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Technological plasticity and structure in stainless steels during hot-working

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Materials

ABSTRACT

Purpose: The high-temperature plastic deformation is coupled with dynamic processes of recovery influencing the structure and properties of alloys. One of crucial issues is finding the interdependence between the hot plastic deformation process parameters, the structure and properties.

Design/methodology/approach: Hot plastic deformation was carried out using a torsion plastometer in the temperature range of 900-1150°C at a strain rate of 0.04-4 s-1. The plastometric investigations enabled the determination of the influence of deformation parameters on technological plasticity. Investigations of the samples' structures were carried out using a light and electron microscope, by a thin film method. A quantitative analysis of structural changes was performed using the „MetIlo" image analysis programme.

Findings: Results of the investigations have been provided referring to the influence of the hot plastic deformation process on the microstructure and the substructure as well as technological plasticity of steels of an austenitic, ferritic and ferritic-austenitic structure. Mathematical models were developed which link the deformation process parameters to the grain size obtained after the deformation as well as the mechanical properties determined in a torsion test.

Practical implications: The research carried out enabled the understanding of the phenomena taking place during deformation and annealing of the investigated alloy. The results will constitute the basis for modelling the structural changes.

Originality/value: The results obtained are vital for designing an effective thermo - mechanical processing technology for the investigated steels.

Keywords: Metallic alloys; Hot deformation; Microstructure; Recrystallization

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1. Introduction

The behavior of metals and alloys during hot deformation is a complex issue and alters with the change of such process parameters as: deformation size, deformation rate and temperature. The analysis of hot working conducted with the application of a torsion test using a torsion plastometer allowed the determination of the influence of deformation conditions on plasticity of the steel. The high-temperature plastic working is coupled with dynamic processes of recovery influencing the structure and properties of alloys. One of crucial issues is finding the interdependence between the hot plastic deformation process parameters, the structure and properties.

The present paper constitutes a part of the investigations of structural phenomena taking placing during heat treatment and hot plastic workin of stainless steels of a diversified structure, carried out at the Materials Science Department, Technical University of Silesia [5,7,8,10]. In the models of thermal-plastic material processing, interdependencies which link the course of deformation with parameters characterizing the structure are proposed [2,3,4,6,14,18]. The structural component are the grain size, dislocation density and the size of the subgrain formed during deformation of the metal [1,9,11,17]. The determination of the above-mentioned parameters describing the deformed material structure requires the application of analytical methods based on microscopy and transmission electron microscopy.

In the article, results of the researches have been provided referring to the influence of the hot plastic deformation process on the microstructure and the substructure as well as technological plasticity of steels of an austenitic, ferritic and ferritic-austenitic structure. Moreover, models were developed which link the deformation process parameters to the grain size obtained after the deformation as well as the mechanical properties determined in a torsion test.

2. Material and methodology

As the test material, hot rolled bars were used, ϕ15 mm in diameter, made of an X5CrTi25 ferritic steel, an X3CrNiMo18-9 austenitic steel as well as a ferritic-austenitic steel (duplex steel) of the X2CrNiMoN22-5-3 grade. The chemical composition of the steels tested is provided in Table 1. Prior to plastic deformation, the steels tested were annealed at a temperature of 1150°C, with soaking time of 60 minutes, and cooled in water.

Plastometric investigations were performed by the hot torsion method in a plastometer manufactured by "Setaram" [12]. The torsion was carried out in the temperature range of 900 - 1150°C at the strain rate of 0.04 - 4s^{-1} according to the pattern provided in Fig. 1. For the purpose of an analysis of changed in the structure, one of the plastometer's auxiliary systems was used, enabling interruption of the torsion process at a selected stage of deformation, with fast cooling of the sample in water – the so-called "structure freezing".

On the basis of the data obtained, flow curves were determined in the stress – strain system. After approximation of the torque, strain ε was determined as a function of the number of the sample's rotations during torsion [12].

$$\varepsilon = \frac{2}{\sqrt{3}} \times \operatorname{arcsinh}\left(\frac{\pi \bar{R} N}{L}\right) \qquad (1)$$

where:
$\bar{R}$ - equivalent radius corresponding to 2/3 of the external radius of sample R [mm];
L - measured length of the sample.[mm],
N - number of sample rotations.

