Defining rolled metal performance for cold bolt upsetting (bolt head)

G V Pachurin¹, S M Shevchenko², A A Filippov¹, M V Mukhina², N A Kuzmin¹

¹ Nizhny Novgorod State Technical University named after R.A. Alekseev, 3024, Minin Street, Nizhny Novgorod, 603600, Russia
² Minin Nizhny Novgorod State Pedagogical University, Cheluiskinstev Street, 9, Nizhny Novgorod, 603138, Russia

E-mail: mariyamuhina@yandex.ru

Abstract. Hardware items are one of the products for mass consumption. Rolled metal for cold forging shall have the required ductility, uniform mechanical characteristics along the mill length, corresponding chemical composition and shall be free from internal or superficial defects. Standard mechanical characteristics have been reviewed in this document and fracture criteria of calibrated rolled steel 40Х have been calculated after its isothermal treatment at different temperatures in nitre bath and subsequent drawing with different deformation degrees. Comparison of synergy fracture criteria showed that rolled stock, treated as per the proposed conditions: bath patenting at the temperature of 400ºС and drawing with reduction rate of 5% and 10%, are more preferable, comparing to processing conditions, existing in the industry.

1. Introduction

More and more stringent requirements are specified to mechanical characteristics, service life as well as new functional properties of metals and main structural materials in machine building [1,2]. Rather a wide assortment and a large variety of hardware properties are explained by specific features of its use in different spheres of machine building. Fasteners refer to hardware items obtained by cold forging.

Material which is used for cold die forging, shall have the required ductility, uniform mechanical characteristics along the mill length and corresponding chemical composition [3,4]. Besides, hot-rolled steel shall not have internal and superficial defects, as for example, chaps, rolled gas pockets, surface backfins, skin decarburization which drastically degrade mechanical characteristics of superficial layers of rolled stock. The surface of the calibrated rolled stock becomes susceptible to scratching and scoring.

Competitive production of hardware items at external and internal markets is achieved by the overall result of all process operations, which ensure process safety and energy intensity, prime cost and the required quality of finished hardware: starting from selection of charging material for melting and milling of rolled stock to preparation of calibrated rolled metal and upsetting of finished hardware items [5]. That is why during development of modern technologies on production of fixing hardware from any steel grade, it is necessary to use additional possibilities for rolled stock quality improvement
at all process stages [6]. The hot rolled stock preparation stage plays an important role in the process chain before its cold upsetting [7].

2. Materials and methods

Up to 60% of fixing elements of quality grade 9.8, 10.9 and higher are manufactured from rolled steel 40X because it is relatively cheap and traditionally is most widely spread for hardenable fixing hardware of any degree of mass production. The main method for high strength bolts production is upsetting from calibrated rolled stock, which has a “globular pearlite” microstructure.

Standard mechanical characteristics at static tension have been defined on smooth cylindrical specimen (GOST 1497-84 “Metals. Methods of tension test”). Hot rolled and calibrated rolled stock static strength tests have been performed on cylindrical specimen from 40X steel (GOST 1497-81) in a TsDM-type tensile testing machine – 100 with 20 kg dial. 300 mm long specimen have been tested at room temperature with strain rate 2x10^{-3}sec^{-1}. As per GOST 1497-81 “Metals. Methods of tension test”, tension test diagram, initial and final dimensions of the specimen have been recorded, strength (σ - modulus of rupture, MPa; σ_{0.2} - offset yield strength, MPa) and plastic (δ - total elongation ratio, %; ψ - total contraction ratio, %) properties of hot rolled stock delivered from metallurgical complex and calibrated rolled stock after treatment have been defined.

The experimental arithmetic mean values, quadratic deviation and sampling variance have been calculated according to the established methods. The experimental data sampling variance have not exceeded 0.021.

