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High Carbon Wire Cracking during Cold Forming Process

Vznik trhlin vysokouhlíkového drátu při tváření za studena

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Abstract

The article focuses on the issue of crack formation in high-carbon steel wires during the cold upsetting process. This operation ensures the fixation of wire ends in prestressing systems, particularly in systems for concrete tower structures of wind turbines. FEM simulations, physical experiments, and metallographic analyses were used to analyse the causes of these defects. Computer simulations confirmed the presence of unfavourable tensile stresses occurring in the upset parts of the wires. This finding led to the design of a modified tool. In the new tool, tensile components are minimized and compressive stresses prevail in the deformed zone, which are safer in terms of plasticity and the risk of material failure. Physical simulations were carried out on samples with varying levels of initiation defects. It was confirmed that defect depth and the magnitude of the applied deformation influence the resulting crack opening. Based on these results, an adjustment of the sample height was proposed for the physical simulation. The results of the study contribute to a deeper understanding of the mechanisms of material failure during forming and may serve as a basis for improving tool design and increasing the reliability of the manufacturing process.

Keywords*: wire, cracking, cold forming, FEM, metallography*

Abstrakt

Článek se zabývá problematikou vzniku trhlin v drátech z uhlíkové oceli během procesu tváření za studena. Tato operace zajišťuje upevnění konců drátů v předpínacích systémech, zejména v systémech pro betonové stožárové konstrukce větrných turbín. K analýze příčin těchto vad byly použity simulace metodou konečných prvků (FEM), fyzikální experimenty a metalografické analýzy. Počítačové simulace potvrdily přítomnost nepříznivých tahových napětí v deformovaných částech drátů. Tento poznatek vedl k návrhu upraveného nástroje, v němž jsou tahové složky minimalizovány a v deformované zóně převládají tlaková napětí, jež jsou bezpečnější z hlediska plasticity a rizika selhání materiálu. Fyzikální simulace byly provedeny na vzorcích s různou hloubkou počátečních vad. Bylo potvrzeno, že hloubka vady a velikost aplikované deformace ovlivňují výsledné otevření trhliny. Na základě těchto zjištění byla navržena úprava výšky vzorku pro fyzikální simulace. Výsledky studie přispívají k hlubšímu pochopení mechanismů selhání materiálu během tváření a mohou sloužit jako podklad pro optimalizaci konstrukce nástrojů a zvýšení spolehlivosti výrobního procesu.

Klíčová slova: *drát, vznik trhlin, tváření za studena, metoda konečných prvků (FEM), metalografie*

1. Introduction

High-carbon steel wire represents a key material for the production of individual segments or more complex units of prestressed concrete, where it serves as the carrier of tensile stress transferred into the concrete structure. These steel wires are used, for example, in the manufacture of prefabricated floor panels, railway sleepers, and in the construction of bridge structures [1, 2].

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For many years, the range of stabilized steel wires has also been used to reinforce the segmental towers of wind turbines. Historically, their construction was based primarily on steel (tubular) shells. However, concrete towers demonstrate higher resistance to extreme loads, particularly in taller structures [3].

Steel tubular towers higher than 85 m are no longer able to provide adequate behaviour under vibrations induced by the wind turbine. The blade size of the wind turbine and the tower height represent essential parameters related to turbine performance. Since the energy generated from wind is a function of the cube of the wind speed, even a small increase in wind velocity can significantly improve the turbine's output [4].

Non-hybrid tower systems consist of prefabricated concrete segments that, once assembled, are subsequently prestressed through openings using post-tensioning systems [5]. This method, referred to as "post-tensioned," provides high resistance to bending and tensile loads, ensures the connection of all segments into a single static unit, and also allows the tower to be prestressed directly at the installation site.

From the perspective of wire material characteristics, these can be described as steels with a higher (essentially eutectoid) carbon content. The required properties [6] are achieved through a combination of chemical composition and wire manufacturing technology, where the wires are cold-drawn or thermomechanically processed in the final stages. This production method guarantees high strength characteristics along with low relaxation, which is desirable for such applications [7, 8].

