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Research Article

FLOW STRESS MODEL FOR COLD-FORMED 40HM CONSTRUCTIONAL STEEL

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ABSTRACT
The paper presents the results of research undertaken to investigate cold forming process for 40HM constructional steel suitable for heat treatment. In the first part of the paper, mechanical properties of this steel and its industrial applications are described. The second part of the paper presents the results of the analysis of flow curves for two kinds of steel specimens: those that were subjected to annealing and those that did not undergo any heat treatment. It was found that the application of heat treatment had a significant effect on improving the forming conditions for this steel at room temperature. The experimental flow curves obtained in a compression test were described by constitutive equations illustrating the dependence between flow stresses and strain value. In order to determine the equation coefficients, the Generalized Reduced Gradient method implemented in Microsoft Excel was used. Based on the obtained equations, a material model will be developed to perform numerical simulations of cold forming for 40HM steel, using FEM-based software that aids the design of metal forming technologies.

Keyword: flow stress, 42CrMo4 constructional steel, cold forming.

INTRODUCTION

The research was undertaken to investigate constructional steel type 40HM (42CrMo4), classified under the PN-EN 10083-1+A1:1999 norm. One of the machinery and alloy steels suitable for heat treatment, this steel type has a carbon content of approximately 0.3–0.5% C, which determines its strength properties, and contains alloy additions, such as Mn, Cr, Ni, Mo, Si that provide the steel with a particular hardening capacity [1]. 40HM steel is used to produce most machinery, vehicle and construction parts. The steel can be heat treated due to a high Re/Rm ratio that ensures high ductility, while the alloy additions ensure a better hardening capacity [2].

The minimum mechanical properties of the investigated steel after heat treatment are as follows: tensile strength Rm of 1000 MPa, yield strength R0.2 of 750 MPa, elongation A5 of 11%. The steel is used for producing machinery elements with very high strength and ductility as well as parts exposed to changing loads, such as axles, crankshafts, gears, disks, rotors, levers, pushers, connecting rods, fasteners, casing elements and gripping elements of tools. 40HM steel is suitable for hot forming. Among others, it is used in processes, such as forging, extrusion and rolling in the temperature range of 850–1050 °C [3].

The analysis of the specialist literature demonstrates that there are no studies providing information on flow curves for 40HM steel subjected to cold forming. Therefore, it is justified that such research be performed to investigate the suitability of this steel for cold forming. The present study offers the results of the investigation undertaken to determine the flow stress model for cold-formed 40HM steel, examining the effect of applied heat treatment on the properties of steel formed at room temperature. The results can find application in the design and analysis of cold forming processes for this steel type.

EXPERIMENTAL DETAIL AND RESULTS

The research objective was to determine flow curves for 40HM steel. To this aim, a compression test method was employed [4, 5]. The forming process for 40HM steel specimens with a diameter of 10 mm and length of 20 mm (Figure 1) was run with lubrication at room temperature using a hydraulic press, at a mean strain rate of. The chemical composition of the investigated steel is listed in Table 1.

Prior to the forming process, some specimens (5 items) were subjected to soft annealing at a temperature of 680 °C for 0.5 h and then furnace cooled until total cool-down [8–10]. The design of the forming process and the view of the specimens after compression are shown in Figure 2 and Figure 3.

During the experimental tests, the specimen compression time, pressure and tool motion were determined. Based on the results of the measurements made, the values of flow stresses and equivalent strains were calculated. The flow stresses as a function of strain for the specimens made from annealed steel and for those formed without heat treatment are shown in Figure 4.

The flow curves determined in the experiments were described by functions (constitutive equations), making the flow stress values dependent on strain parameters. In order to describe the data, the following function was selected:

$$\sigma_p = A \cdot \varepsilon^B \quad (1)$$

where: σ_p – denotes the flow stresses (MPa),
ε – denotes the equivalent strains,
A, B, C – denote the coefficients [6].

In order to determine the constant function coefficients, the Generalized Reduced Gradient (GRG2) method implemented in Microsoft Excel Solver was used. To this aim, the objective function described by the below equation was minimized:

$$\Phi_\sigma = \frac{1}{k}\sum_{i=1}^{k}\frac{(\sigma_{pt} - \sigma_{pe})^2}{\sigma_{pe}^2} \cdot 100\% \quad (2)$$

where:
σ_{pt} – denotes the value of flow stresses calculated on the basis of function (1),
σ_{pe} – denotes the experimental value of flow stresses,
k – denotes the number of measuring points [7].