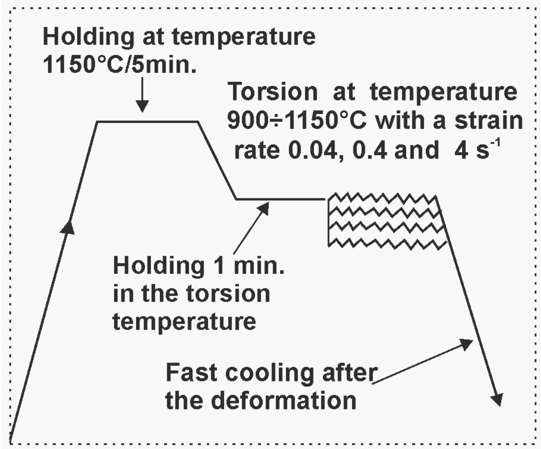


Fig. 1. Scheme of the experiment of hot plastic processing of tested stainless steels

Yield stress ε_p [MPa] was determined according to relation taking account of the corrected torque M', sample radius R, parameters m and p, and axial force F [4]:

$$\sigma_p = \left[\left(\frac{\sqrt{3}M'}{2\pi R^3}\right)^2 \times (3+p+m)^2 + \left(\frac{F}{\pi R^2}\right)^2\right]^{0.5} \qquad (2)$$

On the flow curves determined, the parameters characterizing mechanical properties of the steel in the torsion test were defined - the so-called technological plasticity:
σ_{pp} - peak stress on the flow curve [MPa];
ε_p - deformation corresponding to the peak stress;
ε_f - deformation to fracture, the so-called threshold deformation.

Activation energy of the process Q [kJ/mol] was determined using the computer program ENERGY [13]

The deformation conditions (temperature, strain rate) were described using Zener-Hollomon's parameter:

$$Z = \dot{\varepsilon} \exp\left(\frac{Q}{RT}\right) \qquad (3)$$

where:
$\dot{\varepsilon}$ – strain rate, [s^{-1}];
T – deformation temperature, [°C];
Q – activation energy of the plastic deformation process [kJ/mol];
R – molar gas constant [J/molK].

Table 1.
Chemical composition of the steels tested

Steel grade	C	Cr	Ni	Mo	Ti	Si	Mn	N	P	S
X5CrTi25 (ferritic)	0.03	25.3	0.32	-	0.33	0.38	0.55	-	0.03	0.016
X3CrNiMo18-9 (austenitic)	0.05	18.5	9.20	-	-	0.80	1.2	0.08	0.03	0.022
X2CrNiMo22-5-3 (duplex)	0.02	22.8	5.5	3.1	-	0.30	1.57	0.17	0.02	0.001

After the torsion, the steel structure was analysed on specimens parallel to the plastometric sample's axis. Grinding and polishing of the samples were carried out according to the guidelines specified in the expert system of the STRUERS company. Metallographic investigations were conducted using a light microscope NEOPHOT 2 in the range of magnifications of 100-1000×, using the bright field.

Structural examinations were carried out by applying the thin film technique, using a JEM-100B Joel's transmission electron microscope at the accelerating voltage of 100 kV.

Quantitative metallographic investigations were carried out by superficial method using the MET–ILO3.0 computer program. For the structures analysed, a mean area of the grain plane section $\bar{A}$ was determined. All the mathematical dependencies determined in the course of the study were further elaborated using a two-dimensional and multidimensional regression analysis and correlation by means of the least squares method.

3. Results

After hot processing and prior to deformation, the X5CrTi25 steel shows a single-phase ferritic structure with an average area of the grain plane section. $\bar{A}$ =6400μm^2 (Fig. 2a). The X3CrNiMo18-9 steel is characterized by an austenitic structure of grains ($\bar{A}$ =6000μm^2) with a small amount of annealing twins (Fig. 2b). The X2CrNiMoN22-5-3 steel is characterized by a two-phase ferritic-austenitic structure, with the part of the ferritic structure amounting to 62% (Fig. 2c).

The influence of temperature and strain rate on the course of the yield stress curves from deformation for the samples analysed is displayed in Figures 2 and 3. In the scope of the torsion parameters changeability, the deformability of the analysed ferritic steel samples is very high. The deformability of the austenitic steel samples is average, the strain to fracture being within 1.2 and 2.0. For the austenitic steel, higher values of peak stress are observed. The stainless steel of a ferritic-austenitic structure demonstrates the lowest deformability in comparison with the single-phase steels with correspondingly higher values of yield stress.

Flow curves of the ferritic-austenitic steel indicate (Figs. 3, 4) material strengthening and softening, with a single maximum of the yield stress σ_{pp}. For each of the torsion temperature values, the yield stress ε_p decreases until the sample's failure after reaching its maximum; no steady plastic flow of the tested material was observed, typical of the investigated single-phase stainless steels.