With constant deformation of non-stabilized wires over time, their stress in the "concrete" system decreases, which negatively affects the structural properties and may ultimately lead to structural damage or even catastrophic failure [9].

The aim of this article was to analyse the causes of crack formation occurring in the upset areas of high-carbon wires during or after the cold forming process. This type of end modification ensures the fixation of wires in prestressing systems and, alongside the required wire properties, represents—within this context—a key parameter for the overall functionality of the system.

2. Evaluation of the Geometry of Upset Wire Sections and Tool Design for FEM Simulation

As part of the evaluation of crack occurrence in upset wire sections, a computer simulation was carried out with the aim of better understanding the deformation and stress conditions occurring during this operation. However, the modelling itself was preceded by the need to define the tool shape, whose geometry was not known. Nevertheless, upset wires without cracks were available (if a defect occurs in the upset part, the shape is naturally modified; from this perspective, it was desirable to use upset wires free of defects).

Using a Keyence device [10], which enables fast and accurate measurement of complex shapes through optical scanning, the geometry of the upset wire section was measured. This measurement, which essentially replaces gauging with conventional measuring instruments, was carried out in six differently oriented planes, with the outputs of all six evaluations taken into account during the tool design. The measured values in a selected plane are shown in **Fig. 1**.

Based on these measurements, a tool—or rather a pair of tools (upper and lower die)—was designed. The shape of the upper part reflected the fact that the upset material is in contact with the upper tool only up to a certain stage of the upsetting process. This was recognizable through differences in curvature (for the demonstrated cross-section, this is more clearly visible on the right-hand side of **Fig. 1**, see the R3.135 and R6.022 interfaces). This location therefore represents the point where the material-tool contact ends (or begins).

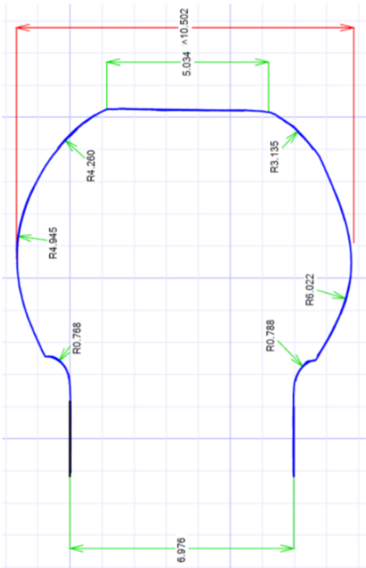

Fig. 1 Measurement results of the geometry of the upsetted wire section

Obr. 1 Výsledky měření geometrie zúženého úseku drátu

3. Physical Simulation of the Upsetting Process

The industrially applied process of wire-end upsetting is often physically simulated in order to verify the potential occurrence of initiation defects present in the wire. This approach can replace, for example, metallographic examination of cross-sections and is faster compared to microscopic techniques (since the samples do not need to be fixed into mounts, ground, or otherwise laboriously prepared for metallographic evaluation).

This process is usually carried out on multi-purpose hydraulic presses, where samples taken from the wire are upset using "dies" that either correspond to or closely approximate the tools used in production. The same approach was taken in this case.

In total, four series of samples were prepared from the manufactured wires (always three samples per series, i.e., 4x3=12 samples). The selection of input material for individual samples was based on previously performed metallographic evaluations. Thus, wire locations containing initiation defects of varying but pre-determined extent was selected. The last series of samples was prepared from defect-free locations.

All 12 cylindrical samples were prepared by turning so that the cylinder bases were perpendicular to the longitudinal axis of the sample. The intention was to prepare samples with a uniform length of 15 mm. The actual length of individual samples is documented in the graph in **Fig. 2a**. It is evident that one of the samples had a significantly lower height compared to the others. All samples were then cold-deformed by upsetting (see **Fig. 2b**).