The results of the conducted optimization calculations are listed in Table 2.

Fig. 1. Cylindrical specimens prepared for rolling

Table 1. Chemical composition of 40 HM steel [%]

C	Mn	Si	P	S	Cr	Ni	Mo	W	V	Cu	C
0.38–0.45	0.4–0.7	0.17–0.37	max 0.035	max 0.035	0.8–1.2	max 0.3	0.15–0.25	max 0.2	max 0.05	max 0.25	0.38–0.45

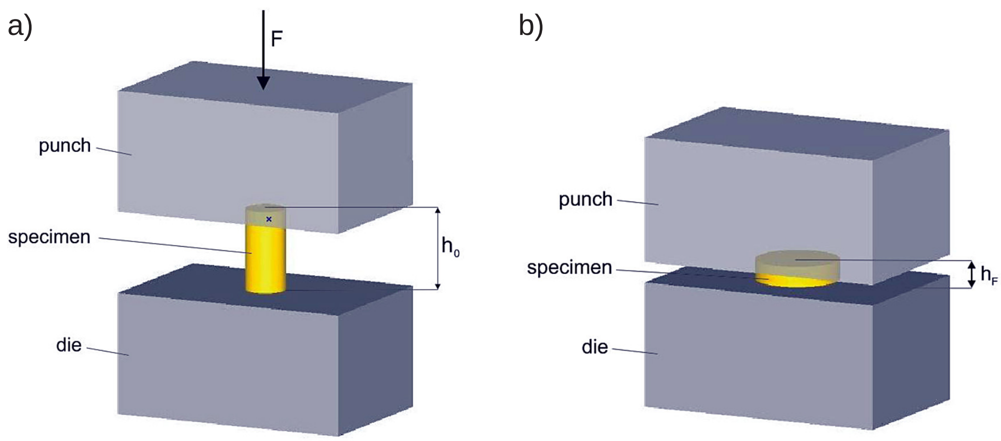

Fig. 2. Design of the compression test

Fig. 3. Surfaces of steel specimens formed: a) without prior heat treatment, b) by annealing

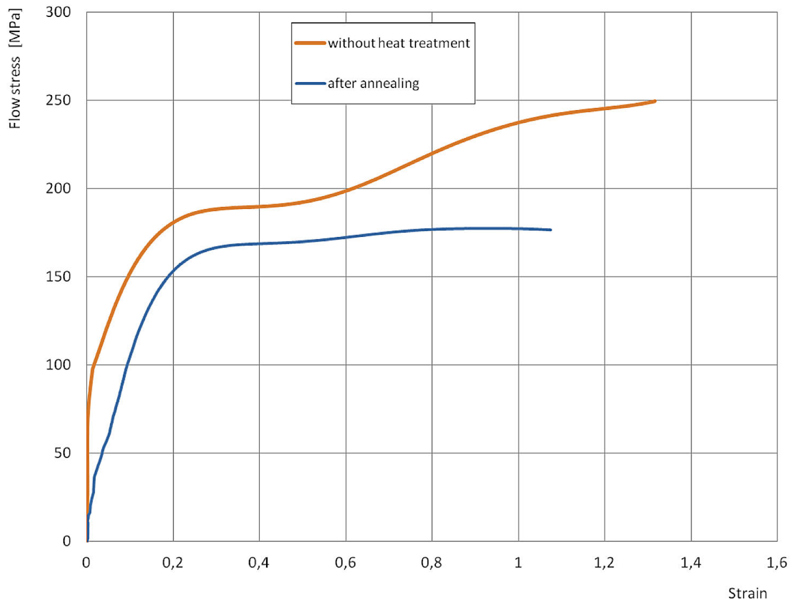

Fig. 4. Experimentally determined flow curves for cold formed 40HM steel: a) without heat treatment, b) after annealing

Table 2. Calculated coefficients of function (1)

Function (1)	Coefficients		Objective function Φ_σ, %
	A	B	
For 40 HM steel without heat treatment	230.7450	0.1903	0.0017
For 40 HM steel after annealing	224.8095	0.4941	0.0583

The following constitutive equations were obtained:

a) for 40HM steel specimens formed without annealing

$$\sigma_p = 230{,}7450 * \varepsilon^{0{,}1903} \quad (3)$$

b) for 40HM steel specimens formed by annealing

$$\sigma_p = 224{,}8095 * \varepsilon^{0{,}4941} \quad (4)$$

Figure 5 presents the comparison of the flow curves described by the determined equations (3) and (4). The curves illustrating the changes in the flow stress of steel after heat treatment (Figure 5) manifest different behaviors. The experimental tests demonstrated that heat-treated 40HM steel specimens were characterized by a much lower flow stress compared to the specimens that were not subjected to annealing, which proves that this steel exhibits better formability after heat treatment.