The influence of the torsion temperature with strain rate of 0.4s^{-1}on the peak stress σ_{pp}, deformation σ_p and strain to fracture ε_f is shown in Figures 4-6. For all of the investigated steels, a decrease of the peak stress σ_{pp} was noticed with an increase of the hot working temperature (Fig. 5).

The ferritic-austenitic steel demonstrates the highest values of σ_{pp} in the whole range of temperature and strain rate. Such course of changes is not to be observed in the analysis of the dependence of deformation ε_p as a function of deformation temperature (Fig. 6). This refers to changes in the duplex steel deformation ε_p, where this value is maintained at the same level (ca. 0.40) throughout the whole range of temperature changes. The influence of deformation temperature on the strain to fracture ε_f of the investigated steels (Fig. 7) disclosed large discrepancies among the values of this parameter for the same deformation temperature. In the whole range of deformation temperature values, the strain to fracture increases as the temperature grows. The increase is the quickest for the steel of a ferritic structure.

a)

b)

c)

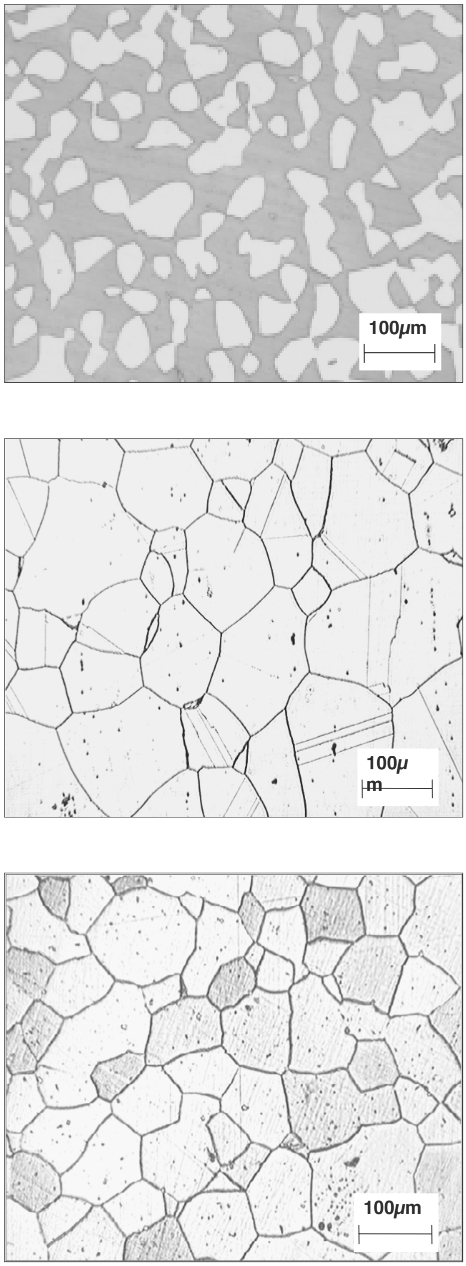


Fig. 2. The microstructure of the steels analysed after annealing at a temperature of 1150°C for 60 minutes and cooling in water. a) ferritic steel (X5CrTi25, b) austenitic steel, c) duplex steel (ferritic-austenitic steel)

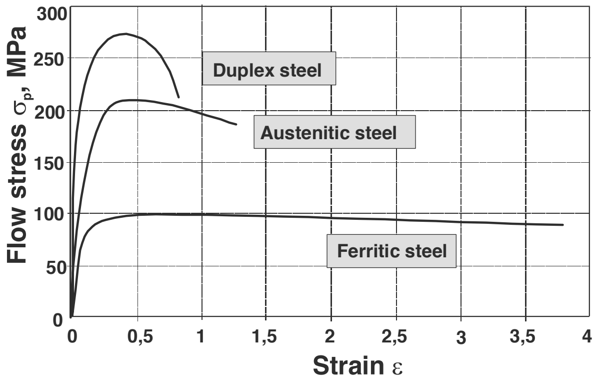


Fig. 3. Flow curves of the analysed stainless steels after torsion at a temperature of 900°C with a rate of $0.4s^{-1}$

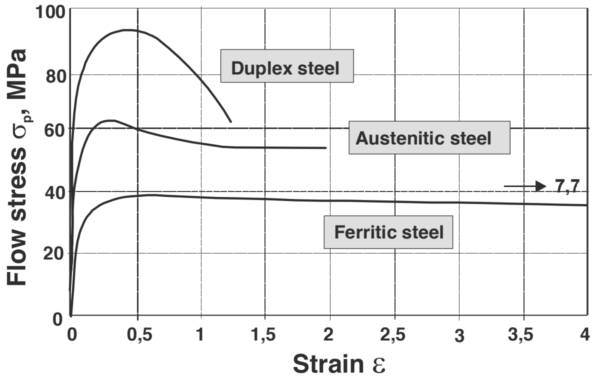


Fig. 4. Flow curves of the analysed stainless steels after torsion at a temperature of 1100°C with a rate of $0.4s^{-1}$

