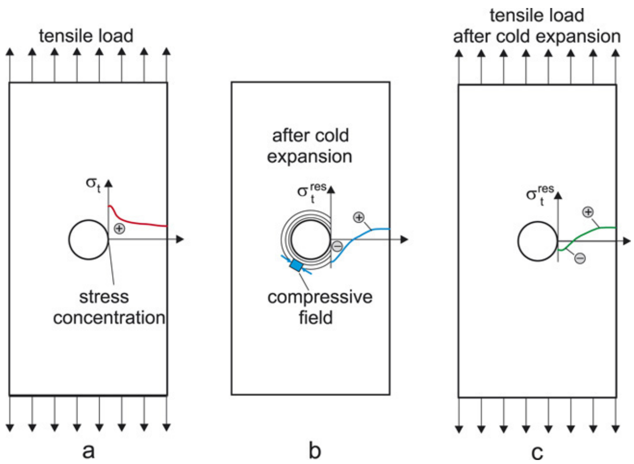


Fig. 1. Stress distribution at critical points of holed structural element undergoing a tensile load: a. hole formed only by cutting; b. residual stress distribution after cold expansion; c. benefit of cold expansion.

solutions [7–9] of residual stresses have been found mostly for the cases of aerospace aluminum alloys when the plate thickness is small. In the cases of steel components which are characteristic of conventional machinery construction, the problem of determination of the residual stress field remains open. In addition to realistic geometry and boundary conditions, an adequate mechanical constitutive model of the material is necessary in the finite element model of the process.

The tool impact on a previously drilled hole causes cyclic loading in the vicinity of each point from the hole surface and as a result, the tangential normal stress changes its sign. As a result, deformation anisotropy appears — it is characterized by an irregular expansion or contraction with the movement of the yield surface in the stress space. Information about deformation anisotropy modelling of cold hole expansion process in medium-carbon steel is not available in the research publications.

The main objective of this is to suggest a solution for suitable model of material hardening in finite element models of the cold hole expansion process in medium-carbon steels.

## 2. Theoretical background of the research

Nevertheless, the cold expansion can be carried out by different methods — (1) A solid mandrel with a bulge in or without conjunction with a split sleeve that has parallel walls [1]; (2) A split mandrel [1]; (3) A tapered mandrel used with a mating tapered split sleeve [2]; (4) Spherical mandrelling [5,6,10], where the tool performs a complex motion — the residual stress distribution in qualitative aspect is the same. A feature common to all four methods is that an oversized tool is forced through the hole to produce a local plastic field surrounded by an elastic one. Once the tool is removed allowing the elastic field to spring back, it results in compressive circumferential normal residual stresses around the hole. In this aspect, chronologically the first method — a solid mandrel without conjunction with split sleeve moving translationally only — appears to be a basic method and it is a subject of modelling and analysis.

Since the workpiece material is medium-carbon steel its constitutive model can be assumed as rate-independent elastic–plastic model in which the type of hardening has to be specified. Because of the cyclic loading in the vicinity of each point around the hole, the hardening model has to account for the following phenomena: Bauschinger effect, cyclic hardening with plastic shakedown, ratcheting and relaxation of the mean stress. Six hardening models of medium-carbon steel have been made on the basis of two experimental one-dimensional tests: a symmetric strain-controlled cyclic experiment with strain range $2\Delta\varepsilon$ that corresponds to the strain range anticipated in the finite element analysis; a half-cycle experiment. These include: (1) nonlinear isotropic/kinematic hardening, (2) nonlinear kinematic, (3) linear kinematic, all obtained by a stabilized cycle, and (4) isotropic, (5) nonlinear kinematic, (6) linear kinematic, obtained by the second test (half-cycle).

For these models the yielding surface and the equivalent Von Mises stress are:

$$F = f(\sigma_{ij}^{a}) - \sigma^{0} = 0, \tag{1}$$

where $\sigma_{ij}^{a} = \sigma_{ij} - \alpha_{ij}$, $\sigma_{ij}$ is a stress tensor, $\alpha_{ij}$ is a micro-stress tensor (back stress tensor), $\sigma^{0}$ is the equivalent stress defining the size of the yield surface, whose initial value is $\sigma|_0$ — equivalent stress defining the size of the yield surface at zero plastic strain ($\sigma^{0}$ is determined through an one-dimensional test and it is assumed that $\sigma^{0}$ is valid for all possible stressed states and loading paths),

$$f(\sigma_{ij}^{a}) = \sqrt{-3I_2(s_{ij}^{a})}. \tag{2}$$

The components of the second invariant $I_2$ of the deviatoric stress tensor are:

$$s_{ij}^{a} = \sigma_{ij}^{a} - \frac{1}{3}\delta_{ij}\sigma_{kk}^{a} \tag{3}$$

where $\delta_{ij}$ is Kronecker symbol.

For a temperature-independent problem the kinematic law is:

$$\dot{\alpha}_{ij} = \frac{C}{\sigma^{0}}\sigma_{ij}^{a}\dot{\bar{\varepsilon}}^{Pl} - \gamma\alpha_{ij}\dot{\bar{\varepsilon}}^{Pl}, \tag{4}$$

where $C$ is the initial kinematic hardening modulus, $\gamma$ is the coefficient which determines the rate of decreasing the kinematic modulus when increasing the equivalent plastic deformation $\bar{\varepsilon}^{Pl}$.

The material parameters $C$ and $\gamma$ must be determined on the basis of experimental tests. When $\gamma = 0$, the nonlinear model (4) transforms into Zeigler linear hardening model [11].

The isotropic hardening can be described by a simple exponential law [12]:

$$\sigma^{0} = \sigma|_0 + Q_\infty\left(1 - \mathrm{e}^{-b\bar{\varepsilon}^{Pl}}\right), \tag{5}$$

where $Q_\infty$ and $b$ are material parameters: $Q_\infty$ is the maximum change in the yield surface size, $b$ defines the rate at which the yield surface size changes with plastic strain growth. When in the isotropic part (5) $Q_\infty$ and/or $b$ are equal to zero, the model