Research of the temperature relaxation process of tension in steels

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Abstract. The purpose of the work is to research the tension relaxation mechanism using the example of steel 08Х15Н24В4ТР and finding an acceptable theoretical model describing this process. Thus, the problem can be formulated as the derivation of an expression describing the dependence of the tension on time in a sample that is given the initial deformation at a certain temperature (the initial tension), after which the deformation and temperature remain constant and the process of tension relaxation occurs. Such an impact corresponds to the operating mode of many parts and components in engineering, as well as the operation of reinforcement with initial tension in the event of a fire. The results of a researching of tension relaxation in steel 08Х15H24B4TP under conditions of state with initial tension and high-temperature impact are presented. The conditional service life of the samples is determined, commensurate with the actual service life of machine parts, components and building structures. Conclusions are given about the timing, depending on the model parameters. Based on the assumption of a linear temperature effect on the tension relaxation process, a model is shown that describes with sufficient accuracy the relaxation of tension in steel with allowance for the temperature effect. The parameters of this model for steel grade 08X15H24B4TP are determined.

1. Introduction

With prolonged loading and high temperatures, the behavior of the material is determined by diffusion processes, which are characterized by creep and tensions relaxation processes [1-3].

With the purpose to provide sufficient strength and certain operational properties, and also for the sake of economy in modern engineering and construction, elements with initial tensions [1-3]

Tension relaxation is characterized by a decrease in operating tensions from \( \sigma_1 \) to \( \sigma_2 \) for a given deformation.

Relaxation of tensions is dangerous because after a certain time the element with initial tensions loses some of its internal tensions and already cannot meet the requirements laid down in the design, and also in that when the part of the elastic deformation moves into the plastic, the elastic elements after unloading change the size and shape [1].

The purpose of this work is to research the tension relaxation mechanism using the example of 08X15H24B4TP steel and finding an acceptable theoretical model describing the given process [2]. Therefore, the problem can be formulated as the search for an expression describing the dependence of the tensions on time in a sample that is given the initial deformation at a certain temperature (and,
consequently, the initial tension), after which the deformation and temperature remain constant, and the process of tension relaxation occurs.

2. Methods

Existing models of a solid body with varying degrees of accuracy describe the process of tension relaxation. Based on the experimental data, we can say that for most steels the most accurate model turned out to be the solid Kelvin model [4], represented by the following analytical expression:

$$\sigma(\tau) + \tau_r \frac{d\sigma(\tau)}{d\tau} = H E + \tau_r E \frac{d\varepsilon}{d\tau}$$

Here $\sigma(\tau)$ - dependent tension function is the conditional relaxation time - $\tau_r$, $\varepsilon$ - is the deformation of the element, $H$ - is the long modulus of elasticity of the material, $E$ - is the instantaneous modulus of elasticity of the material. This model does not take into account the influence of temperature, so for our task it needs to be improved. From the point of view of the physics of the process, it is logical to assume that the temperature affects the tension linearly, since it remains constant throughout the test. Thus, to the Kelvin model, we can add a constant force, which tends to reduce the tensions in the sample, then the new model, taking into account the statement of the problem, will look like this:

$$\sigma(\tau) + \tau_r \frac{d\sigma(\tau)}{d\tau} = H E_0 - k \tau$$

where $k$ - is the velocity of the temperature part of the tension relaxation, the term $\tau_r E \frac{d\varepsilon}{d\tau} = 0$ because the deformations are constant and equal $\varepsilon_0$.

The initial condition:

$$\sigma(0) = \sigma_0$$

Therefore, the solution of the given differential equation (1) taking into account the initial condition (2):

$$\sigma(\tau) = H E_0 + k \tau_r - k \tau + (\sigma_0 - k \tau_r - H E_0) e^{-\frac{\tau}{\tau_r}}$$

Let's rename

$$k \tau_r + H E_0 = \sigma_c$$

And then the final expression:

$$\sigma(\tau) = (\sigma_0 - \sigma_c) e^{-\frac{\tau}{\tau_r}} + \sigma_c - k \tau$$

This can be represented graphically as follows:
This model has one significant drawback - after reaching zero tensions they will continue to decrease, changing the sign which is physically incorrect. Most likely in the vicinity of zero, there is a kind of "inhibition" of relaxation, and some residual tensions remain in the steel, or they reach zero, and then remain unchanged. But since the critical tension point necessary to meet the technological requirements for the structural element obviously lies substantially above zero, we will assume that when this point is reached our model is still valid. Let us now look for unknown parameters that enter into this equation. Table 1 shows the experimental test data for a sample of steel grade 08X15H24B4TP.