The hot rolled stock in the initial state and calibrated rolled stock microstructure after all kinds of process treatments have been examined by means of visual inspection of the surface of specially prepared specimen (transverse microsections) using microscope MIM – 8 of x600 magnification and using horizontal microscope “Neophot-21” of x100 and x600 magnification. The changes in the pickled specimen surface microstructure have been witnessed at each process operation with photographic recording. Metallographic microsections have been prepared as per the following technology: coarse grinding, fine grinding and polishing. The micrographical pickling has been performed in the 4% nitric acid solution in ethyl alcohol.

One of the most important features of calibrated rolled stock structural and energy state is specific energy (work) spent to deform it till the moment of its fracture \( W_c \) (ultimate specific strain energy) [8]. The behavior of any structures under load is controlled by three interrelated values: yield strength (\( \sigma_y \)), specific bulk density of strain energy (\( W_c \)), and specific ultimate strain energy in the area before a crack (\( W_{c, crit} \)). \( W_c \) specifies metal power intensity (unit of measurement MJ/m³) and is defined using the formula:

\[
W_c = 0.5\times(\sigma_y + \sigma_k)\varepsilon_{\text{lim}},
\]

where \( \sigma_y \) - is yield strength, MPa;
\( \sigma_k = \sigma_y (1+\delta) \) - true fracture resistance, MPa;
\( \varepsilon_{\text{lim}} = \ln [1/(1-\psi)] \) - true relative fracture strain,
\( W_c \) - metal power intensity index, unit of measurement [MJ/m³].

The formula includes strength and ductility characteristics. In this case, the changes of strength and ductility characteristics of the rolled stock depend on the microstructure parameters, which, in its turn, depend on chemical composition, conditions of thermal and plastic treatment. The initial data have been specified on the basis of features obtained during rolled stock specimen testing at different conditions of isothermal treatment and subsequent pressure shaping by drawing with different reduction ratio.

Plastic strain precedes crack initiation in the calibrated rolled stock. Crack initiation criterion \( K_{ci} \), which quantifies the capability of the rolled stock to resist crack initiation during deformation, is defined by expression [8]:

\[
K_{ci} = W_c / \sigma_y.
\]


\( K_{ci} \) value is dimensionless. The higher is the \( K_{ci} \) value, the less calibrated rolled stock of 40X steel is supposed to crack initiation during cold deformation by drawing.

The crack propagation criterion \( K_{cp} \) quantifies the capability of rolled stock to resist crack propagation during drawing of rolled stock under conditions of achieved critical stress state and equals to

\[
K_{cp} = W_{c \text{ crit.}} \cdot \sigma_y, \text{ (MJ/m³)MPa,}
\]

where \( W_{c \text{ crit.}} \) – is a critical value of ultimate specific strain energy before crack tip, and is defined in critical stress state, when plastic strain energy equals to elastic strain energy distortion. The \( W_{c \text{ crit.}} \) value is \( \approx (0.75-0.5) W_c \). \( K_{cp} \) is measured in \( [(\text{MJ/m}^3)\text{MPa} \approx (\text{MJ/m}^3)^2] \).

3. Results of study

This document comprises the obtained values of the standard mechanical characteristics and fracture criteria of the calibrated rolled stock of 40X steel after its isothermal treatment by different temperatures nitre bath and subsequent drawing with different deformation ratio. Tables 1-4 outline mechanical characteristics and synergy fracture criteria \((W_c, K_{ci}, K_{cp})\) of rolled stock 40X steel after patenting at 370, 400, 450, 500 and 550ºC and subsequent drawing with different deformation ratio. Thermal operation of steel patenting at the temperature of nitre bath of 400, 424, 450 and 550ºC results in obtaining of «patenting sorbite» microstructure. The obtained microstructure is homogenous, because austenite turns into «patenting sorbite» at a constant temperature. After isothermal treatment (patenting) at the temperature of 500ºC, the steel microstructure is “sorbite with martensite areas”. After patenting at the temperature of 370ºC, the steel microstructure is «troostite».