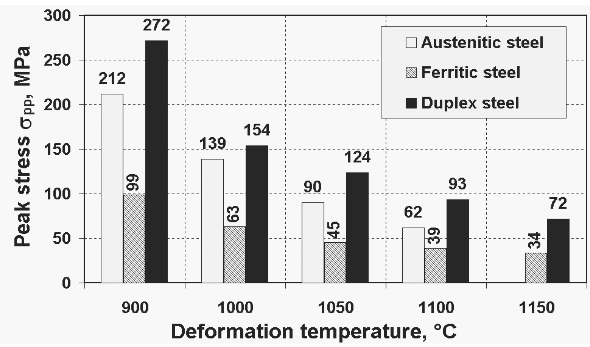


Fig. 5. Influence of deformation temperature on peak stress σ_{pp} of the steels analysed.

On the basis of the maximum yield stress σ_{pp} and deformation ε_p ,using the computer program ENERGY, activation energy of plastic deformation Q was calculated. For the ferritic steel with a high chromium content, in the range of the torsion process parameters applied, activation energy amounts to 330 [kJ/mol]. The value of activation energy of the deformation process is lower in comparison with the austenitic steel (383.2 [kJ/mol]), therefore, no intense strengthening of the steel analysed was observed during deformation.

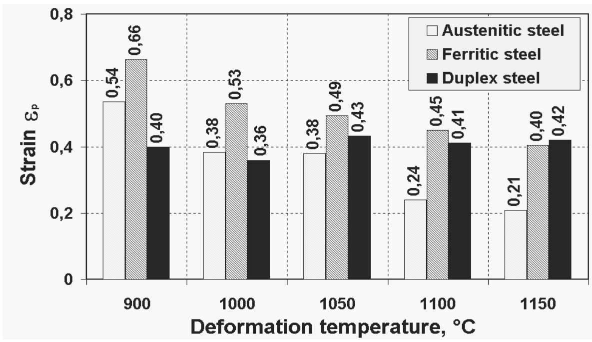


Fig. 6. Influence of torsion temperature on strain ε_p of the steels analysed

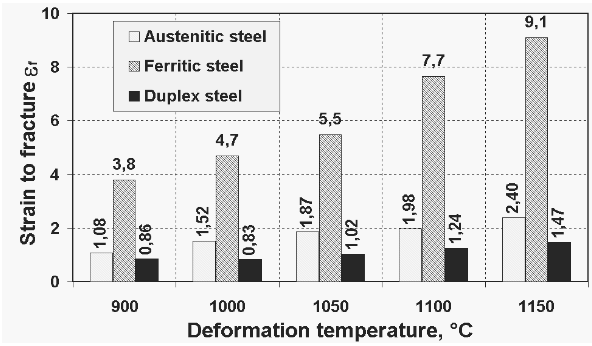


Fig. 7. Influence of torsion temperature on strain to fracture ε_f of the steels analysed

The activation energy of hot plastic deformation process Q for the duplex steel in the analysed range of torsion parameters changeability was highest and equaled 547 [kJ/mol], hence the intensive material strengthening during deformation.

Where deformation of ferritic steel takes place at a temperature of 900-1100°C, in the initial phase of the process, limited nucleation of new recrystallized grain is observed at the boundaries of primary grain, as well as its further growth as the deformation increases (Fig. 8a-c).

Changes in the structure of austenitic steel after deformation at the temperature of 1100°C are shows in Fig. 9. In the steels analysed, with torsion at the temperature of 1000°C or higher, in the whole range of strain rate tested, changes in the substructure were observed induced by the dynamic recrystallization process (Fig. 9). Together with increase of deformation until the value corresponding to the peak stress is reached. The primary grains' boundaries deform and lengthen influenced by deformation (Fig. 9a). After the deformation increase in the microstructure, new recrystallized grains appear on the corrugated boundaries of the primary grains first, and then, also inside the deformed primary grains (Fig. 9b). Dynamic processes are characterised by the simultaneous continuity of strengthening (higher defectability) and softening. The process of microstructure reconstruction begins with a dislocation reannihilation, the creation of dislocation subgrain boundaries, the growth of dislocation within these boundaries and the coalescence of subgrains. The repeatability of such a reconstruction depends on deformation rate (Figs. 10, 11).

