Experimental Testson the Plasticity and Deformability Characteristics of Several Stainless Steel Grades used for Hydro–Pneumatic Equipment's Manufacturing

Vasile Alexa, Imre Kiss

University Politehnica Timișoara, Faculty of Engineering Hunedoara
Department of Engineering and Management
5, Revolutiei, 331128 Hunedoara, Romania
e-mails: vasile.alexa@fih.upt.ro,imre.kiss@fih.upt.ro

Abstract: Many of the hydraulic and pneumatic devices are made from high quality stainless steels, through complex and elaborated manufacturing technologies. Thus, not infrequently the semi–finished product used for obtaining the pneumatic and hydraulic equipment is subjected to different kinds of strains in the manufacturing process. Obviously, the units that are currently producing pneumatic and hydraulic equipment should focus on the manufacturing of products mostly requested in a market economy. This requires the modernization of existing production capacities in line with the EU requirements, followed by the update of technologies to the standards applied in the EU economy. The knowledge about the characteristics of deformability has for the technologist, as well as for the designer and researcher, a great practical significance, because they are important elements in establishing a correct technological process. The change of deformation conditions existing in the industrial process, such as the temperature and rate of deformation, are difficult to consider for correcting the deformability determined by testing. In this paper, through "deformability" we understand all the properties characterizing the deformation behavior of the metals and alloys, and the „deformation resistance" of the metals is expressed through the unit strain required to produce a certain degree of plastic deformation, under the conditions of a particular diagram of tensions, deformations and deformation rates, in the absence of external friction forces. Thisstudy includes the results of the experimental tests conducted to find the plasticity and deformability characteristics of several stainless steel grades: one martensitic stainless steel (grade X46Cr13), one ferritic stainless steel (grade X6Cr17) and one austensitic stainless steel (grade X5CrNi18–10).

Keywords: plasticity; deformability; stainless steel grades; temperature; heating; tests

1 Introductory Remarks

In many industries and in many types of technical operations, the hydraulic equipment requires steel to withstand high operating temperatures combined with the corrosive action of the environment. These requirements cannot be met without the proper development of the high–alloy and quality steel manufacture, including the thermostable stainless steels. [1-3, 5-6, 16]

Currently, we know various types of stainless steels, which have multiple features and properties, designed to withstand corrosive environments, various working conditions, and weathering, thus providing safety conditions in enterprises, longer life in constructions and hygiene in everyday life. [1-3] The stainless steels are used in all industries today: mechanical engineering, metallurgical fields, medical equipments and instruments, ship–, automotive– and aviation–building, food processing, energy and power engineering, chemical and petrochemical, traffic engineering, construction, etc.

The knowledge about the characteristics of deformability has for the technologist, as well as for the designer and researcher, a great practical significance, because they are important elements in establishing a correct technological process. [2-6, 10-11] The change of deformation conditions existing in the industrial process, such as the temperature and rate of deformation, are difficult to consider for correcting the deformability determined by testing. [2, 5-7, 10,11, 13]

In view of this, the deformability is the ability of a material to be plastically deformed without the occurrence of undesired conditions (cracking or tearing of the material during the plastic deformation, inadequate quality of the surface, wrinkling or curling of the stamped steel sheets, coarse structure, difficulty of material flowing when filling the moulds, or other commercially–imposed conditions). [2, 6, 10,11, 13, 16]

The stainless steels can undergo structural changes under the action of the following technological processes: [5, 10, 11]

- a heat treatment(required by the manufacturing process);
- a cold plastic deformation(austenitic steels);
- annealing,after cold deformation;
- a high temperature thermo–mechanical treatment (e.g. required for hot rolledsteel or subjected to mechanical stress at high temperature).

Regardless of the adopted method for deformability determination, when the technological process are decided, the people involved should bear in mind that, the results have a relative value, i.e. they are significant only in comparison with other steels, whose plastic deformation behavior as deformability indices are already known. [2-6, 10-11]

The processing of metals and alloys via plastic deformation is based on the property of plasticity, which defines their ability toa cquire permanent deformations under the action of external forces. [2-6, 8-12, 14] When processing by plastic deformation, the shape modification of a semi–finished product is made by redistributing its elementary volumes under the action of external forces; therefore, unless some unavoidable losses due to equipment imperfection, the processing takes place without any removal of material.

The deformability of metals and alloys characterizes their ability to permanently deform without breaking the internal structural bonds. [2-5] As the deformability of a material is expressed by the degree of deformation to which the first cracks appear, i.e. its tearing resulting from a standard mechanical test or from one specific to the industrial deformation process, it should be pointed out that the breaking process, for all industrial processes of plastic deformation, as well as for the materials plastically deformed in these processes, appears in the form of ductile fracture. [2-6, 10, 11]

The main factors that influence the deformability can be grouped into two categories: [2-6, 10, 11]

- material related factors: composition, structure, purity, metallurgical development, localization of the deformation;
- process related factors: deformation temperature, deformation rate, state of stress and strain, hydrostatic pressure, friction between the tool and workpiece, geometry of the tool and workpiece.