Table 1 Calibrated rolled stock of 40X steel mechanical characteristics and fracture criteria after patenting at 370ºC and subsequent drawing

| Reduction rate,\% | HB | \( \sigma_b \), MPa | \( \sigma_y \), MPa | \( \Psi \), % | \( \delta \), % | \( W_c \), MJ/m³ | \( K_{ci} \) | \( K_{cp} \), (MJ/m³) \( 10^{-6} \) |
|------------------|----|------------------|------------------|-----------|-----------|----------------|----------|----------------|
| 5                | 306| 1097             | 970              | 47        | 10.8      | 635            | 0.6      | 0.37           |
| 10               | 306| 1098             | 965              | 47        | 11        | 692            | 0.71     | 0.40           |
| 20               | 316| 1160             | 985              | 45        | 9.8       | 674            | 0.68     | 0.39           |
| 30               | 298| 1320             | 1190             | 20        | 6.9       | 290            | 0.24     | 0.21           |
| 40               | 306| 1340             | 1180             | 17        | 5.2       | 235            | 0.2      | 0.17           |
| 60               | 330| 1360             | 1190             | 17        | 5.2       | 238            | 0.2      | 0.17           |

Table 2 Calibrated rolled stock of 40X steel mechanical characteristics and fracture criteria after patenting at 400ºC and subsequent drawing

| Reduction rate,\% | HB | \( \sigma_b \), MPa | \( \sigma_y \), MPa | \( \Psi \), % | \( \delta \), % | \( W_c \), MJ/m³ | \( K_{ci} \) | \( K_{cp} \), (MJ/m³) \( 10^{-6} \) |
|------------------|----|------------------|------------------|-----------|-----------|----------------|----------|----------------|
| 5                | 285| 950              | 840              | 57        | 13        | 886            | 1.05     | 0.46           |
| 10               | 280| 995              | 910              | 56        | 12.5      | 857            | 0.94     | 0.46           |
| 20               | 315| 1110             | 970              | 55        | 11.5      | 881            | 0.91     | 0.51           |
| 30               | 283| 1270             | 1110             | 45        | 9.5       | 702            | 0.63     | 0.46           |
| 40               | 302| 1250             | 1070             | 40.9      | 7.8       | 635            | 0.59     | 0.41           |
| 60               | 318| 1290             | 1240             | 22.1      | 6.9       | 326            | 0.26     | 0.24           |
**Table 3** Calibrated rolled stock of 40X steel mechanical characteristics and fracture criteria after patenting at 450°C and subsequent drawing

| Reduction rate, % | HB | $\sigma_0$, MPa | $\sigma_y$, MPa | $\Psi$, % | $\delta$, % | W, MJ/m$^3$ | $K_{\text{ci}}$ | $K_{\text{cp}}$, $10^6$ MJ/m$^3$ |
|------------------|----|----------------|----------------|----------|-----------|-------------|--------------|-------------------|
| 5                | 260 | 973           | 910           | 49.2     | 13        | 680         | 0.75         | 0.37              |
| 10               | 235 | 1010          | 940           | 53       | 12.5      | 783         | 0.83         | 0.44              |
| 20               | 255 | 1075          | 940           | 50       | 11        | 785         | 0.83         | 0.44              |
| 30               | 313 | 1310          | 1200          | 32       | 5.2       | 483         | 0.40         | 0.34              |
| 40               | 298 | 1280          | 1130          | 30       | 4.4       | 441         | 0.39         | 0.30              |
| 60               | -   | -             | -             | -        | -         | -           | -            | -                 |

**Table 4** Calibrated rolled stock of 40X steel mechanical characteristics and fracture criteria after patenting at 500°C and subsequent drawing with different deformation rate

| Reduction rate, % | HB | $\sigma_0$, MPa | $\sigma_y$, MPa | $\Psi$, % | $\delta$, % | W, MJ/m$^3$ | $K_{\text{ci}}$ | $K_{\text{cp}}$, $10^6$ MJ/m$^3$ |
|------------------|----|----------------|----------------|----------|-----------|-------------|--------------|-------------------|
| 5                | 298 | 1110          | 996           | 40       | 10.8      | 568         | 0.57         | 0.34              |
| 10               | 247 | 1055          | 990           | 40       | 8.9       | 546         | 0.55         | 0.32              |
| 20               | 247 | 1160          | 1050          | 29       | 8.35      | 394         | 0.38         | 0.25              |
| 30               | -   | -             | -             | -        | -         | -           | -            | -                 |
| 40               | -   | -             | -             | -        | -         | -           | -            | -                 |
| 60               | -   | -             | -             | -        | -         | -           | -            | -                 |

Table 5 outlines mechanical characteristics and fracture criteria of calibrated rolled stock of 40X steel treated using the existing production technology.

