Experimental Researches of Carbon Steels Plasticity Changes in the Field of Phase Transformations

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Abstract. Results of experimental researches of carbon steels plasticity changes in steel grades 10, 35 and U8A, depending on deformation temperature are provided to vicinities of critical points $A_{C_1}$ and $A_{C_3}$. Change of plasticity in the studied materials analyzed on values of an aspect ratio and strength. It is revealed that the aspect ratio of these steels as the characteristic of plasticity raises with increase in temperature, reaches a maximum, higher than temperature of critical point decreases and increases with the subsequent increase of temperature. In steels with small carbon content the main contribution to increase in plasticity is made by a condition of pretransformation near a point of phase transition $A_{C_3}$. In eutectoid steel grade U8A the main increase of plasticity is provided with a condition of pretransformation near eutectoid phase transition in a point $A_{C_1}$. In steel grade 35 on curve dependence of plasticity on temperature two extremum corresponding to a condition of pretransformation before points $A_{C_1}$ and $A_{C_3}$ are observed. It is established that in all three steel grades of the studied carbon steels in a condition of pretransformation plasticity is higher, than in an austenitic state. The revealed patterns and the received mathematical dependences describing changes of plasticity at phase transformations of carbon steels give the chance of practical application of the found plasticity resource when processing by pressure of different classes of steels. Processing in this case can be made at lower temperatures and forces of deformation that will allow reducing risk of emergence of scale, to increase processing productivity. The received results can be used when developing power- and resource-saving technologies of processing by pressure of carbon steels.

1. Introduction
Problems of a condition of pretransformation at diffusion and without diffused phase junctions in metals and alloys are a subject of detailed researches of representatives of domestic and foreign leading schools of sciences [1-5], especially in the last decade [6-10]. These decisions show possibilities of acquisition of new knowledge of crystalline solids structure, the activated condition of atoms, mechanisms of physical and mechanical properties change, stability of alloys crystal structures, patterns of emergence and development of extreme effects, definition of the optimum modes of their implementation at different external interfaced temperature, mechanical and a physicochemical effect [11-14].

Studying of the states preceding transition in steels, which are characterized by abnormally high rates of plasticity opens opportunities for creation power- and resource-saving technologies of processing of metals pressure [10, 12, 14].

Considering complexity of physical processes and structural transformations, proceeding in steels and alloys in the range of temperatures covering area of phase transformations, and also insufficient basic researches in the field of plasticity studying at phase transformations, experimental research methods
of the reasons and conditions, at which plasticity different steels changes at temperature influence, remain the defining research methods for today.

The objective of this research was definition of plasticity steels zones in areas of phase transformations.

2. Objects and methods of experimental researches

As objects of research of plasticity near temperature of diffused phase junction were chosen proeutectoid steel grades 10, 35 (C 1010 and C 1035 of ASTM Standard) and U8A eutectoid steel (W 108 of ASTM Standard) in an annealed state. The structure steels grades 10 and 35 in an initial state represents ferrite and perlite, and steel grade U8A - perlite [15, 16]. As authors did not set a task of obtaining the increased plasticity on investigated steels, the research of plasticity investigated by the steels were conducted without preliminary preparation of structure.

For tension tests of the steels used cylindrical steel samples with a diameter in working part of 5 mm (State standard specification 1497-84). Tests were carried out as at the room temperature (20°C), and in the range of temperatures from 700°C to 890°C, and to vicinities of critical points Ac1 and Ac3. Temperatures of the critical points investigated by the steels are specified in Table 1 [17, 18].

| Material          | Temperature, °C |
|-------------------|-----------------|
|                   | Ac1  | Ac3  |
| Steel 10 (C 1010) | 730  | 870  |
| Steel 35 (C 1035) | 730  | 810  |
| Steel U8A (W 108) | 765  |      |

Tension tests of steel samples were carried out on a test machine MIRI-100K in accordance with GOST 28840-90. The heating speed of the steels was 25 °C per minute. The deformation speed of samples throughout all research remained constant, equal to \( V = 1 \) mm/min. Limits of the allowed measurement error of loading and deformation were ±1% of the measured size in the measurement range.

To heat the tested samples, a tubular furnace with a nickel-chromium heater was used. The furnace was located between two hydraulic captures of a test machine. Temperature monitoring in working space of the furnace was exercised by the electronic thermocouple series M83 with manual adjustment. The endurance of a sample at a required temperature was made within 10 min. After that, the sample was stretched according to the set parameters was carried out. When carrying out tests in the conditions of the increased temperatures non-stick and anti-seize grease ASPF-2/RgU according to TU 0254.001.26470233-2001 for the purpose of prevention of a sample material adhesion and captures of a test machine during experiment was applied on thread segment of samples. For each value of temperature from the chosen range tested on 3…7 samples. Plasticity was estimated the size of an aspect ratio of a sample after stretching, and durability - the size of strength of material.