In determining the hot deformability of steels in the laboratory, in general, but especially those stainless, the following conditions in which the plastic deformation takes place under industrial conditions must be taken into account: [5, 6, 10, 11]

- steel heating temperature;
- deformation temperature;
- tensions scheme where the deformation occurs;
- steel–tool contact friction;
- steel structure at the deformation temperature;
- steel deformation rate.

There are several methods for determining the deformability of the steels, such as: [2-6,10]

- compression, rolling and forging (taking account of friction);
- tensile, bending and torsion (without taking account of friction).

The above mentioned methods enable that, besides the determination of deformability characteristics (plasticity and deformation resistance, depending on temperature), to study the influence of the deformation conditions (rate of heating, holdingtime at heating temperature, friction with the tools, rate of deformation, structural changes in terms of deformation, rate of recrystallization, etc.). [5, 10, 11]

2 Determination of the Stainless Steel Deformability by Torsion

This method is the only one that allows obtaining large deformationsa long the length of the specimen, so it is mainly used to determine the characteristics of large deformations.[5, 10, 11]

Since the shear strains play san important role in the process of rolling and forging, the deformability caused by torsion reflects quite accurately the steel behavior at hot plastic deformation, and due to the fact that the specimen can be maintained in the ovenduring deformation, we can ensure the stability of temperature. By this method, the hot deformability of the stainless steel is determined by subjecting to torsion a cylindrical specimen maintained at the deformation temperature in a tubular oven. [5, 10, 11]

The size of the required moment for torsion the specimen expresses the resistance to deformation, and the number of torsions before failure expresses the plasticity limit of that steel.[5, 10, 11]

There are several methods for determining the deformability by hot torsion, such as: [5, 10, 11]

- torsion by maintaining the specimen at constant length;
- torsion by tensioning the specimen;
- torsion with free change of the specimen length.

2.1 Torsion by Maintaining the Specimen at Constant Length

This variant of the method for determining the hot deformability, which does not imply a deformation through pure shearing, is preferable because the rate of deformation can be easily maintained constant throughout the specimen. [5, 10, 11]

The torsional deformation on the specimen surface is:

$$\gamma = r \cdot \frac{\theta}{l} \text{ [rad]} \tag{1}$$

in which: r – the specimen radius, [m]; θ – torsion angle,[rad]; l – the specimen length, [m].

Then, the deformation rate on the specimen surface is:

$$v_{\gamma} = \frac{d\gamma}{dt} = \frac{d\left(\frac{r}{l}\theta\right)}{d\theta} \cdot \frac{d\theta}{dt} = \frac{r}{l} \cdot \frac{d\theta}{dt} = \frac{r}{l}\frac{2 \cdot \pi \cdot n}{60} \text{ [rad/sec]} \tag{2}$$

in which: dθ – the specimen's torsion speed, [–]; t – time, [sec], n – number of rotations, [rot/min].

From the value of the torque, we can calculate the shear resistance on the specimen surface:

$$\tau = \frac{(3-k) \cdot M}{2 \cdot \pi \cdot r^3} \text{ [N/m}^2\text{]} \tag{3}$$

in which: M – the torque moment, [N·m]; r – the specimen radius, [m]; k – sensitivity coefficient expressing resistance to the speed of deformation, for a particular steel, at a certain temperature, [–].

This method, although it does not imply a deformation through pureshearing, it is preferable because the rate of deformation can be easily maintained constant throughout the specimen.

2.2 Torsion by Tensioning the Specimen

The specimen heated in the oven is subjected to a constant tensile strain during the torsion test. Having no calibrated portion, the deformation length depends on the heated length of the test specimen and, therefore, the reproducibility is poor and the deformability characteristics are only informative, being not suitable for scientific processing and interpretation.[5, 10, 11]

Because the specimen is maintained under constant tensile strain, we cannot speak about the balancing of the axial force,which tends to shorten the specimen during coolinga nd hence its dimensions are changing during the test, resulting the fact that the deformation on the specimen surface does not occur at a constant speed, and due to changes in diameter we cannot calculate the shear resistance on the specimen surface.

