DEFORMATION BEHAVIOUR OF LOW-ALLOY STEEL 42CrMo4 IN HOT STATE

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Abstract

The installation of the advanced equipment, determined for coiling of hot rolled bars in the small section rolling mill at Třinecké železárny a.s., requires the performance of numerous experimental tests to achieve the full-value utilization of this equipment. The low-alloy steel 42CrMo4, belonging to the range of products of the small section mill, was so far supplied to the customers in the form of straight bars. The steel bars can recently be coiled – thanks to Garret coilers – after finish rolling into coils. The steel 42CrMo4 is determined, above all, for heat treatment. For its higher hardenability it is suitable mainly for the production of the parts working under high stress that are used in the mechanical engineering and automotive industry.

For reasons of the comprehensive study of deformation behaviour of this steel in the hot state, a whole set of torsion tests was carried out on the plastometer SETARAM. From the results of continuous tests to rupture the characteristics of dynamic recrystallization were evaluated; the start of the dynamic recrystallization is defined by coordinates of the peak stress. These values were then used for determination of the activation energy in hot forming by means of the specialized software ENERGY 4.0. Formability of the studied steel could be represented, on the basis of results of torsion tests, by the 3D graph in relation to temperature and strain rate. The performance of the anisothermal interrupted torsion tests was used for the evaluation of phase transformations in the steel and these phase transformations were afterwards confronted with the decomposition diagrams designed by the dilatometric tests and by means of software QTSteel. The diagrams were executed in two modes (CCT – Continuous Cooling Transformation) and DCCT (Deformation 35 % + Continuous Cooling Transformation).

Key words:
Low-alloy steel, torsion test, activation energy, transformation diagrams, phase transformation temperatures

1. INTRODUCTION

Třinecké železárny a.s. is constantly updating its production facilities, among which also the continuous small section mill is ranked. This rolling mill is equipped with a new coiling line of Garret type, which enables to coil the hot rolled bars of the round cross section with diameter 50 mm into coils. The low-alloyed steel 42CrMo4, which is a part of the production assortment of the small section mill, has so far been delivered to the consumers in the form of straight bars. Recently the steel bars can be coiled – thanks to Garret coilers – after the finish rolling into coils [1]. The steel 42CrMo4 is intended above all for the heat treatment. Thanks to its higher hardenability it is suitable for the parts subject to high stress in the mechanical engineering. The well balanced proportion of strength, ductility and wear resistance makes it possible to use this steel in the automotive industry as well (manufacturing of crankshafts, axles, spindles, etc.) [2, 3].

The continuously increasing demands on the quality and properties of formed products require that new knowledge on the properties of the formed steels should be gained. To research the deformation
characteristics of materials the laboratory equipment and special programmes may be used, which are able to physically or mathematically simulate in a simplified manner the real operational conditions. Among this laboratory equipment e.g. plastometers of Gleeble type, torsion plastometers, simulators of working cycles and the complete laboratory rolling mills are ranked [4]. All this equipment has lots of advantages, but – of course – also some limitations. For a comprehensive study of the deformation behaviour of steel 42CrMo4 in the hot state, a series of torsion tests was performed on the plastometer SETARAM, which is beneficial with regard to a chance of obtaining many pieces of information from the only one test [5]. This information can subsequently be used for example for the description of kinetics of the dynamic recrystallization and determination of the formability of the investigated steel [6]. The deformation behaviour of steel 42CrMo was already studied before [7], nevertheless, the constant increase in demands on the properties of this steel requires the optimization of the deformation parameters of this steel. With the effort to determine the temperatures of phase transformations of steel 42CrMo4, the anisothermal interrupted test on the torsion plastometer was carried out. These temperatures were then compared with the CCT (Continuous Cooling Transformation) and DCCT (Deformation Continuous Cooling Transformation) diagrams, obtained by the dilatometry testing [8] and by means of software QTSteel 3.1 that enables to simulate the heat treatment of the carbon, alloyed, and tool steels [9].

