The rolling simulation for cold work metal hardening

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Abstract. This article describes the results of a calculation and experimental analysis of destructive physical phenomena that appear in critical sections of industrial and power-related equipment, and lead to occurrence of various operational damages. It was shown that pipeline welded connections are the sections most prone to crack development, therefore the traditional strength calculations need to be combined with fracture mechanics criteria and thorough materials analysis of flawing and structural imperfection. The cold work hardening technique was proposed as a solution for the problem of critical sections performance property restoration. The technique uses surface plastic deformation phenomenon to change the material’s through-thickness stress distribution. In order to optimise surface hardening for welded connections prone to defect formation, we proposed a simulation for analysing an actual pipeline sections load. To assess the applicability of the simulation results, the cold work hardening technique was developed and introduced using a full-scale test sample for damaged areas of welded connections in ø426×40 vent pipes at Novovoronezh NPP Unit No.5.

1. Introduction
The long history of industrial facilities operation shows that fabrication and power-generation equipment operating in extreme conditions usually has critical components or sections with a higher damage rate due to an insufficient structural margin. It is most apparent in case of processes that involve pipelines operating in high temperature and pressure differentials. A large number of welded connections increase service damage risk [1-8].

This problem is usually associated with a risk of severe environmental and property damage. A prompt replacement of failed equipment is not always possible. In such cases there is a need for remedial operations to restore equipment service properties to an acceptable level by hardening machine parts and structural components for the entire service life or, at the very least, until a scheduled replacement of equipment.

The occurrence kinetics of service defects, that cause a facility’s critical components’ integrity damage, is related to structural features of the components (i.e. the materials used, assembly process specifics, geometrical configuration of an item), loads unaccounted for during the design stage, medium characteristics (corrosive power, scale buildup, thermal and distortional stress, etc.).
A possible solution to the problem described would be to implement surface cold work hardening, which uses surface plastic deformation phenomenon to change the material’s through-thickness stress distribution.

2. Stress-related properties of equipment’s damaged surface

Pipe welded connection surfaces are especially susceptible to cracks formation and development, therefore the traditional strength calculations need to be combined with fracture mechanics criteria, as well as in-depth material defect causes and structural discontinuity analyses.

It is not enough to discover a crack before it is late – it is also important to analyse all of its propagation stages – from causes and factors of crack formation to its extension rate that led to an unacceptable state. An important part of such analysis is development of procedures for control and calculated analysis of actual loads in pipe sections prone to service-induced damage, with a follow-up measures for service defect prevention.

The purpose of calculational and experimental justification is to optimise surface hardening for welded connections prone to defect formation. The cold surface rolling causes elasto-plastic strain in metal, with only primary stress, which defines the elastic strain value, decreasing after load action is cancelled [9,10]. The additional strains, that are locked-up in the material after the deformation ends, are called residual stresses. The residual stresses lead to a deformation resistance increase and changes in through-thickness stress distribution. The cold work hardening itself leads to alteration of stress-related properties and structure in section affected by plastic deformation.

The residual stress values are affected by the following factors [9]:

- Metal structural discontinuity (the higher this value is – the higher the Type II stresses are).
- Deformation resistance value (the higher this value is – the higher residual stresses are).
- Deformation degree (combined residual stresses rise until deformation degree reaches 30%, and then decreases considerably).
- Processing type and conditions (external friction, greasing and other factors).
- Deformation speed (it increases irregularity in residual stresses distribution; note that it is essential to take heat exchange processes into account).
- Deformation and operating temperature (residual stress level gradually decreases at elevated temperatures).

The residual stresses are essential in solving the problem, as they increase fatigue resistance. To optimise the rolling process, which provides a protective level of surface residual stresses, it is necessary to perform calculated modelling of chosen surface hardening technology in order to assess the optimal parameters for surface plastic deformation.

The cold surface rolling causes elasto-plastic strain in metal with residual stresses left after load action is cancelled. The residual stresses lead to a deformation resistance increase and changes in through-thickness stress distribution. The cold work hardening itself leads to alteration of stress-related properties and structure in section affected by plastic deformation [9]. The distribution of hardness and residual stress is shown in figure 1.

Residual stresses are divided in three types: Type I (equilibrate in large volumes); Type II (equilibrate in grain-scale volumes); Type III (equilibrate in volumes at crystalline grid size level). It is important to keep in mind that Type I residual stress energy amounts to 0.1% of the total strain energy, Type II residual stress energy – to around 1%, while for Type III – 99%.