2.3 Torsion with Free Change of the Specimen Length

Fo rtaking into account the results of the hot torsion test measurements in determining the resistance to deformation, the specimen is necessary to do not miss its straightness, and the deformation to be uniform throughout the specimen; in this case, instead of the axial force, we measure the length of the specimen during its torsion.[5, 10, 11]

Based on the law of specimen volume constancy before and after the deformation, we can write:

$$r_o^2 \cdot l_0 = r^2 \cdot l \qquad (4.1)$$

or

$$r = r_0\sqrt{\frac{l_0}{l}}[m] \qquad (4.2)$$

in which: r – the specimen radius, before and after the deformation, [m]; l – the specimen length before and after the deformation, [m].

As at high temperatures, the deformation resistance is a function of the deformation rate and not of the degree of deformation (due torecrystallization), its value at the specimen surface is:

$$\tau = \frac{1}{2\pi}\left[3 \cdot \frac{M}{r^3} + v \cdot \gamma \cdot \frac{\partial\left(\frac{M}{r^3}\right)}{\partial v\gamma}\right][N/m^2] \qquad (5)$$

in which: M – the torque moment, at a time, [N·m]; r – the specimen radius, at a time, [m]; v – the deformation speed at the specimen surface.

The radius variation in time and the torsion moment variation with the deformation speed can be obtained only by logarithmisation. Therefore, it is preferred to plot diagrams for representing the torsion moment variation versus the number of torsions and the torsion rate.

3 The Research Methodology

The experimental equipment used to study the stainless steel deformability by hot torsion belongs to the Faculty of Engineering Hunedoara, University Politehnica Timişoara.

The facility is provided with acentral shaft on which two side discs and an intermediate disc are mounted in the central area. Spacer bushes have been mounted between the left side disc and the intermediate one, as well as between the intermediate disca nd the right side one, capable of keeping the discs at a distance, for fixing the experimental samples, the specimens.

The so-equipped central shaft is connected to an electric motor which provides its rotation along with the specimens. At the top of the facility, above the central area of the shaft (where the experimental sample sare fixed), is placed an electric oven which provides the sample heating in the range 20-1300^{o}C. The temperature is maintained at the desired value by means of a control box, and the speeds can be changed by attaching to the electric motor of astatic frequency converter.

The ensemble of the experimental equipment used to study the stainless steel deformability by hot torsion,with and without the heating oven, is shown in Fig. 1.

The specimens for hot torsions were mechanically taken from Φ20 mm hot-rolled steel bars, having the form and dimensions presented in Figure 2. The test specimens are typically cylindrical, with a calibrated small–diameter central portion, having the ration $\frac{l}{d} = 5$ in the point of deformation.

a.

b.

Figure 1
The experimental facilityfor determining the hot deformability of the stainless steels
a. without the heating oven; b. with the heating oven

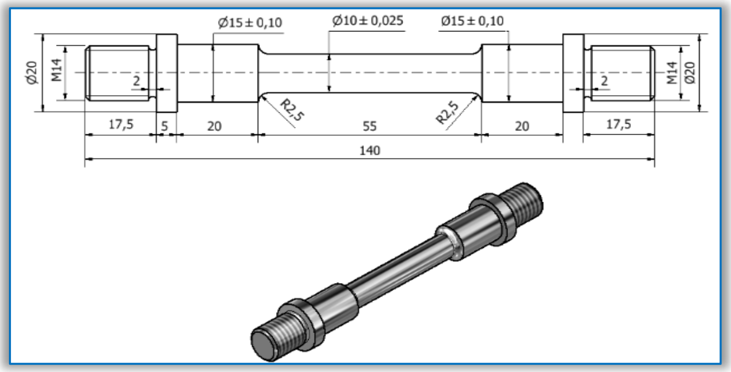


Figure 2
Samplefor determining the hotdeformabilityby torsion

The ends are screwed, and the specimen must have a shoulder in the continuation of the thread, to prevent further screwing during the torsion.

The choice of heating regime is currently mostly based on the practical experience of the companies; therefore, the process of establishing the hot processing technology for these steels is primarily related to the definition of heating conditions, according to their technological characteristics.

4 Results and Discussions

For the experimental tests, we used several stainless steel grades. This study includes the results of the tests conducted to find the plasticity and deformability characteristics of the martensitic stainless steel, grade X46Cr13 (Table 1 and Table 2), the ferritic stainless steel, grade X6Cr17 (Table 3 and Table 4) and the austensitic stainless steel, grade X5CrNi18–10 (Table 5 and Table 6).