2. DESCRIPTION OF EXPERIMENTS

For the torsion tests of steel 42CrMo4 on the plastometer SETARAM the test bars with diameter of the deformed part 6 mm and length 50 mm were prepared. The chemical composition of steel 42CrMo4 was as follows: 0.431 C – 0.77 Mn – 0.276 Si – 0.016 P – 0.026 S – 1.14 Cr – 0.175 Mo (wt %). The torsion tests were carried out at temperatures 800, 900, 1000 and 1100 °C and torsion speeds 8, 40, 200, 400 and 1000 rpm, and in case of temperature 1100 °C at torsion speeds 80 and 400 rpm as well. These torsion speeds correspond with strain rates 0.02, 0.1, 0.2, 0.5, 0.9 and 2.3 s^{-1}. From results of the continuous tests to fracture the activation energy of steel 42CrMo4 was determined and the characteristics of the dynamic recrystallization were evaluated, the start of which is defined by the coordinates of the stress peak. Based on the results of the torsion test, also the formability of the investigated steel was evaluated.

For the reason of the evaluation of phase transformations in steel 42CrMo4 the anisothermal test on the torsion plastometer SETARAM was carried out in the range of deformation temperatures 1200 – 550 °C. The pause between particular deformations was 5 seconds, the strain was equal 0.053 and the strain rate was 0.096 s^{-1}. After the first deformation the heating was switched off and the specimens were cooled in the free air. The temperatures of the phase transformations found out in such a way were then confronted with the decomposition diagrams. The modes for determination of the decomposition diagrams on the dilatometer DIL 805A/D were as follows: for the determination of the decomposition diagram in the mode CCT (Continuous Cooling Transformation) the cylindrical specimens with diameter 5 mm and length 50 mm were prepared, heated in vacuum (min. 10^{-4} mbar) at speed 4.7 °C/s to temperature 850 °C. The dwell time on this temperature was 1200 s. Then the specimens were cooled at various speeds to the ambient temperature. The determination of the decomposition diagram in the mode DCCT (Deformation Continuous Cooling Transformation) was similar as in the previous case: in addition to, in case of this mode the test specimens were subjected at temperature 850 °C to the height reduction 35 %. The cooling speeds of specimens in both testing modes varied between 67 °C/s and 3 °C/min [8]. The decomposition CCT and DCCT diagrams were also determined, under conditions stated above, by means of software QTSteel 3.1 created by the ITA company.

3. MATHEMATICAL PROCESSING OF GAINED DATA

The activation energy is an important material constant that is used for the description of kinetics of the dynamic recrystallization. The activation energy depends on the chemical composition and microstructure of
the hot formed material. The determination of the activation energy was carried out, using the special developed software ENERGY 4.0. The data obtained experimentally were subsequently processed, using partial linear regressions, which enabled to suppress scattering of the input data and the recognition of the phase transformation, as the case may be. The values modified in this way were automatically smoothed by means of the non-linear regression, which included two on each other independent variables – temperature and strain rate.

The value of the activation energy is possible to calculate from the relation [10]:

\[
\dot{e} = C \cdot \exp \left( - \frac{Q}{R \cdot T} \cdot \sinh(\alpha \cdot \sigma_{\text{max}}) \right)^n
\]  

(1)

where \( \dot{e} \) is strain rate [s\(^{-1}\)], \( R \) is molar gas constant, equal 8.314 J.mol\(^{-1}\).K\(^{-1}\), \( T \) is temperature of deformation in [K], \( \sigma_{\text{max}} \) [MPa] is maximum flow stress corresponding to peak strain, \( C \) [s\(^{-1}\)], \( \alpha \) [MPa\(^{-1}\)] and \( n \) are material constants. The knowledge of the activation energy in hot forming is very important. Zener-Hollomon parameter \( Z \) [s\(^{-1}\)], known also as temperature-compensated strain rate, is used for the description of stress-strain curves. The relation (2) determines the value of \( Z \) and includes the activation energy that represents the material factor [11]:

\[
Z = \dot{e} \cdot \exp \left( \frac{Q}{R \cdot T} \right)
\]  