There are following main surface plastic deformation parameters: elastic and plastic strains in deformation source, tool and working surface contact area, force impact on the tool, the resulting stresses and force application ratio [9].
Figure 1. Alteration in the surface level of surface-hardened metal. Herein: \( \text{HV}(z) \) – Vickers hardness number; \( \text{HBV}(z) \) – Brinnel hardness number; \( Q_{i}^{ES} \) - residual stress intensity; \( Q_{a}^{ES} \) – axial residual stress; \( R_{s}, R_{a} \) – surface roughness parameter.

3. Rolling calculated model

To determine optimal performance for a finite element method rolling, a simulation was developed, which allowed to calculate elasto-plastic strain in material using rolls with different initial geometry. During the development of the simulation, the following assumptions were made:

- Roll is deemed completely rigid.
- Roll moves without slip.
- There is no friction between the roll and the treated surface [10].

Key parameters of the calculated model:

1. At the first stage the treated material is deemed homogenous – steel 10GN2MFA in reference state. True stress behaviour graph and its’ approximation, used in the simulation, are shown in figure 2. The initial experimental graph was made in accordance with the National State Standard GOST 1497-84; the calculation factors in stress-related properties of welded connection components [10, 11].

2. The roll’s radius \( R_{P} = 20 \) mm, the roll’s sections’ radii \( R_{pr} = 1.6/2.5/4.0 \) mm.

Figure 2. True stress behaviour graph for steel 10GN2MFA (1) and its’ approximation (2).

The load model, adopted for the calculation, is shown in figure 3 [10]. Rolling can be carried out either with bulge height \( U [\text{mm}] \) controlled, or with load rate \( P [\text{H}] \) controlled. \( V [\text{mm/min}] \) – rolling speed, \( \omega [\text{rad/min}] \) – roll angular rotation rate, \( S \) – advance. If treating a cylindrical surface, advance is measured in mm/rotation, if treating a flat surface, advance is measured in mm.
Figure 3. Roll view with a load distribution scheme.

The resulting model, calculated using the finite element method, with area affected by surface plastic deformation outlined, is shown in figure 4. The sample is 5 mm thick. Its’ bottom surface is rigidly fixed, while profile planes are in symmetrical border-line conditions, therefore the sample reacts in the same way as an infinite in size plate along X and Y directions.

Figure 4. Simulation of welded joint rolling.

To take into account the objective geometric characteristics of a welded connection, as well as natural distribution of properties and factoring in a combined stress strain behaviour of metal in contact with a roll, a detailed 3-dimensional finite element model of a composite welded joint was developed. The overview of that model is shown in figure 5. The model comprises around 1 200 000 nodes. It is developed using UZOR 1.0 software, which is designed to perform finite-element calculations based on superelement method. Equilibrium of a certain level superelement is described using node parameters with a following model:

\[
\{q^\alpha, \delta\} = \{P^\alpha, \delta\}
\]

where \(\alpha\) - number of the reference design sequential partitioning level; \(\delta\) - superelement number for a given partitioning level.

Let us divide nodal values (nodes) of a superelement into internal and external ones, and write a superelement equilibrium as a block expression:

\[
\begin{bmatrix}
K_{ii} & K_{is} \\
K_{si} & K_{ss}
\end{bmatrix}
\begin{bmatrix}
q_i \\
q_s
\end{bmatrix}
=
\begin{bmatrix}
q_i \\
q_s
\end{bmatrix}
\]

where \(i\) - internal nodal value index; \(S\) - boundary nodal value index; \(\{q_i\}\) - internal nodal displacement vector; \(\{q_s\}\) - boundary nodal displacement vector; \(\{P_i\}\) - internal nodal load vector; \(\{P_s\}\) - boundary nodal load vector.
The complete design shows up as an assembly of coordinated elements of various levels. The model provides detailed deformation and stress fields for rolling process, while factoring in the distribution of initial residual stresses.

4. Conclusion

This kind of a 3-dimensional finite element model allows to factor in various imperfections in pipelines, like repair samples in composite welded connection areas.

The model was used to search an area of maximum operational damaging due to a heat current stratification effect, which results in a considerably uneven temperature distribution across pipe cross-section.

The stress strain behaviour analysis shows that due to a difference in material thermal expansion factor, a welded joint expands more than the parent metal and bulges towards radius increase, which results in local bending tension stress on an external part of a joint and pressure tension stress on an internal part. Also, a pipe cross-section deforms as a result of an impact of uneven temperature pattern due to heat current stratification and proximity of elbows.

To assess the applicability of the simulation results, the cold work hardening technique was developed and introduced using a full-scale test sample for damaged areas of welded connections in Ø426×40 vent pipes at Novovoronezh NPP Unit No.5.

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