Table 1

The results of the tests conducted to find the plasticitycharacteristics of themartensiticstainless steel (hardenable stainless steel, grade X46Cr13)

No.	Deformation temperature [^oC]	Maximum torque moment [daN·cm]				
		1	2	3	4	Average
1.	800	274	300	240	250	266
2.	850	242	268	250	280	260
3.	900	266	276	258	269	267.25
4.	950	194	191	188	174	186.75
5.	1000	156	158	134	134	145.50
6.	1050	127	121	119	118	121.25
7.	1100	101	83	112	112	102
8.	1150	90	93	98	88	92.25
9.	1200	69	69	60	40	57
10.	1250	47	48	45	–	46.66

Table 2

The results of the tests conducted to find the deformabilitycharacteristics of themartensiticstainless steel (hardenable stainless steel, grade X46Cr13)

No.	Deformation temperature [^oC]	The number of torsions before failure [–]				
		1	2	3	4	Average
1.	800	6	5	7	5	5.75
2.	850	5	7	10	10	8
3.	900	9	10	8	9	9
4.	950	10	10	11	13	11
5.	1000	13	11	12	12	12
6.	1050	13	13	12	13	12.75
7.	1100	14	13	14	13	13.75
8.	1150	7	14	14	14	12.25
9.	1200	8	8	8	8	8
10.	1250	8	9	7	–	8

Table 3

The results of the tests conducted to find the plasticitycharacteristics of the ferritic stainless steel (non–hardenable stainless steel, grade X6Cr17)

No.	Deformation temperature [^oC]	Maximum torque moment [daN·cm]				
		1	2	3	4	Average
1.	800	135	135	140	–	136
2.	850	126	126.5	123	–	125.16
3.	900	108	112	111	–	110.33
4.	950	94	73	77	–	81.33
5.	1000	63	57	57	–	59
6.	1050	9	22	38	–	23
7.	1100	83	36	41	–	53.33
8.	1150	29	28	29	–	28.66
9.	1200	21	21	20	–	20.66
10.	1250	18	–	14	–	16

Table 4

The results of the tests conducted to find the deformabilitycharacteristics of the ferritic stainless steel (non–hardenable stainless steel, grade X6Cr17)

No.	Deformation temperature [^oC]	The number of torsions before failure [–]				
		1	2	3	4	Average
1.	800	31	34	42	–	35.66
2.	850	29	22	26	–	25.66
3.	900	27	17	29	–	24.33
4.	950	34	33	28	–	31.66
5.	1000	35	36	48	–	39.66
6.	1050	62	58	68	–	62.66
7.	1100	15	71	75	–	53.66
8.	1150	105	69	94	–	89.33
9.	1200	43	57	134	–	78
10.	1250	460	–	425	–	443

Table 5

The results of the tests conducted to find the plasticitycharacteristics of the austensitic stainless steel (non–magnetic stainless steel, grade X5CrNi18–10)

No.	Deformation temperature [^oC]	Maximum torque moment [daN·cm]				
		1	2	3	4	Average
1.	800	200	392	340	390	330.5
2.	850	192	362	314	359	306.75
3.	900	276	326	306	316	306
4.	950	194	230	220	227	218.25

5.	1000	170	176	156	194	174
6.	1050	144	130	142	130	136.5
7.	1100	133	123	127	129	128
8.	1150	98	–	100	80	92.66
9.	1200	97	83	84	77	81
10.	1250	58	44	61	–	53.33

Table 6

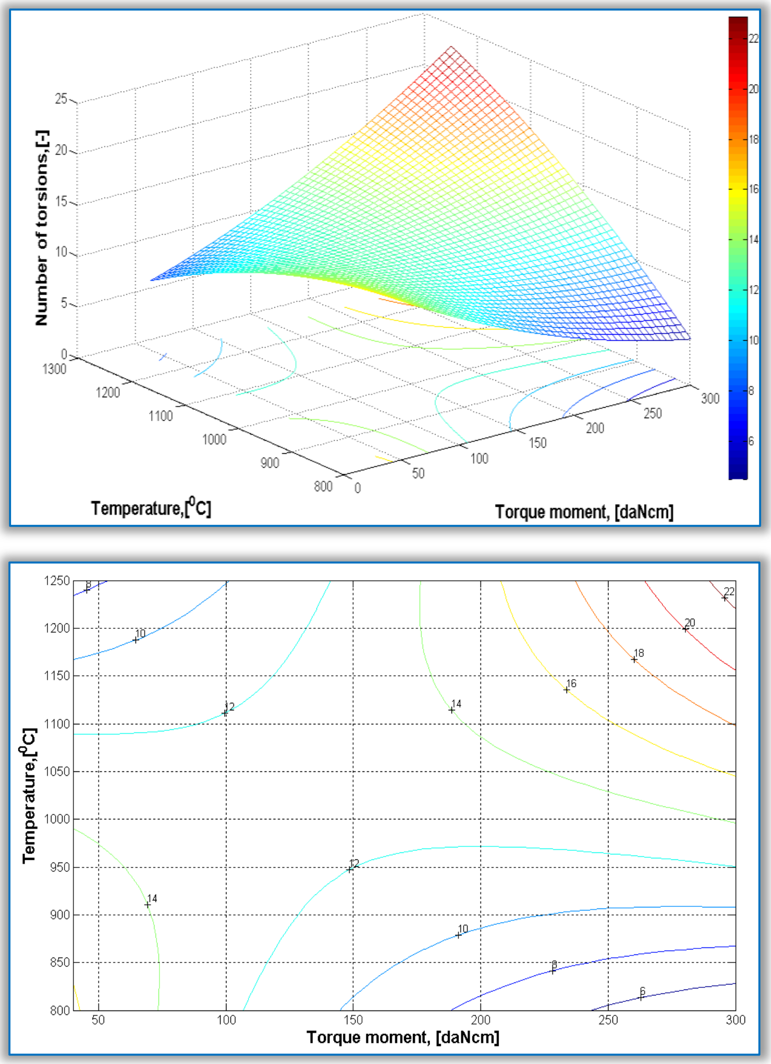
The results of the tests conducted to find the deformabilitycharacteristics of the austensitic stainless steel (non–magnetic stainless steel, grade X5CrNi18–10)