The heating speed, speed of stretching of samples and temperature interval chosen for carrying out researches provide uniformity of course of deformation investigated steels. On the received charts there are no jumps of stretching, and on prototypes multiple necks on working part of samples that testifies to uniformity of course of process of deformation were not observed.

Statistical processing of experimental results for the studied materials showed that the relative error in determining the relative elongation was ±3 %, and in determining the tensile strength was ±5 %. Fixing of parameters of testing, calculation of necessary characteristics and the printing of the test sheet it was carried out by a control system of a test machine.
The results of experimental researches of steels plasticity at the room temperature and in areas of points of transformations $A_{C1}$ and $A_{C3}$ are given in Table 2.

The analysis of experimental researches results (see Table 2) showed availability of intermittent change of the relative elongation size for steel grades 35 and U8A in areas of points of transformations $A_{C1}$ and $A_{C3}$. In this regard, for ensuring further correct and adequate approximation of experimental researches results additional expanded series of experiments (see Table 3) were carried out.

| Steel 10 (C 1010) | $T$, °C | $T_{STD}$, °C | $T_{STD}$, MPa | $\delta$, % |
|-------------------|---------|----------------|-----------------|------------|
|                   | 20      | 700            | 732             | 760        | 780        | 800        | 820        | 840        | 870        |
|                   | 15      | 551.4          | 143.4           | 111.6      | 75.8       | 74.3       | 78.7       | 85.3       | 109.9      | 51         |
|                   | 32.6    | 44.7           | 49.7            | 52.8       | 53.1       | 50.2       | 25.3       |            |            |
| Steel 35 (C 1035) | $T$, °C | $T_{STD}$, °C | $T_{STD}$, MPa | $\delta$, % |
|                   | 20      | 700            | 720             | 730        | 740        | 760        | 780        | 810        | 840        |
|                   | 5.4     | 127.7          | 130.1           | 133        | 122.3      | 87.3       | 84.1       | 84.7       | 85.1       |
|                   | 8       | 42             | 45.3            | 46.3       | 16.7       | 41.8       | 42         | 47.7       |            |
| Steel U8A (W 108) | $T$, °C | $T_{STD}$, °C | $T_{STD}$, MPa | $\delta$, % |
|                   | 20      | 700            | 710             | 720        | 730        | 740        | 765        | 780        | 800        |
|                   | 4       | 21.3           | 28              | 34.5       | 37         | 28.3       | 35         | 40.3       | 43.8       |

Table 3. Extended results of experimental researches of plasticity of steels grades 35 and U8A

| Steel 35 (C 1010) | $T$, °C | $T_{STD}$, °C | $T_{STD}$, MPa | $\delta$, % |
|-------------------|---------|----------------|-----------------|------------|
|                   | 710     | 715            | 725             | 735        | 750        | 770        | 785        | 790        | 795        | 800        | 820        | 830        |
|                   | 40.4    | 41.7           | 44              | 47.1       | 28.3       | 28.6       | 43.1       | 42.5       | 40.2       | 41         | 43.7       | 45.1       |
| Steel U8A (W 108) | $T$, °C | $T_{STD}$, °C | $T_{STD}$, MPa | $\delta$, % |
|                   | 705     | 715            | 725             | 735        | 745        | 750        | 755        | 760        | 770        | 775        | 785        | 790        |
|                   | 25      | 31.5           | 36.5            | 32.6       | 28         | 29         | 31.4       | 33.3       | 37         | 38.6       | 41.8       | 42.8       |

3. Statistical processing and approximation of experiments results

Statistical processing of experimental data was carried out with use of the mathematical computing software MATLAB and its standard `polyfit` program with centering and scaling (normalization) of data for improvement of a polynom numerical properties and calculation algorithm, using QR-decomposition of the Vandermonda matrix.

For each steel grade scaled temperature on a formula

$$ T = \frac{T_i - \overline{T}}{STD(T)}, $$

where $T_i$ – the current value of temperature from a variation interval, °C; $\overline{T}$ – mean value of temperature on a variation interval, °C; $STD(T)$ – a standard (mean square) deviation of temperature on a variation interval, °C.

3.1. For the material of steel grade 10 (Figure 1).

Dependences of the relative elongation and tensile strength on temperature are approximated by polynomials of the sixth degree.
\[ \delta = -2.863 T^6 - 0.7879 T^5 + 8.377 T^4 - 4.066 T^3 - 12.87 T^2 + 13.09 T + 49.91, \]

where \( T = \frac{T_i - 779.7}{58.12} \) – the centered and scaled value of temperature according to expression (1); standard deviation \( STD(\delta) = 0.71 \% \).

\[ \sigma_b = -7.743 T^6 - 0.2044 T^5 + 4.480 T^4 - 8.489 T^3 + 41.43 T^2 - 3.416 T + 73.01, \]

where \( T = \frac{T_i - 779.7}{58.12} \); standard deviation \( STD(\sigma_b) = 6.6 \) MPa.