(2)

Using the knowledge of Zener-Hollomon parameter enables to determine the coordinates of peaks of the stress-strain curves and thus predict the start of the dynamic recrystallization. The value of the peak strain and corresponding peak stress (maximum stress \( \sigma_{\text{max}} \)) may be calculated from the following relations:

\[
e_p = U \cdot Z^w
\]  

(3)

\[
\sigma_{\text{max}} = \frac{1}{\alpha} \cdot \arg \sinh \left( \frac{Z}{C} \right)
\]  

(4)

The constants \( U, W, \alpha, n \) and \( C \), which feature the respective material, are determined by the regression analysis by means of software ENERGY 4.0.

4. DISCUSSION OF RESULTS

The stress-strain curves were determined from the results of the continuous tests to fracture, for corresponding temperatures and strain rates. Examples of these curves, found with strain rate 0.1 s\(^{-1}\) or at torsion speed 40 rpm, are demonstrated in Fig. 1. The values gained by the torsion test were subjected to the regression analysis in the programme ENERGY 4.0. The value of the activation energy for the investigated steel was determined and the material constants enumerated - see Table 1.

![Fig. 1. Stress-strain curves at constant torsion speed 40 rpm](image)

Table 1. Material constants for description of kinetics of dynamic recrystallization of steel 42CrMo4

<table>
<thead>
<tr>
<th>( Q ) [kJ/mol]</th>
<th>( n ) (1100 °C)</th>
<th>( \alpha ) (900 °C) [MPa(^{-1})]</th>
<th>( C ) [s(^{-1})]</th>
<th>( U )</th>
<th>( W )</th>
</tr>
</thead>
<tbody>
<tr>
<td>344.33</td>
<td>4.1992</td>
<td>0.0156</td>
<td>4.48•10(^{11})</td>
<td>0.00753</td>
<td>0.114</td>
</tr>
</tbody>
</table>
In Fig. 2 and 3 the dependences of peak strain $e_{p}$ or maximum stress $\sigma_{max}$ on strain rate and deformation temperature are pictured. From these graphs it is visible that the highest values of the peak strain and maximum stress are achieved at low deformation temperatures and high strain rates.

![Fig. 2. Relation between deformation to peak and deformation temperature](image1)

![Fig. 3. Relation between maximum stress and deformation temperature](image2)

By means of the three-dimensional (3D) chart the formability of the investigated steel in dependence on deformation temperature and strain rate is shown pictorially in Fig. 4. With the increasing deformation temperature the deformation to fracture rises. The lowest value of deformation to fracture was reached when torsion speed was 1000 rpm and temperature 800 °C. The combination of high strain rate and high deformation temperature led to the highest values of deformation to fracture.

In Fig. 5 the particular decomposition CCT diagrams of steel 42CrMo4, determined by means of dilatometry or programme QTSteel 3.1, are shown. If we compare the CCT diagrams of steel 42CrMo4 determined on the dilatometer with the diagrams determined by means of software QTSteel 3.1, a good conformity is seen between the CCT diagrams determined on the dilatometer and QTSteel.

![Fig. 4. 3D map of formability of steel 42CrMo4](image3)

![a) CCT diagram of steel 42CrMo4 constructed on dilatometer](image4)

![b) CCT diagram of steel 42CrMo4 constructed by means of software QTSteel 3.1](image5)

Fig. 5. CCT diagrams determined on dilatometer, or by means of QTSteel.
If we compare the phase transformation temperatures found out by the dilatometry testing and modelling in the programme QTSteel, we can draw a conclusion that a good compliance of temperatures $A_c_1$ was achieved. Temperature $A_c_1$ determined on the dilatometer was equal 753 °C, temperature $A_c_1$ determined by QTSteel software was equal 740 °C. The difference between temperatures $A_c_3$ determined by dilatometry (801 °C) and QTSteel (775.1 °C) was only a little higher than in the case of temperatures $A_c_1$.