No.	Deformation temperature [^{o}C]	The number of torsions before failure [–]				
		1	2	3	4	Average
1.	800	2	2	2	2	2
2.	850	3	3	4	2	3
3.	900	4	2	3	3	3
4.	950	6	5	8	4	5.75
5.	1000	4	6	7	3	5
6.	1050	9	8	8	7	8
7.	1100	10	8	15	12	11.25
8.	1150	9	–	9	9	9
9.	1200	9	12	6	6	9
10.	1250	7	8	6	–	7

The austensitic stainless steel (nonmagnetic stainless steel), grade X5CrNi18–10, is the standard for the austenitic grades of stainless steel due to its good corrosion resistance, ease of formability and fabrication.

The ferritic stainless steel (non–hardenable stainless steel), gradeX5CrNi18–10, is resistant to corrosion in most environments. Although the corrosion resistance of X6Cr17 is inferior to the austenitic grades of stainless steels, its ferritic microstructure makes it resistant to the effects of stress corrosion cracking, a form of corrosion to which most of the conventional austenitic stainless steels are susceptible to. The X6Cr17 is characterized by its good corrosion resistance is displayed inmoderately corrosive media/environments.

The martensitic stainless steel (hardenable stainless steel), gradeX46Cr13, is characterized by its good corrosion resistance in moderately corrosive environments. Stainless heat–resistant steels are always in demand when extreme technical requirements are imposed on the material, due of their outstanding chemical corrosion and mechanical properties.



a.

b.

Figure 3

Deformability diagram for the martensitic stainless steels (grade X46Cr13), at the experimental heating temperature values (800–1250°C)

a. the regression surface of plasticity and deformability characteristics, described by the number of torsions before failure [equation type: $z = a_{(1)}x^2 + a_{(2)}y^2 + a_{(3)}xy + a_{(4)}x + a_{(5)}y + a_{(6)}$, standard deviation:$r^2 = 0.8298$]

b. the level curves and the technological domains area

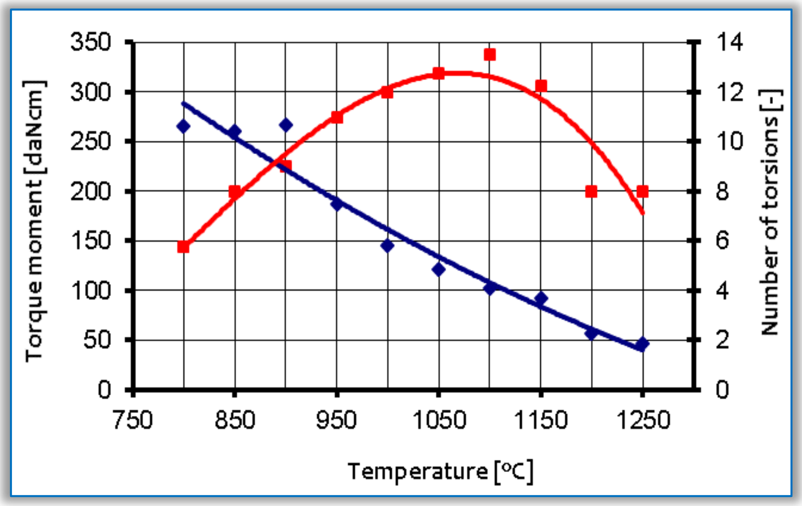


Figure 4

The variations of plasticity (number of torsions to failure) and deformation resistance (maximum torque) in case of the martensitic stainless steels (grade X46Cr13), at the experimental heating temperature values (800–1250°C)