**Table 5** Mechanical characteristics and fracture criteria of calibrated rolled stock of 40X steel treated using existing production technology

| HB | $\sigma_0$, MPa | $\sigma_y$, MPa | $\Psi$, % | $\delta$, % | W, MJ/m$^3$ | $K_{\text{ci}}$ | $K_{\text{cp}}$, $10^6$ MJ/m$^3$ |
|----|----------------|----------------|----------|-----------|-------------|--------------|-------------------|
| 235| 860           | 695           | 57       | 13        | 708         | 1.02         | 0.33              |

The performance criteria have enabled to obtain a quantitative evaluation of inverse effect which the fracture process has on the strengthening during patenting and plastic strain by drawing, which is expressed in synergic power intensity value. They supplement the standard mechanical characteristics of calibrated rolled stock in assessment of performance and crack resistance.

**4. Discussion**

Synergy criteria have advantages compared to standard mechanical characteristics and supplement them in evaluation of material performance and crack resistance. It is known that since the moment of load application and till fracture the processes of plastic deformation and fracture take place in metal structure affecting each other. Fracture criteria enabled to perform quantitative evaluation of inverse effect which the fracture process has on hardening process during plastic deformation in a new way, which is expressed in the energy intensity. This gives reasons for us to say that synergy criteria are objective and are required to perform evaluation of calibrated rolled stock strengthened by patenting and plastic deformation.
The values of mechanical characteristics and synergy fracture of calibrated rolled stock of 40X steel after its patenting at different temperatures interval and subsequent drawing with different deformation rates have been analyzed. Comparison of power intensity indices $W_c$ in different process conditions is shown in Figures 1 and 2.

![Figure 1](image1.png)

**Figure 1.** The dependence of power intensity indices $W_c$ on different deformation rates at different patenting temperatures

![Figure 2](image2.png)

**Figure 2.** The dependence of power intensity indices $W_c$ on the patenting temperature at different deformation rates.

The calibrated rolled stock treated as per conditions: patenting at the temperature of 425$^\circ$C and drawing with deformation rate of 20% has the highest strength values (1300 MPa), and the calibrated rolled stock treated as per conditions: patenting at the temperature of 550$^\circ$C and drawing with 60% deformation rate has the lowest strength (900 MPa).

The calibrated rolled stock treated as per the conditions: patenting at the temperature of 400$^\circ$C and drawing with deformation rate of 5% has the highest power intensity index ($W_c$), and the calibrated rolled stock treated as per the conditions: patenting at the temperature of 370$^\circ$C and drawing with 40% deformation rate has the lowest one. According to data [1], the higher is the total power consumption, the less rolled stock is subjected to crack initiation and propagation, and the better is the material and the higher is the item performance.

Comparison of performance criteria based on different processing options showed that the calibrated rolled stock of 40X steel treated as per the conditions: isothermal treatment at the temperature of 400$^\circ$C and drawing with reduction rate of 5% is more preferable than the rolled stock treated under other conditions for the above mentioned rolled stock, including the existing production method.