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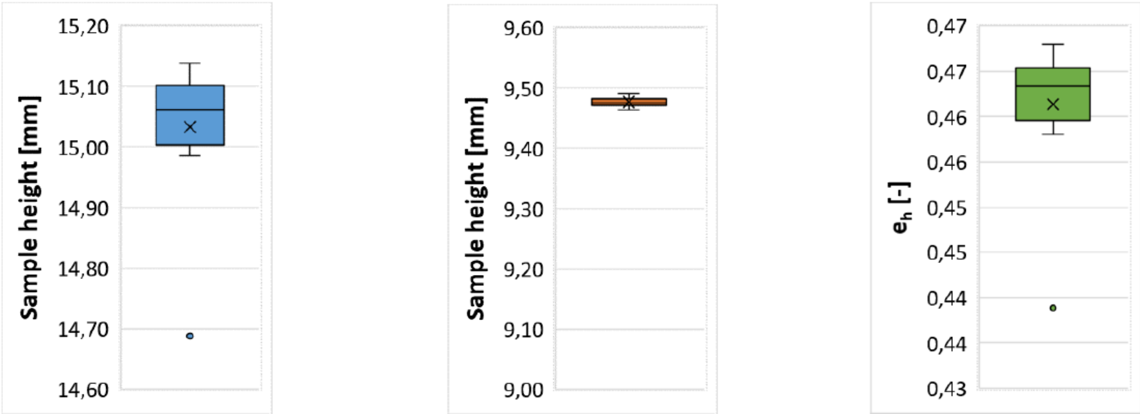
Considering the practically identical height of the samples after upsetting, the actual height reduction of each sample depended on its initial height dimension (**Fig. 2c**). After the upsetting test, the geometry of all samples, including the width of the observed defects, was measured. Defects in the upset areas were found only in samples numbered 1 to 9 (those with present initiation cracks).



a) before upsetting
b) after upsetting
c) calculated strain

Fig. 2 Height and strain of tested samples / **Obr. 2** Výška a deformace testovaných vzorků

4. Metallographic Analysis and Results of Defect Width/Depth Measurements

Microstructural evaluation was performed on industrially processed wires in which defects of the upset sections were recorded. Cross-sections were examined in areas beneath the upset part, as well as in other (more distant) locations from the upset area, in order to assess the variability of the initiation crack depth. Sections in these distant locations were also used as "inputs" for preparing samples for physical simulation of the industrial upsetting process. Based on measurements of defect opening width in the upset part and the depth of the initiation defect, relationships were established, as documented in the graph in **Fig. 3**.