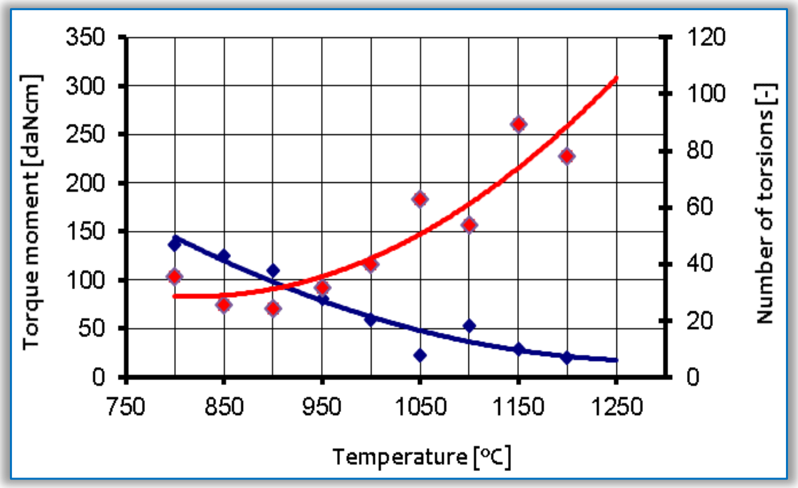
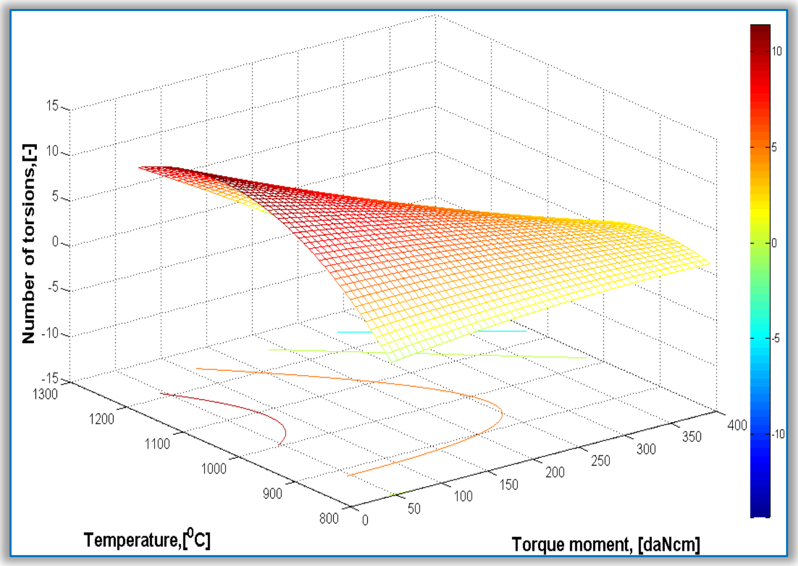
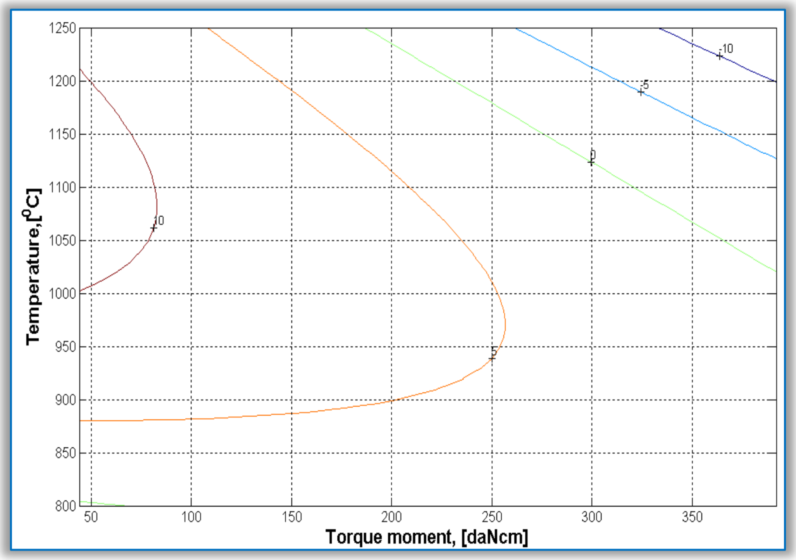


Figure 5

The variations of plasticity (number of torsions to failure) and deformation resistance (maximum torque) in case of the ferritic stainless steel (grade X6Cr17), at the experimental heating temperature values (800–1250°C)



a.