The tests undertaken to investigate whether 40HM steel can be formed at room temperature confirmed that the non-heat treated material was less suitable for cold forming, which was

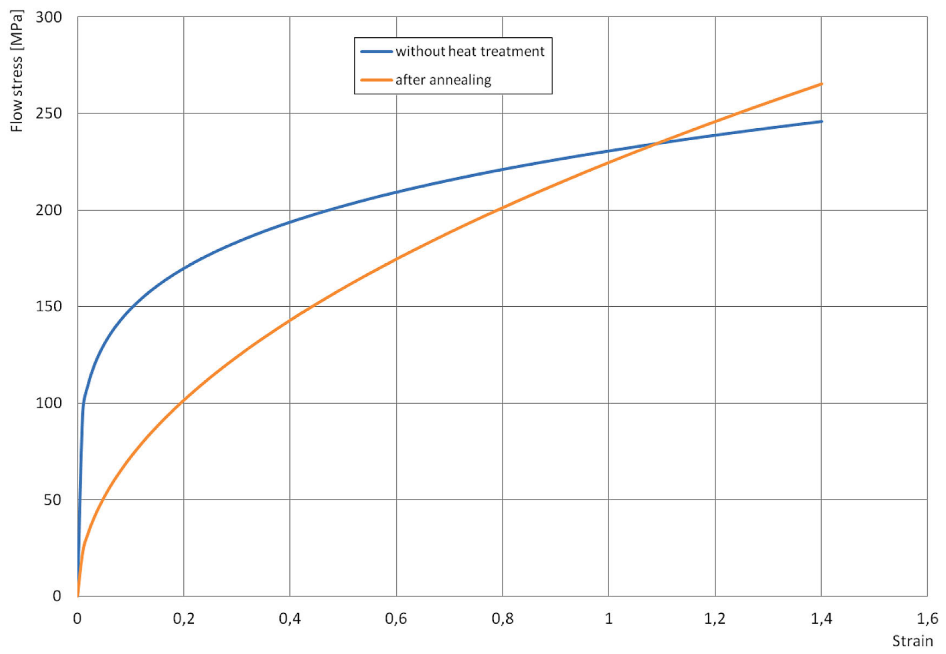

Fig. 5. Comparison of the flow curves described by the determined equations (3) and (4)

proved by the surface of the compressed specimens (Figure 3). The flanks and flat surfaces of the compressed non-heat treated 40 HM steel specimens had cracks, while the specimens subjected to annealing were crack-free. The heat treated steel specimens had a better surface quality, too.

CONCLUSIONS

Based on the conducted theoretical and experimental tests, the following conclusions can be drawn:

1. The performed plastometric compression tests allowed for the determination of flow curves for 40 HM constructional steel subjected to cold forming. The obtained flow curves were described by the function (1), making the flow stress values dependent on the equivalent strains.
2. The results of the conducted tests were used to design a flow stress model for this steel prior to and after heat treatment. The constitutive equations (3) and (4) were defined, and their parameters were determined using the GRG2 optimization method. The experimental flow curves show a good agreement with their values calculated based on the determined constitutive equations.
3. The results demonstrate that heat treatment has a significant effect on both the flow curves for cold-formed 40HM steel and flow stress values. The specimens that did not undergo heat treatment have a higher flow stress value. The investigated steel type exhibits good formability at compression at room temperature after the prior application of annealing. For the parameters applied, only the specimens not subjected to heat treatment had their material cohesion broken. Owing to that, it is recommended that 40Hm steel be heat treated in order to reduce deformation resistance in the cold forming process.
4. The knowledge of the flow characteristics of 40 HM steel under the investigated forming conditions is indispensable for developing a material model that will constitute the basis when designing technological processes for cold forming of this material. The results will be used to perform numerical simulations of forming 40HM steel by the finite element method.

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