The boundaries of original grains partly etched, which becomes particularly clear when juxtaposing the microstructure images of the same zone in the deformed plastometric sample in both perpendicular planes. Thus, it is possible to compare the shape and size of deformed and recrystallised grains (Fig. 12)

Changes in the duplex steel microstructure after torsion at the temperature of 900°C and rate of $0.04s^{-1}$ are displayed in Fig. 13.

In the ferrite areas, the subgrain structure is well developed. In austenite, one can observe formation of subgrains of high density of defects at the boundaries. Therefore, the substructure indicates diversified rate of the structure recovery of the individual phases which has a significant influence on the steel deformability.

The influence of hot plastic deformation (deformation temperature, deformation rate, deformation size) on the inhomogeneity and size of ferrite grains in ferritic-austenitic steel deformed at the temperature range of 900-1100°C indicates that increase in deformation size at the tested temperature range results in the reduction of an average area of plane section of a ferrite grain (Fig. 13).

The creation of a subgrain austenite structure, whose defects' density decreases along with increase in deformation size (Fig. 14), rise of deformation temperature leads to an increase in an average size of ferrite grain.

The influence of temperature and deformation rate, described with Zener-Hollomon's parameter Z, on technological plasticity of the samples analysed is shown in Table 2 (equations 4, 7, 8).

Together with increase of the parameter, one can notice increase of stress ε_p and deformation ε_p for the steels analysed. In the case of ferritic–austenitic steel, the influence of deformation conditions on ε_p does not demonstrate such a conformity as in the case of single-phase steels.

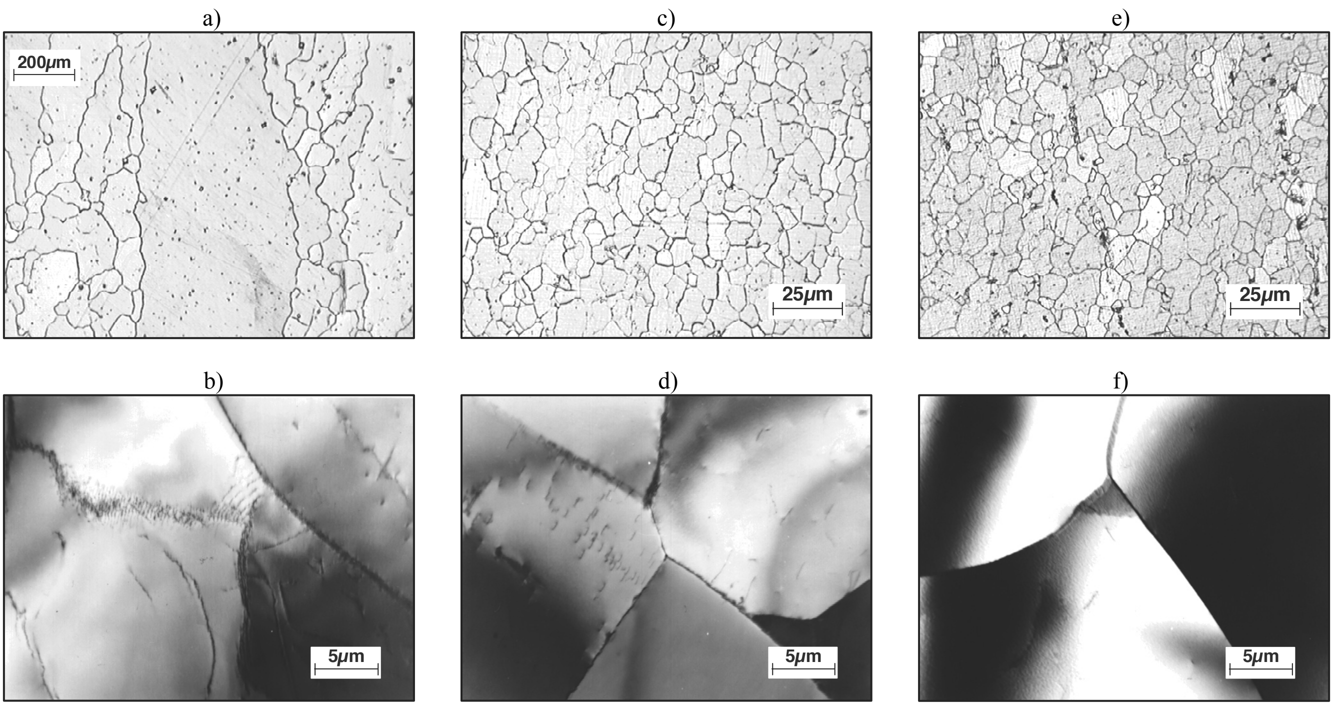


Fig. 8. Changes in the micro- and substructure of ferritic steel after torsion at a temperature of 1100°C and a rate of $0.04s^{-1}$. a, b) strain ε =1.0; c, d) strain ε =3.25; e, f) strain ε =8.5