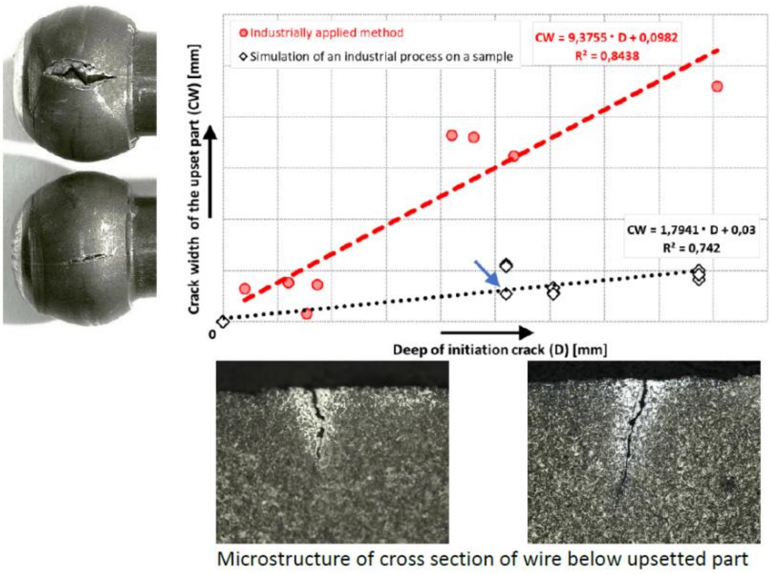


Fig. 3 Correlation between initial crack depth and crack opening after upsetting

Obr. 3 Vztah mezi počáteční hloubkou trhliny a jejím rozšířením po tváření

For both the industrially applied upsetting process and the physically simulated wire upsetting process, the crack opening in the upset section increases with the increasing depth of the initiation defect. In this evaluation, other influences (such as structural heterogeneities, inclusions, grain size, etc. [11, 12]) were not considered. It is evident that the slope of the linear relationship is approximately five times higher for the industrial process compared to the physical simulation. This may partly be related to the different tool shapes or to the lower deformation applied in the simulated process. Measurements of the diameters of upset sections at the point of maximum bulging revealed higher values for the industrially processed wires. The effect of deformation magnitude on crack opening width is also visible in the distribution of a selected data series (indicated by an arrow in the graph in **Fig. 3**). In this case, one of the three samples experienced a lower degree of deformation (in **Fig. 2a** and **Fig. 2c** this is represented by an outlier), which ultimately resulted in a smaller crack opening.

From a practical point of view, it seems more appropriate that the simulation of the industrial upsetting process should, in terms of initiation defect opening, provide results analogous to the industrial process itself. In this sense, a calculation was carried out to determine the actual deformation required during sample upsetting, i.e., what the initial sample dimension should be in order to ensure that the results of the physical simulation approach those achieved in industrial upsetting. This is described by the following equation (1), where "d" represents the maximum diameter (maximum bulging) of the upset sample (a value of 10.5 mm was measured on industrially upset samples), "h0", and "h1" represent the height of the sample before and after deformation, respectively.

$$h_0 = \left[e^{\left(\frac{d-6,075}{8,691}\right)} \right] \cdot h_1 \text{....[mm]} \qquad (1)$$

It is worth noting the character of the microstructure in the vicinity of the initiation cracks. The presence of a ferritic phase in steel of this composition indicates that these defects originated before hot rolling. During the drawing of the rolled wire, the existing surface defects are modified. For a crack that is characterized by a low width-to-depth ratio, i.e., a ratio lower than one, it is recommended to remove the defect from the wire before drawing [13, 14].

Cracks of this type (parallel to the loading direction) are associated with surface defects. In addition to these cracks, there also frequently occur cracks inclined at an angle of 45° to the loading direction (**Fig. 4**). These cracks, referred to as shear cracks, are related to the exhaustion of plasticity or the increase in strength due to strain hardening [15]. Their inclination with respect to the loading direction is associated with the maximum shear stress, which, under uniaxial stress conditions, reaches its highest values precisely on planes inclined at 45° to the direction of loading.

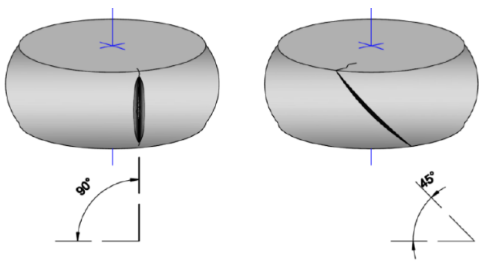


Fig. 4 Types of cracks occuring during the upsetting process

Obr. 4 Druhy trhlin vznikajících při procesu tváření

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5. FEM Simulation

Mathematical modelling of the upsetting process was carried out using the finite element method, which enables a detailed analysis of the stress–strain state. The FE analysis was performed as a 2D axisymmetric task without considering the generation of deformation heat. To describe the material's deformation behaviour, a rigid–plastic model was used. For the description of the yield strength of the material, a model based on Spittel's equation (2) was developed.

The constants in the equation were determined from a series of tensile tests performed on the specific material at room temperature:

$$\sigma_y = 2163 \cdot e^{0.056} \quad ....[MPa] \tag{2}$$

The Tresca friction model was applied, with the friction factor "m" set to 0.6, which corresponds to cold forging without the use of lubrication [16].

Within the simulations, two variants of cold heading were carried out. The purpose of the first variant, based on previously performed measurements of upset wire shapes, was to evaluate the stress–strain states during the industrial process. Using this knowledge, the forming process was then optimized in order to eliminate the occurrence of unfavourable tensile tangential stresses in the surface layers of the wire.