Table 6 presents comparison of mechanical characteristics and performance criteria of calibrated rolled stock of 40X steel treated using the existing (1) and proposed (2) production technologies.
Table 6 Comparison of mechanical characteristics and performance criteria of calibrated rolled stock of 40X steel treated using the existing (1) and proposed (2) technologies

| Option | HB | $\sigma_a$, MPa | $\sigma_y$, MPa | $\Psi$, % | $\delta$, % | $W$, MJ/m$^3$ | $K_{ci}$ | $K_{cp}$, (MJ/m$^3$)$10^{-6}$ |
|--------|----|----------------|----------------|-----------|-------------|--------------|---------|-----------------|
| 1      | 235| 860           | 695           | 57        | 13          | 708         | 1.02    | 0.33            |
| 2      | 269| 950           | 840           | 57        | 13          | 886         | 1.05    | 0.46            |

The obtained values of the power intensity index ($W_c$) of calibrated rolled stock of 40X steel are defined by combining the strength (modulus of rupture and yield strength) and ductility (homogenous and ultimate strain) characteristics.

The crack initiation criteria of the examined rolled stock are controlled mostly by the values of ductility indices. The delivered rolled stock and the rolled stock right before long-length bolts manufacturing (both the existing and proposed technologies) has quite a high ductility index ($\Psi$=55-60%). The rolled stock is treated as per the conditions: patenting at the temperature of 400°C and subsequent drawing with deformation rate of 5% has the highest $K_{ci}$ values.

5. Conclusion

A reasonable combination of such mechanical characteristics as high strength and the lowest plastic resistance is archived by means of patenting at 400°C and subsequent drawing with reduction ratio of 5%. In case of further increase of reduction ratio in the course of drawing up to 60%, the growth of rupture modulus and yield strength values is observed, as well as reduction of relative elongation and contraction.

The 40X steel microstructure after isothermal treatment (patenting) and subsequent drawing at the temperature of 500°C is “sorbite with martensite areas”. Patenting at the temperature of 500°C and subsequent drawing with 30, 40 and 60 % reduction rates leads to a complete loss of ductility and rolled stock rupture due to formation of internal cracks. This microstructure is not recommended for rolled stock which is used for manufacturing of bolts by cold forging method.

After patenting at the temperature of 370°C, the steel microstructure is “troostite”. This microstructure is not recommended for manufacturing of rolled stock for further production of bolts using cold forging method due to its high strength and low ductility characteristics.

The temperature of isothermal exposure at 550°C leads to drastic increase of ductility ($\Psi$=58-62%), reduction of strength (905 MPa) and hardness (229 HB). These characteristics do not correspond to the requirements of the strength grade 9.8.

At all patenting and drawing conditions of calibrated 40X steel rolled stock, the crack propagation criterion is reduced along with the increase of crack initiation criterion and proportionally to the growth of rolled stock plasticity level.

Comparison of the synergy fracture criteria showed that rolled stock treated as per the proposed conditions (patenting at the temperature of 400°C and drawing with 5% and 10% reduction rates) is more preferable than the treatment conditions based on existing technology.

References

[1] Pachurin G V 2012 Life of Plastically Deformed Corrosion-Resistant Steel Russian Engineering Research 9–10 661–664
[2] Guslyakova G P, Zhbannikov S I, Pachurin G V 1993 Fatigue failure resistance of deformed structural steels Materials Science 2 182-185
[3] Pachurin G V 2008 Ruggedness of structural material and working life of metal components Steel in Translation 3 217-220
[4] Pachurin G V, Vlasov V A 2014 Mechanical properties of sheet structural steels at operating temperatures Metal Science and Heat Treatment 3-4 219-223
[5] Pachurin G V, Filippov A A 2008 Economical preparation of 40X steel for cold upsetting of bolts *Russian Engineering Research* 7 670–673

[6] Filippov A A, Pachurin G V, Naumov V I, Kuzmin N A 2016 Low-Cost Treatment of Rolled Products Used to Make Long High-Strength Bolts (Vol. 59) *Metallurgist* 9-10, January 810-815

[7] Pachurin G V, Shevchenko S M, Mukhina M V, Kutepova L I, Smirnova J V 2016 The Factor of Structure and Mechanical Properties in the Production of Critical Fixing Hardware 38XA *Tribology in Industry* 3 385-391

[8] Skudnov V A 2007 *Synergy of Issues and Processes in Metal Science, Strengthening Technologies and Fracture: Manual for Graduate Students* (V. A. Skudnov: NNSTU Nizhny Novgorod)