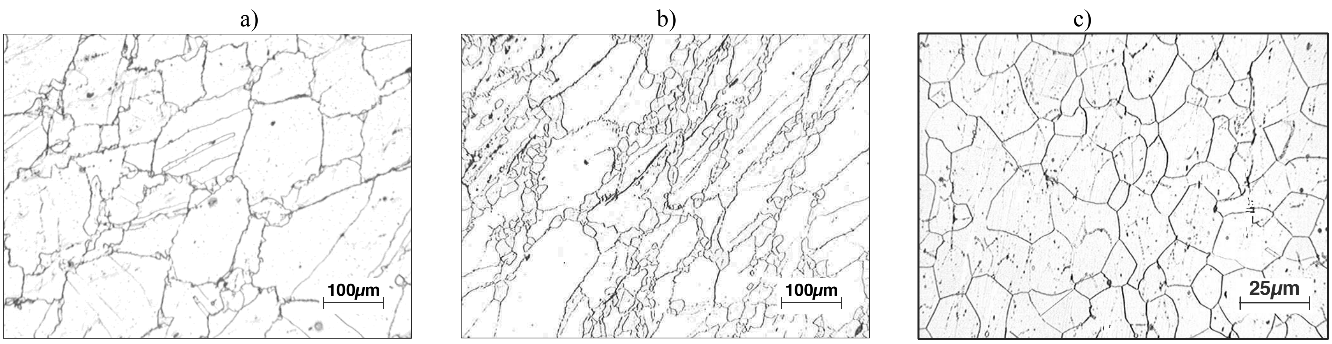


Fig. 9. Changes in the austenitic steel microstructure after torsion at the temperature of 1100°C and a rate of $0.04s^{-1}$; a) strain ε = 0.2, b) strain ε = 0.6, c) strain ε = 1.2

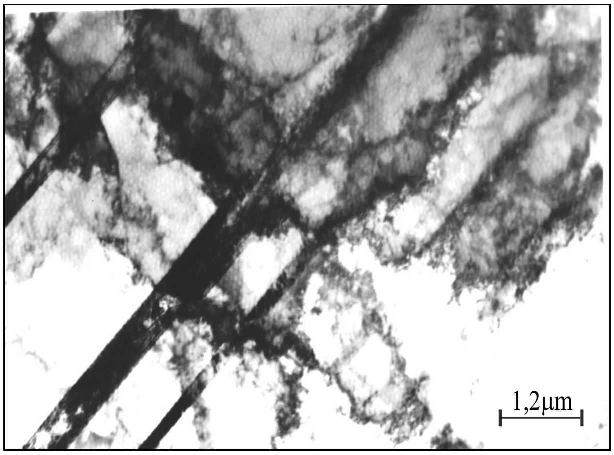


Fig. 10. Substructure of the Cr-Ni steel after deformation $\varepsilon = 0.66$ at the temperature of 1100°C and rate 0.4 s^{-1}

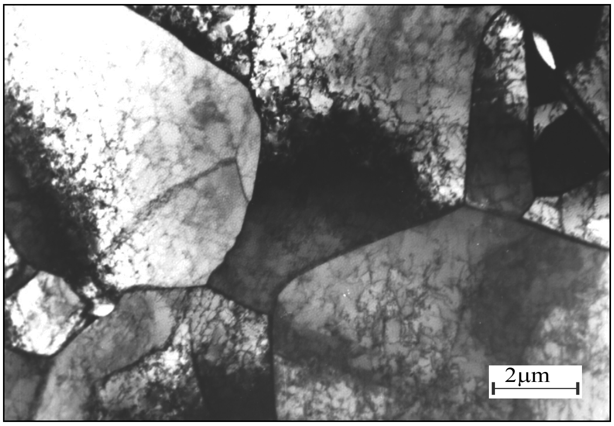


Fig. 11. Substructure of the Cr-Ni steel after deformation $\varepsilon = 1.2$ at the temperature of 1200°C and rate 0.04 s^{-1}