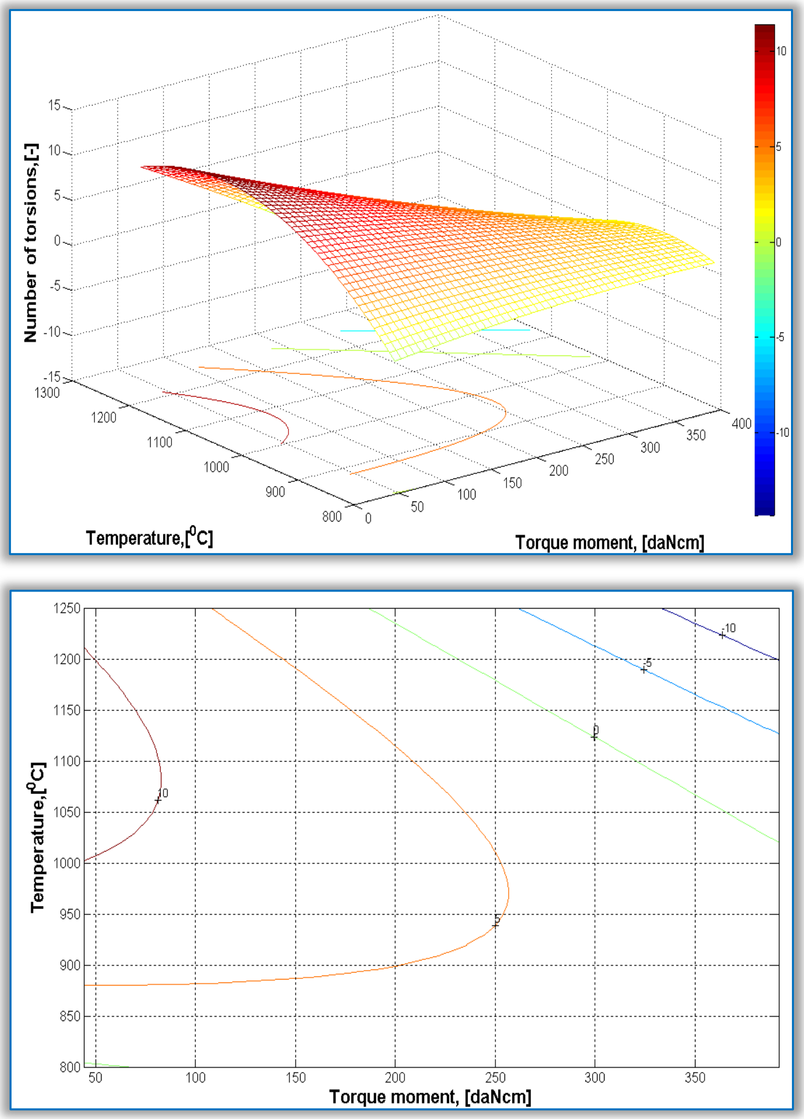
b.

Figure 6

Deformability diagram for the ferritic stainless steel (grade X6Cr17), at the experimental heating temperature values (800–1250°C)

a. the regression surface of plasticity and deformability characteristics, described by the number of torsions before failure [equation type: $z = a_{(1)}x^2 + a_{(2)}y^2 + a_{(3)}xy + a_{(4)}x + a_{(5)}y + a_{(6)}$, standard deviation:$r^2 = 0.8056$]

b. the level curves and the technological domains area



b.

c.

Figure 7

Deformability diagram for the austenitic stainless steel (grade X5CrNi18–10), at the experimental heating temperature values (800–1250°C)

a. the regression surface of plasticity and deformability characteristics, described by the number of torsions before failure [equation type: $z = a_{(1)}x^2 + a_{(2)}y^2 + a_{(3)}xy + a_{(4)}x + a_{(5)}y + a_{(6)}$, standard deviation:$r^2 = 0.8056$]

b. the level curves and the technological domains area

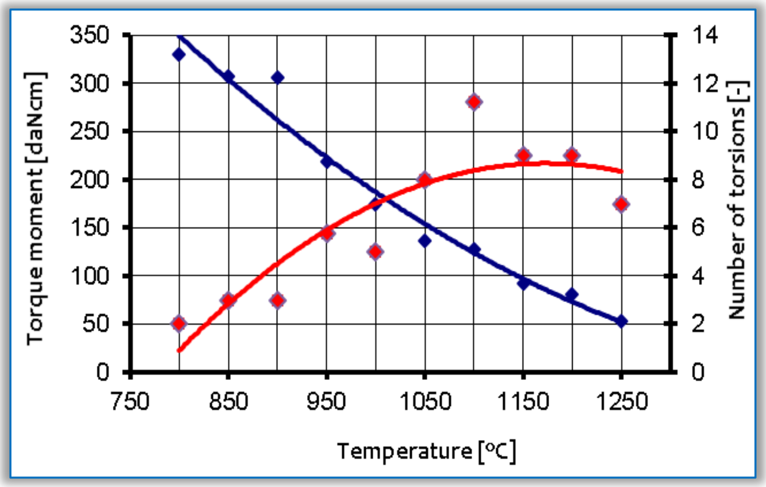


Figure 8

The variations of plasticity (number of torsions to failure) and deformation resistance (maximum torque) in case of the austenitic stainless steel (grade X5CrNi18–10), at the experimental heating temperature values (800–1250°C)

For the hot torsion test, we prepared 36 samples from each steel grade. They were subjected to torsional deformation by maintaining the deformation temperature in the experimental facility, from 50 to 50°C, within the range 800-1250°C.