**Table 1.** Relaxation resistance of steel 08X15H24B4TP at $[\tau] = 10000$ h

| $t$, °C | $\sigma_0$, MPa | $\sigma$, MPa, for the time $\tau$, h. |
|---------|----------------|----------------------------------|
|         |                | 160 | 500 | 1000 | 2000 | 5000 | 10000 |
| 550     | 200            | 155 | 154 | 153 | 152 | 152 | 152 |
|         | 250            | 219 | 218 | 218 | 216 | 216 | 200 |
|         | 300            | 273 | 273 | 271 | 269 | 265 | 249 |
| 600     | 200            | 185 | 183 | 182 | 179 | 176 | 166 |
|         | 250            | 227 | 226 | 224 | 219 | 213 | 198 |
|         | 300            | 268 | 266 | 266 | 263 | 256 | 243 |
| 650     | 200            | 177 | 174 | 169 | 162 |  -  | 132 |
|         | 250            | 204 | 198 | 189 | 186 |  -  | 153 |
|         | 300            | 248 | 245 | 236 | 228 |  -  | 188 |
| 700     | 200            | 162 | 143 | 131 | 123 | 108 | 85  |
|         | 250            | 189 | 174 | 159 | 148 | 134 | 100 |
|         | 300            | 238 | 210 | 179 | 172 | 156 | 113 |
3. Results and discussions
Tables 2 and 3 show the results of interpolation of tension values between test points.

Table 2. Interpolation values of tensions at \( \tau = 7000 \)h

| \( \tau \), \( \sigma_{0} \) | 1500 | 2500 | 3000 | 3500 | 4000 | 4500 | 5000 | 6000 | 6500 | 7000 |
|---|---|---|---|---|---|---|---|---|---|---|
| \( ^{\circ} \text{C} \) | MPa | MPa | MPa | MPa | MPa | MPa | MPa | MPa | MPa | MPa |
| 550 | 200 | 152.3 | 152.0 | 152.0 | 152.0 | 152.0 | 152.0 | 152.0 | 152.0 | 152.0 |
| 250 | 218.0 | 218.0 | 217.9 | 217.3 | 217.0 | 216.5 | 215.4 | 214.6 | 213.7 | 212.6 |
| 300 | 269.6 | 268.5 | 268.0 | 267.4 | 266.8 | 265.9 | 263.9 | 262.6 | 261.2 | 259.7 |
| 600 | 200 | 180.7 | 177.8 | 177.0 | 176.6 | 176.4 | 176.2 | 175.6 | 175.0 | 174.3 |
| 250 | 221.5 | 217.1 | 215.8 | 214.9 | 214.2 | 213.6 | 212.2 | 211.1 | 209.9 | 208.5 |
| 300 | 265.0 | 261.2 | 259.8 | 258.6 | 257.7 | 256.9 | 255.0 | 254.0 | 252.8 | 251.6 |
| 650 | 200 | 165.0 | 159.5 | 157.8 | 156.2 | 154.8 | 153.5 | 150.6 | 148.9 | 147.1 |
| 250 | 186.1 | 186.0 | 185.3 | 183.8 | 181.8 | 179.5 | 179.5 | 172.1 | 169.6 | 167.2 |
| 300 | 230.3 | 226.2 | 224.4 | 22.5 | 220.5 | 218.5 | 213.9 | 211.4 | 208.7 | 206.0 |
| 700 | 200 | 126.1 | 120.3 | 117.7 | 115.2 | 112.7 | 110.5 | 105.7 | 103.3 | 101.0 |
| 250 | 151.5 | 145.4 | 143.1 | 140.9 | 138.7 | 136.4 | 131.3 | 128.5 | 125.4 | 122.1 |
| 300 | 172.9 | 170.9 | 168.9 | 166.3 | 163.2 | 159.7 | 152.1 | 148.0 | 143.9 | 139.6 |

Table 3. Interpolation values of tensions at \( \tau = 9500 \)h, characteristic coefficients of the curves, an estimate of the coincidence of the curves, and the relaxation time of the tensions in the samples