Tangential stresses act in the polar coordinates used in this 2D model in the direction of angle α. If these stresses are tensile, they cause the opening of longitudinal defects that are already present in the drawn wire, originating from hot rolling or steel casting (see decarburization in the vicinity of defects visible in **Fig. 3**, which indicates that these flaws existed in the material before heating). Conversely, if these stresses are compressive, they can lead to complete or at least partial forging welding of already opened defects (the degree of integrity of such a weld depends on the extent of surface contamination of the defect by original oxides originating from the hot rolling stage). If these stresses exceed the strength of the wire, they cause the formation of cracks (most often shear cracks) after a certain level of deformation is reached, even without the presence of an initial defect.

In the manner described above, a modified shape of the upper and lower tool was gradually developed. The model shape of the wire termination for the current variant, as well as the newly designed shape, including the strain intensity field at the end of forging, are shown in **Fig. 5**. As can be seen from the **Fig. 5**, in order to ensure lateral pressure on the head while maintaining its maximum width of 10.5 mm, the newly designed "head" must be slightly smaller than the original (originally 7.7 mm, now 6.8 mm). This results in a higher value of maximum strain intensity, which is 1.40 for the original tools and 1.67 for the new tools. By using a higher input, the same head height could also be achieved for the new tools. Under these conditions, however, the key forging ratio of initial height to initial diameter h0/d0 would exceed the value of 2.5, which in practice often leads to bending of the forging and its collapse during forging (under the current conditions, h0/d0 = 2.42!).

Fig. 6 shows the results of tangential stress in the key stages of head forging. As expected, the tangential stress when using the modified tools (**Fig. 6b**) just before contact with the die sidewall is lower (+1,493 MPa) than in the case of the original tools (**Fig. 6a**) at the end of forging (+1,590 MPa), mainly due to the use of a flat upper anvil.

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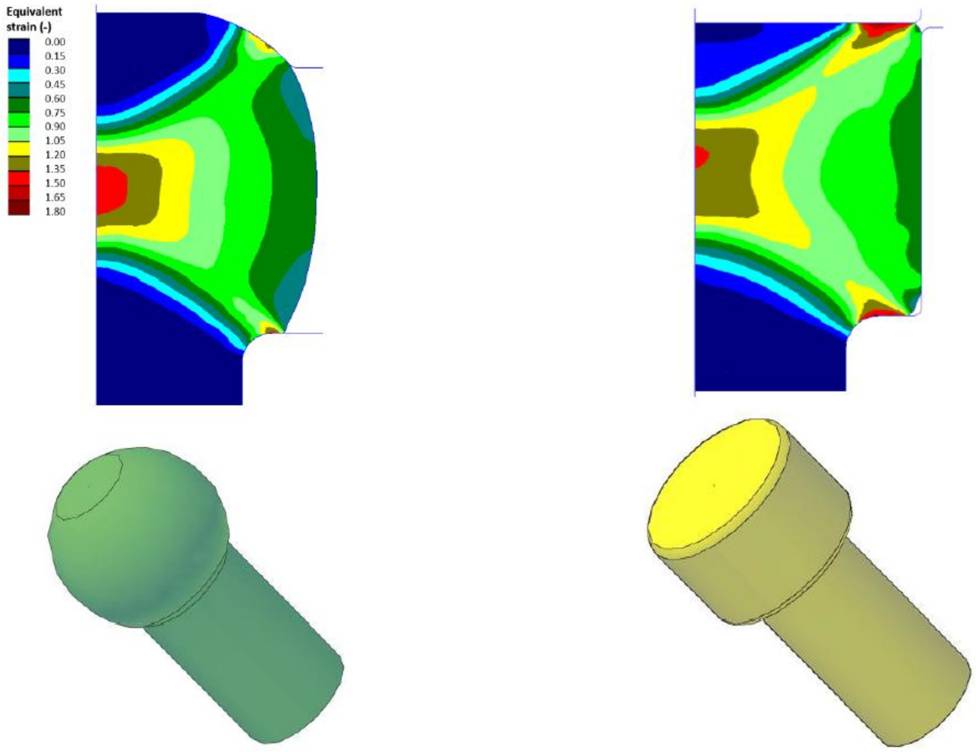
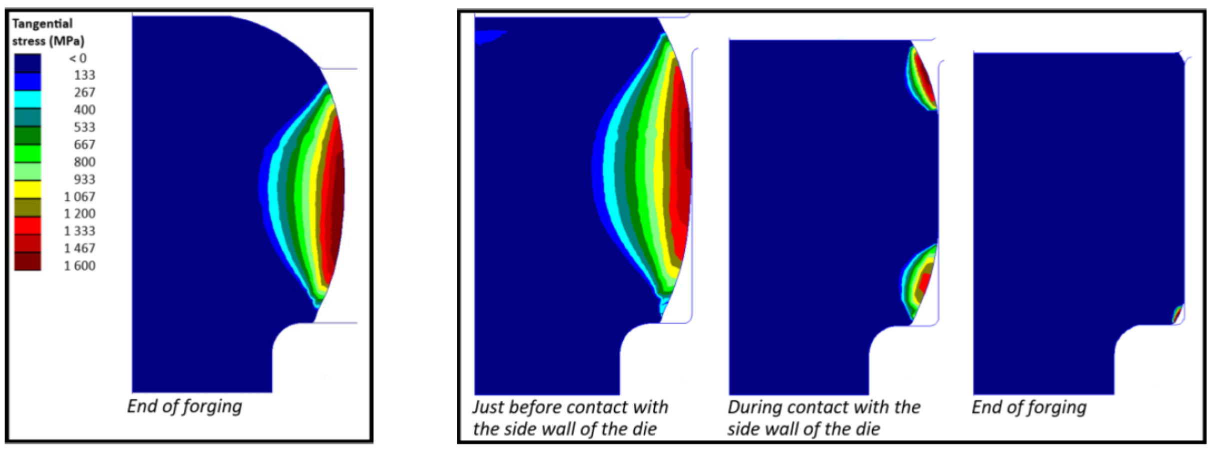