It was verified before that it is possible to determine the temperatures of phase transformations during cooling of steels by means of the anisothermal interrupted test [12]. Unfortunately, in this case temperatures of phase transformations could not be determined exactly because the graph in Fig. 6 does not show any significant change of the relation between the flow stress and the strain in the area of temperatures where the transformation of austenite to ferrite is expected. The specimen was cooled in the interim between particular deformations in the free air at speed 5.7 °C/s. By comparison of the time-related temperature of the specimen in case of the anisothermal test, expressed by means of the blue cooling curve in Fig. 5a and Fig. 5b, with the decomposition CCT diagram a conclusion can be derived that the structural state of the specimen does not change at the cooling itself, the austenitic structure remains stable. With regard to the course of the measured deformation resistance characteristics in the anisothermal test it may be supposed that neither deformation affects the structural state of the investigated steel with the given conditions of deformation. To manifest phase transformations it would be necessary to perform the anisothermal interrupted test with another interim between subsequent deformations and, mainly, smaller cooling speed, which already falls into the field of the physical simulation of forming on the torsion plastometer.

![Fig. 6. Anisothermal interrupted test of steel 42CrMo4](image)

However, from the particular stress-strain curves in Fig. 6 it may be judged if some softening of the specimen between particular deformations occurred. From a detail of the fourth stress-strain curve, i.e. from the test performed at temperature 959 °C, it may be judged that before the partial deformation itself the partial softening of the material by the static recrystallization occurred. By contrast, the detail of the seventeenth curve, gained at temperature 595 °C, shows no indications of material softening in the pause before the given deformation and it may be assumed that the material was only strain-hardened.

5. CONCLUSIONS

The compact series of torsion tests performed on the plastometer SETARAM was used to study the hot deformation behaviour of low-alloyed steel 42CrMo4, intended for the heat treatment. From the results of
torsion tests the activation energy of steel 42CrMo4 was determined by means of software ENERGY 4.0. Its value, \( Q = 344.33 \text{ kJ/mol} \), was used for the description of kinetics of the dynamic recrystallization. By means of Zener-Hollomon parameter the coordinates of peaks of the stress-strain curves were described, which predict the start of the dynamic recrystallization of steel 42CrMo4.

The formability of steel 42CrMo4 in dependence on temperature of deformation and strain rate was shown by 3D graph, based on the results of torsion tests. The low formability was achieved at the highest strain rate and lowest deformation temperature. The best formability was achieved at the highest strain rate and highest deformation temperature. Hence, the temperature of deformation essentially influenced the formability of the investigated steel.

On the torsion plastometer SETARAM the anisothermal interrupted test was also carried out, with the aim to evaluate the phase transformations in steel 42CrMo4 and confront them with the decomposition CCT and DCCT diagrams. The determination of temperatures of the phase transformations of steel 42CrMo4 by this method was considerably deteriorated, as no characteristic change of stress in dependence on deformation temperature, indicating the phase transformation of austenite to ferrite, was observed. It was caused by a relatively high speed of cooling of the specimen, which did not enable to achieve the transformation of austenite to ferrite. Therefore, only temperatures of phase transformations were compared, derived from the decomposition diagrams that were determined on the dilatometer, or by the programme QTSteel 3.1. A quite good conformity of found out temperatures \( A_1 \) was achieved. The difference between values of temperatures \( A_3 \), determined by the dilatometry testing and computer simulation in the programme QTSteel 3.1, was 25.9 °C, which was more than in the case of temperature \( A_1 \).

ACKNOWLEDGEMENT

The research was realized within the project MSM6198910015, supported by the Ministry of Education, Youth and Sports of the Czech Republic, and within the students’ grant project SP2011/149 supported at VŠB – TU Ostrava by the Ministry of Education of the Czech Republic.

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