**Figure 1.** Dependences of the relative elongation \( \delta \) and tensile strength \( \sigma_b \) for steel grade 10

**Figure 2.** Dependences of the relative elongation \( \delta \) and tensile strength \( \sigma_b \) for steel grade 35

3.2. For the material of steel grade 35 (Figure 2). Dependence of the relative elongation on temperature is approximated by a polynomial of the sixteenth degree

\[ \delta = 8.47T^{16} - 28.6T^{15} - 54.6T^{14} + 257.6T^{13} + 101.6T^{12} - 963.3T^{11} + 76.7T^{10} + 1927T^9 - 556.3T^8 - 2209T^7 + 855.5T^6 + 1432T^5 - 610.4T^4 - 471.7T^3 + 201.6T^2 + 55.5T + 19.7, \]

where \( T = \frac{T_i - 764.5}{45.23} \); standard deviation \( STD(\delta) = 1.45 \% \).

Dependence of tensile strength on temperature is approximated by a polynomial of the fourth degree

\[ \sigma_b = -14.96 T^4 + 21.98 T^3 + 30.72 T^2 - 48.73 T + 95.0, \]

where \( T = \frac{T_i - 759.4}{48.14} \); standard deviation \( STD(\sigma) = 11.5 \) MPa.

3.3. For the material of steel grade U8A (Figure 3). Dependence of the relative elongation on temperature is approximated by a polynomial of the sixteenth degree

\[ \delta = 2.95T^{16} - 3.15T^{15} - 32.1T^{14} + 32.36T^{13} + 142T^{12} - 136.4T^{11} - 327.3T^{10} + 305.1T^9 - 412.9T^8 - 389.1T^7 - 264.9T^6 + 279.2T^5 + 52.7T^4 - 96.35T^3 + 21.71T^2 + 11.09T + 28.3, \]
where $T = \frac{T_i - 747.6}{28.96}$; standard deviation $STD(\delta) = 0.8\%$.

Dependence of tensile strength on temperature is approximated by a polynom of the sixth degree

$$\sigma_b = -9.515 T^6 + 4.391 T^5 + 39.02 T^4 - 16.23 T^3 - 38.88 T^2 - 27.67 T + 137.3,$$

where $T = \frac{T_i - 743.1}{35.35}$; standard deviation $STD(\sigma) = 1.61$ MPa.

4. Results and discussions

The received dependences for the steels illustrate increase of plasticity near temperature of phase transition that testifies to mechanical instability and instability of the maternal phase crystal grid, which is followed by alternation of hardening processes and the return having an appearance of oscillations on the chart of stretching and decrease in strength in the range of phase transition temperatures.

As a result of destruction at tension tests steel grade 10 which structure consists mainly (more, than for 80 \%) of the solution alloyed $\alpha$-solid and the carbide strengthening phases has the greatest values of an aspect ratio. It is probable that because of small amount of perlite in low-carbon steels the main contribution to increase in their plasticity brings a condition of pretransformation close with a point of phase transformation $Ac_3$ (see Figure 1). Upon transition through critical point $Ac_1$ all perlite turns into austenite. At further heating above critical point $Ac_1$ there is $\alpha \rightarrow \gamma$-transformation and at the same time a saturation of the forming austenite carbon from earlier formed perlite. In steel grade 35 on the received dependence of an aspect ratio on temperature (see Figure 2) two extremum corresponding to conditions of pretransformation before points $Ac_1$ and $Ac_3$ are observed. In eutectoid steel grade U8A the main growth of plasticity is provided with a condition of pretransformation into vicinities of a point of phase transition $Ac_1$ (see Figure 3).

The obtained data testify that the steel of the considered classes, near temperature of phase transition show similar signs and in a condition of pretransformation their level plasticity above, than in the most flexible austenitic state at more high temperatures.

According to authors, increase of plasticity-investigated steels in the range of temperatures of phase transitions is caused by reorganization of a crystal grid and is a sign of metal system transition to other phase.

5. Conclusions

By results of pilot studies of patterns of change of plasticity at phase transformations of carbon steel grades 10, 35 and U8A the mathematical dependences (in the form of polynomials of different
degrees) which describe changes of steels relative elongation and tensile strength in a temperature interval 700…870 ºC are received and are able, to the previous phase transition of the first sort. It is revealed that the relative elongation changes not monotonously: raises with increase in temperature, reaching a maximum, and then decreases at achievement of critical point and increases at the subsequent temperature increase. It is established that in all three studied carbon steels their plasticity level in a condition of pretransformation is higher in comparison with an austenitic state. The revealed patterns and the received mathematical dependences describing changes of plasticity at phase transformations of carbon steels give the chance of practical application of the found plasticity resource when processing by pressure (stamping) steels of different classes. Processing in this case can be made at lower temperatures and forces of deformation that will allow reducing risk of emergence of scale, to increase processing productivity and to provide development perspective power- and resource-saving technologies of processing of metals with pressure.

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