a) current shape b) new shape

Fig. 5 Distribution of strain intensity and shape of the current vs. newly designed wire termination

Obr. 5 Rozložení intensity napětí a tvaru stávajícího a nově navrženého zakončení drátu

Once contact with the die sidewall occurs, the region where the highest tensile stress originally appeared is subjected to triaxial compression. The areas of maximum tangential stress shift upward and downward, and the stress values there do not exceed +1,500 MPa for the remainder of the forging process. Contact of the material with the die sidewall in the case of the newly designed tools, however, has a negative impact on the maximum forging force, which increased more than fivefold compared to the original design (from 122 kN to 622 kN).



a) current tool design b) new tool design

Fig. 6 Distribution of tensile tangential stress during forging of the current vs. newly designed wire termination

Obr. 6 Rozložení tangenciálního tahového napětí při kování stávajícího a nově navrženého zakončení drátu

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6. Conclusion

Using FEM simulations, an analysis of stress distribution occurring during the industrial wire upsetting process was carried out. The simulations confirmed the presence of "unfavourable" tensile stresses occurring in selected locations of the upset wire sections.

Based on the conducted evaluations, the tool geometry was subsequently modified so that the newly designed shape would eliminate the occurrence of unfavourable tensile stresses to the greatest possible extent.

Microstructural analysis of industrially processed wires, as well as physical simulations of this process, confirmed that the occurrence of a defect in the upset part of the wire requires the presence of an "initiation" defect. The level of tensile stress reached, in the absence of an "initiation" defect, does not cause material failure manifested by this type of defect (a crack parallel to the loading direction – see Fig. 4 left).

Physical simulations, i.e., the evaluation of the effect of initiation defect depth on defect opening during upsetting, demonstrated that crack opening width is influenced, among other factors, by the depth of the initiation defect and the applied deformation.

The industrial upsetting process leads to a significantly greater opening of initiation cracks. To increase the "sensitivity" of the physical simulation, it is recommended to use higher samples with the current tool design, thereby achieving greater deformation. It can be assumed that the extent of defect opening will then approach the values observed in industrially upset wires. Based on the analysis, a sample height of 16 mm is recommended.

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