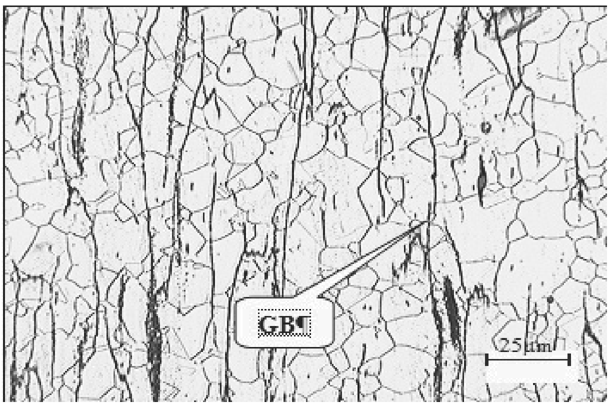
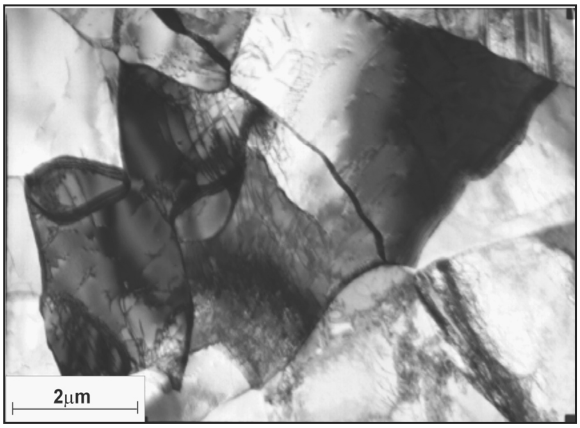


Fig. 12. Microstructure of the austenitic steel after deformation ε=1.2 at the temperature of 1000°C, longitudinal section. Etched traces of the location of original austenite grain boundaries (GB)

a)



b)

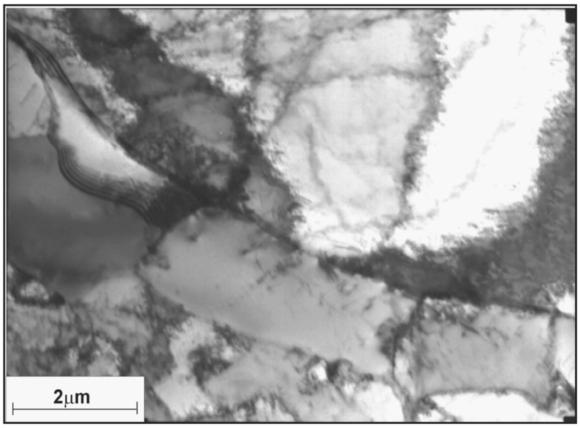


Fig. 13. Substructure of the two-phase ferritic-austenitic steel after torsion at the temperature of 900°C and rate of 0.04s^{-1}; strain $\varepsilon = 0.8$ a) ferrite substructure, b) austenite substructure

A significant influence of Zener-Hollomon's parameter on technological plasticity parameters has been evidenced; the grain size in stainless steels is provided in Table 2. The data obtained indicate that the influence of Zener-Hollomon's parameter on peak stress σ_{pp} for the analysed steels can be expressed in the form of a power function (equations 4, 6, 8).

The relation between deformation ε_p and Zener-Hollomon's parameter for the ferritic and austenitic steel is shown by the power dependence (equations 5, 6). No such definite relation has been determined for the two-phase steel.

4. Conclusions

The phenomena taking place in the course of hot deformation of stainless steel were analysed. In particular, the issues of recovery and dynamic recrystallization and changes of the microstructure were analysed. The investigations of hot working conducted with application of torsion test using torsion plastometer enabled determination of the influence of deformation conditions on the steel plasticity. The discrepancies in deformation to the maximum of yield stress ε_p of materials result from a different dislocation capability for splitting and association during deformation. They also result from the discrepancies in the stacking fault energy. The dynamic recrystallization nucleuses are initially located in the surrounding of the grains' boundaries in austenitic steel. Later, nucleation develops inside the grains on local, heterogeneous deformations. Dynamic recrystallization nucleuses may be formed as a result of coalescence of the dislocation cells and the subgrain formed during the earlier dynamic recovery, or through bulging of the old grain boundaries. The nucleuses formed do not grow until they have contact with the neighbouring ones, like during static recrystallization, since they quickly reach the permanent size resulting form the deformation parameters.