The magnitude of the torque required to the specimen's torsion expresses the resistance to deformation, and the number of torsions to failure expresses the plasticity limit of that steel. The plasticity limit is expressed by the number of torsions to failure at a given temperature and deformation rate. Each point within the temperature range studied in the two diagrams (Figures 3-8) represents the arithmetic mean of four determinations.

In the graphical representationof the experimental tests results, presented above in the Figures 3-8, we have the following comments and remarks:

- the variations of plasticity (number of torsions to failure) and deformation resistance (maximum torque) are plotted in the Figure 4, Figure 5 and Figure 8. The variations, as shown in the above mentioned figures, indicate that the deformation resistance of a stainless steel (regardless of the steel grade) decreases with increasing the heating temperature; for the martensitic and austenitic steel grades (Figure 4 and Figure 8), due to the measurement error sat high values of the torsion moment at low temperatures, the value of the maximum torque is lower than the technological requirement;
- the regression surface of plasticity and deformability characteristics of the martensitic stainless steels (grade X46Cr13), described by the number of torsions before failure, is shown in Figure 3(a); This can be interpreted as

deformability diagram, plotted in shown in Figure 3(b), which is typical for the martensitic stainless steels, X46Cr13 being such a steel grade;

- the regression surface of plasticity and deformability characteristics of the ferritic stainless steel (grade X6Cr17), described by the number of torsions before failure, is shown in Figure 6(a); This can be interpreted, plotted in shown in Figure 6(b), as deformability diagram, which is typical for the ferritic stainless steel, grade X6Cr17;
- the regression surface of plasticityanddeformabilitycharacteristics of the austenitic stainless steel (grade X5CrNi18–10), described by the number of torsions before failure, is shown in Figure 7(a); This can be interpreted, plotted in shown in Figure 7(b), as deformability diagram for the grade X5CrNi18–10, which illustrate a much better the deformation resistance than the ferritic stainless steel grade X6Cr17, being an austenitic stainless steel grade;
- the upper limit of the optimum range of heating temperatures applied for deforming the studied steels, results clearly from the plasticity – temperature diagrams, as follows:
  - 1100^{o}C, for the martensitic stainless steel, grade X46Cr13 (Figure 4);
  - 1050^{o}C, for the ferritic stainless steel, grade X6Cr17 (Figure 5);
  - 1150^{o}C, for the austenitic stainless steel, grade X5CrNi18–10 (Figure 8);
- the temperature may be limited due to the risk of excessive grain growth during heating under industrial conditions (phenomenon that does not occur during heating at the torsion machine – and, therefore, the values given for plasticity at high temperatures); [5, 10, 11, 15]
- regarding the end heating temperature, for the hot deformation of the studied stainless steel grades, we have the following experimental values (or ranges):
  - 900-950^{o}C, for the martensitic stainless steel; it has a lower limit due to the high deformation resistance and the cracking hazard;
  - 800^{o}C, for the ferritic stainless steel; sometimes it is recommended that the last two passes (processing) to be carried out at temperatures below 800^{o}C, for completion of granulation;
  - 950^{o}C, for the austenitic stainless steel.

5 Conclusions

This study includes the results of the experimental tests conducted to find the plasticity and deformability characteristics of several stainless steel grades: one martensitic stainless steel (grade X46Cr13), one ferritic stainless steel (grade X6Cr17) and one austensitic stainless steel (grade X5CrNi18–10).

The indications regarding the variation of plasticity with the temperature, using the hot torsion method, allowed for establishing the temperature range within which the steel plasticity is optimal and in which, in general, it is recommended to perform the entire hot plastic deformation. Also, depending on the plasticity variation with temperature, we can achieve a more rational distribution of the reduction coefficients per passes, so that the plasticity property of the steel to be used as much as possible.

Starting from the temperature of 900^oC, all steel grades have a sufficient plasticity, but the value of the deformation resistance is still high up to the temperature of 950^oC. The growth dynamic of the plasticity characteristics is continuous, reaching the maximum value at the temperature of 1250^oC, while reducing the resistance to deformation. Thus, from the tests carried out to determine the hot deformability, it results that the optimal plasticity of the analyzed steels is found within the temperature range $950\text{-}1250^oC$.

Acknowledgement

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