| \( \tau \), \( \sigma_{0} \) | 7500 | 8000 | 8500 | 9000 | 9500 | \( k \times 10^{3} \), MPa/h | \( \tau_{r} \), \( \sigma_{\tau} \), MPa | \( \Delta \), \% | \( R^{2} \) | \( \tau_{r} \) *, years |
|---|---|---|---|---|---|---|---|---|---|---|
| \( ^{\circ} \text{C} \) | MPa | MPa | MPa | MPa | MPa | MPa | MPa | MPa | MPa | MPa |
| 550 | 200 | 152.0 | 152.0 | 152.0 | 152.0 | 0.00 | 56.73 | 152.16 | 1.2 | 0.998 |
| 250 | 211.3 | 209.8 | 207.9 | 205.7 | 203.1 | 5.67 | 10.81 | 242.07 | 9.2 | 0.558 |
| 300 | 258.1 | 256.4 | 254.6 | 252.7 | 250.9 | 3.75 | 7.89 | 281.92 | 3.0 | 0.889 |
| 600 | 200 | 172.3 | 171.2 | 170.0 | 168.7 | 167.3 | 2.67 | 10.33 | 188.79 | 2.4 | 0.874 |
| 250 | 206.9 | 205.3 | 203.5 | 201.7 | 199.9 | 3.74 | 8.68 | 231.23 | 2.2 | 0.936 |
| 300 | 250.2 | 248.9 | 247.4 | 246.0 | 244.5 | 2.98 | 9.95 | 270.73 | 1.2 | 0.981 |
| 650 | 200 | 143.1 | 141.0 | 138.8 | 136.6 | 134.3 | 4.57 | 72.19 | 175.04 | 2.4 | 0.981 |
| 250 | 164.8 | 162.4 | 160.1 | 157.7 | 155.4 | 4.71 | 72.54 | 199.19 | 3.1 | 0.990 |
| 300 | 203.1 | 200.2 | 197.2 | 194.2 | 191.1 | 6.16 | 72.54 | 246.43 | 2.9 | 0.984 |
| 700 | 200 | 96.4 | 94.1 | 91.8 | 89.6 | 87.3 | 4.55 | 248.32 | 131.22 | 3.5 | 0.996 |
| 250 | 118.6 | 115.1 | 111.4 | 107.6 | 103.8 | 7.64 | 114.16 | 171.74 | 5.5 | 0.982 |
| 300 | 135.3 | 130.9 | 126.5 | 122.0 | 117.5 | 9.13 | 187.17 | 199.83 | 7.1 | 0.983 |

According to the characteristic features of the graphs describing the obtained data, we can say that in the region \( \tau > 9000 \) h, the tension relaxation occurs linearly. That is, there was almost complete damping of the viscoelastic component of relaxation, and only the temperature remained. Then we can take the rate of temperature relaxation to be:

\[
k = \frac{\sigma(10000) - \sigma(9000)}{1000}, \quad [\text{MPa/h}]
\]

The values of the coefficient \( k \) are given in Table 3.

Thus, the unknown parameters remain \( \tau_{r} \) and \( \sigma_{\tau} \) we can find their values numerically, using the method of least squares. The results of the selection are presented in Table 3.

It will be expedient to immediately note the maximum discrepancies \( \Delta \), [%] of the experimental and matched curve (at either point of the two curves), and also calculate the determination coefficient

\[
\text{R}^{2}
\]
\[ R^2 \], which helps to mathematically evaluate how well the curve describing the experimental data has been matched. All the values found are presented in Table 3.

Comparison of the real process and the theoretical model for \( t = 700 \, ^\circ \text{C} \) and \( \sigma_0 = 300 \, \text{MPa} \):

![Figure 2. Comparison of real results and theoretical model](image)

To draw the reader's conclusions, let's set the criterion for the sample to mismatch the technological requirements - internal tensions in it are less or equal to the initial ones divided by the base of the natural logarithm.

That is, we need to find the relaxation time measured in years such that:

\[
\sigma(\tau^i) = \frac{\sigma_0}{e^i}
\]

This is done quite easily, the results are shown in Table 3.

4. Conclusions

Thus, from the data obtained, the following conclusions can be drawn:

The model of the solid Kelvin (3) that has been modified to take into account the effect of temperature successfully describes the process of tension relaxation in a solid form, this is evidenced by the determination coefficients \( R^2 \) practically equal to unity (the sample makes an exception at \( t = 550 \, ^\circ \text{C} \) and \( \sigma_0 = 250 \, \text{MPa} \), for it \( R^2 \) was 0.5581. This can most likely be an error of interpolation, because of which there appeared a smooth convex part of the graph, obviously not inherent in our theoretical model). Also about the success of the model say the maximum deviations of the experimental data from the calculated ones, which in most cases did not exceed the 5% mark (except for the following samples: \( t = 550 \, ^\circ \text{C} \) and \( \sigma_0 = 250 \, \text{MPa} \) - 9.2%; \( t = 700 \, ^\circ \text{C} \) and \( \sigma_0 = 250 \, \text{MPa} \) - 5.5%; \( t = 700 \, ^\circ \text{C} \) and \( \sigma_0 = 300 \, \text{MPa} \) - 7.1% - which, however, is also not large values).

We estimated the relaxation time \( \tau^i \) and can say that it is commensurate with the service life of many elements with initial tensions in modern engineering. Therefore, when these elements operate under high-temperature conditions, one cannot help assessing the effect of temperature relaxation on the tensions in the sample. If we talk about reinforcement with initial tensions used in construction, then fires can be dangerous for it. And although the fire lasts a rather short time, the temperatures with which it accompanies reach values far greater than those considered here (1000 \( ^\circ \text{C} \)-1100 \( ^\circ \text{C} \) in a
household fire). And the rate of tension relaxation with increasing temperature increases significantly and also the strength characteristics of the material are greatly reduced, which can lead to the destruction of parts or structures [5].

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