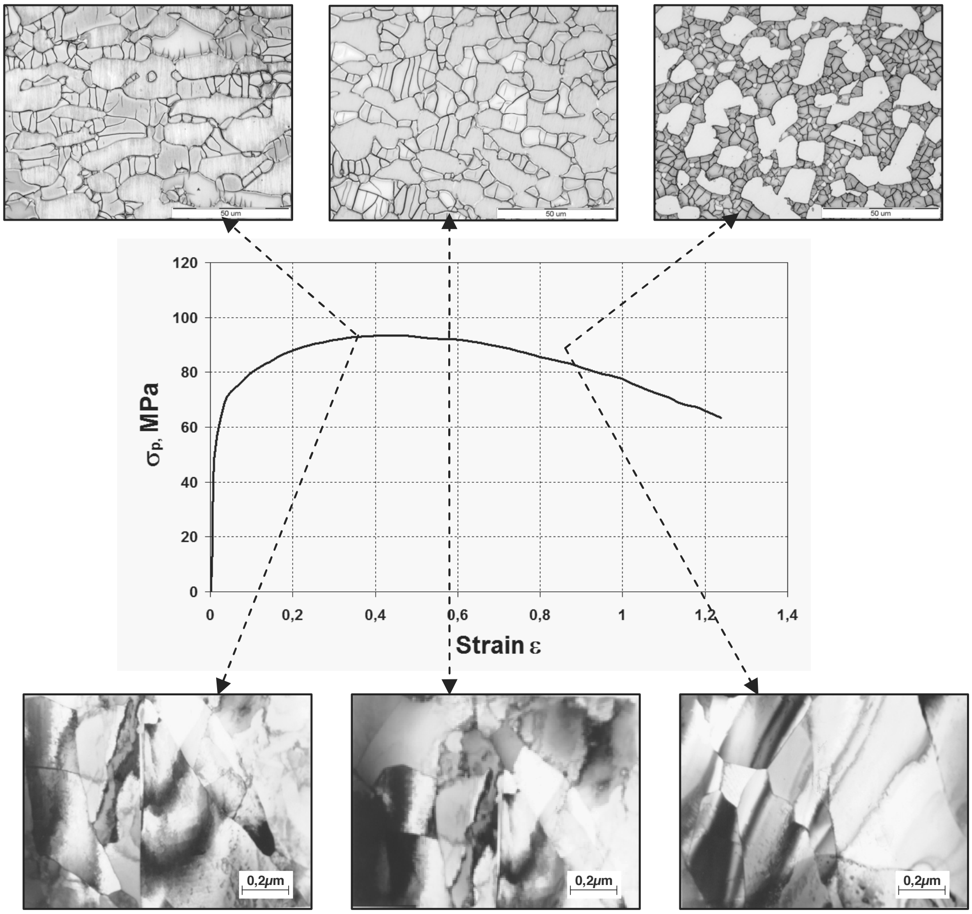


Fig. 14. The influence of deformation on the changes in the micro- and substructure based on the selected deformation phases after torsion at the temperature of 1100°C and rate of $0.4 s^{-1}$

Table 2.
Relations between the process parameters with the technological plasticity determined in a torsion test, and the average grain size for the steels analysed

steel grade	dependence	detailed equation	
X5CrTi25	σ_{pp}=f (Z)	$\sigma_{pp} = 0.17 \times Z^{0.194}$ [MPa]	(4)
	ε_p=f (Z)	$\varepsilon_p = 0.03 \times Z^{0.1}$	(5)
X3CrNiMo18-9	σ_{pp}=f (Z)	$\sigma_{pp} = 0.69 \times Z^{0.150}$, $[MPa]$	(6)
	ε_p=f (Z)	$\varepsilon_p = 0.017 \times Z^{0.09}$	(7)
X2CrNiMoN22-5-3	σ_{pp}=f (Z)	$\sigma_{pp} = 0.28 \times Z^{0.150}$, $[MPa]$	(8)

In the ferritic steel, the structure break-up, similarly to the aluminium alloys, may be a result of the so-called geometric dynamic recrystallization. This procces taken place with high deformation. No large number of recrystallization nucleuses was observed. High deformability of ferritic steel results from low strengthening inclination during a torsion process. As a result of hot torsion, a substructure was obtained characterized by large subgrain and small density of defects. On the other hand, the recrystallized grains in the ferritic steel samples are larger in comparison with austenitic steel, with identical torsion conditions.

There is a possibility of a multiple size reduction of initial grain in the austenitic and ferritic steels through an appropriate selection of the thermal and plastic processing parameters In the steels where the phase changes do not take place, it is an efficient method of the grain size regulation.

In the duplex ferritic-austenitic steel, for the whole range of deformation rate and temperature analysed, greater intensity of the structure recovery processes was observed in ferrite in comparison with austenite. The difference between the rate of those processes results in localization of the deformation at the interphase boundaries and leads to a considerable strengthening. Localization of the deformation in the microareas also results in small deformability of the two-phase steel. The determined empirical dependencies 4-10 enable the calculation of the technological plasticity parameters based on the knowledge of the deformation process parameters.

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