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DEFORMABILITY OF MARTENSITIC STAINLESS STEEL (grade X46Cr13) BY HOT TORSION

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Abstract: 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. For the experimental tests, we used several stainless steel grades. This study include the results of the tests conducted to find the plasticity and deformability characteristics of the martensitic stainless steel (hardenable stainless steel, grade X46Cr13).
Keywords: plasticity and deformability, martensitic stainless steel (grade X46Cr13), temperature and heating, hot torsion tests

1. INTRODUCTORY NOTES

The stainless steel is an essential part of modern life. Stainless steel's strength, resistance to corrosion and low maintenance make it the ideal material for a wide range of applications. It also has a long life cycle. The single most important property of stainless steels, and the reason for their existence and widespread use, is their corrosion resistance. Currently, we know various types of stainless steels, which have multiple features and properties, designed to withstand corrosive environments, various working conditions, weathering, thus providing safety conditions in enterprises, longer life in constructions and hygiene in everyday life. [1–5, 10]

There are over 150 grades of stainless steel, of which 15–20 are commonly used in everyday applications. Stainless steel is made in various forms including plates, bars, sheets and tubing for use in industrial and domestic settings. The stainless steels are used in all nowadays industries: chemical and petrochemical, metallurgical, mechanical engineering, food processing, energy and power engineering, medical equipment, traffic engineering, construction, ship–, automotive– and aviation–building etc. Renewable energy technologies including solar, geothermal, hydro and wind power also use stainless steel components as it is able to withstand the rigors of highly corrosive sea water environments.[1–5, 10]

In many types of operations, in many industries, 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. [4–11]

The chemical, oil and gas industries operate in demanding environments involving high heat and highly toxic substances. Special grades of stainless steel have been developed for use in these industries which feature enhanced resistance to corrosion over a wider range of temperatures. High–grade stainless steel is vital in the construction of storage tanks, valves, pipes, and other components. It should also be noted that only vessels for small units are completely made of corrosion–resistant material. This protection method is too expensive for large vessels. They can be more economically protected by a liner of corrosion–resistant material containing Mo, Cr, Ni and V. Multilayer vessels require corrosion–resistant steel only for the inner layer. [4–6, 8–11]

Stainless steels are corrosion resistant materials that contain a small amount of Carbon (usually 0.08–0.25%) and a high concentration of Chromium (12–26%) and sometimes Nickel (up to about 22%). There are several classes of stainless steels with various mechanical properties. Martensitic stainless steels are a group of chromium steels ordinarily containing no nickel developed to provide steel grades that are both corrosion resistant. Martensitic stainless steels can be high– or low–carbon steels built around the composition of Iron, 12% up to 17% Chromium, Carbon from 0.10% up to 1.2%. [1–5, 10]

This study include analyse of the one corrosion–resistant high–temperature steel from the group of martensitic stainless steels, the hardenable stainless steel, grade X46Cr13 (Table 1).

Table 1. Chemical composition in % for grade X46Cr13 (corrosion–resistant high–temperature steel)

Carbon [C]	Silicon [Si]	Manganese [Mn]	Nickel [Ni]	Sulphur [S]	Phosphorus [P]	Chromium [Cr]
0.35 – 0.44	max 0.6	max 0.6	max 0.6	max 0.025	max 0.03	12 – 14

2. ABOUT THE DEFORMABILITY OF METALS AND ALLOYS

The processing of metals and alloys via plastic deformation is based on the property of plasticity, which defines their ability to acquire permanent deformations under the action of external forces. [6–11] 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 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. [4, 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. [4, 8–11] 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). [4, 8–11]

The deformability of metals and alloys characterises their ability to permanently deform without breaking the internal links. 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. [4, 8–11]

The main factors that influence the deformability can be grouped into two categories:

- material related factors: composition, structure, purity, metallurgical development, localisation 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.

The stainless steels can undergo structural changes under the action of:

- 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 rolled steel or subjected to mechanical stress at high temperature).

3. DETERMINATION OF STEEL DEFORMABILITY BY HOT TORSION

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: [4, 8–11]

- steel heating temperature;
- deformation temperature;
- voltages 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, such as: [4, 8–11]

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

The methods mentioned above enable that, besides the determination of deformability characteristics (plasticity and deformation resistance, depending on temperature), to study the influence of deformation conditions (rate of heating, holding time at heating temperature, friction with the tools, rate of deformation, structural changes in terms of deformation, rate of recrystallization, etc.). [4, 8–11] The determination of steel deformability by hot torsion method is the only one that allows obtaining large deformations along the length of the specimen, so it is mainly used to determine the characteristics at large deformations.

Since the shear strains plays an important role in the process of rolling and forging, the deformability caused by torsion reflects quite accurately the steel behaviour at hot plastic deformation, and due to the fact that the specimen can be maintained in the oven during 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. [4, 8–11]

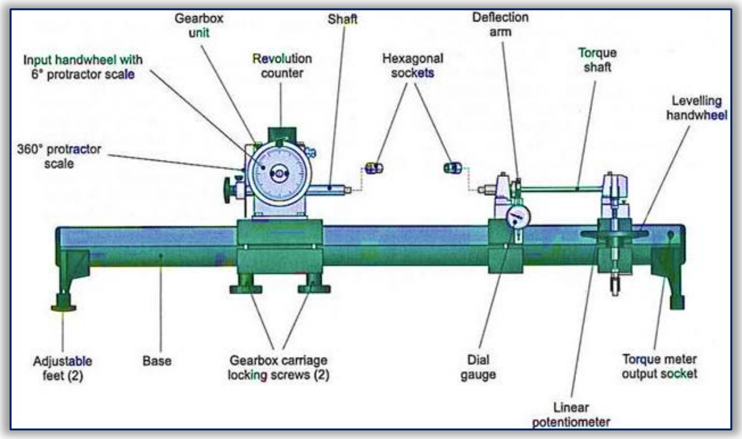

Figure 1. The principle of deformability test by torsion

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.

4. THE RESEARCH METHODOLOGY

The equipment used to study the steel deformability by hot torsion belongs to the Faculty of Engineering Hunedoara, part of the University Politehnica Timişoara. [4, 8–11] The equipment is provided with a central 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 disc and the right side one, capable of keeping the discs at a distance, for fixing the experimental samples, the specimens. [4, 8–11]

The so–equipped central shaft is connected to an electric motor which provides its rotation along with the specimens. At the top of the equipment, above the central area of the shaft (where the experimental samples are fixed), it is placed an electric oven which provides the sample heating in the range 20–1300°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 a static frequency converter. The ensemble of the equipment, with and without the heating oven, is shown in Figure 2. [10]

a) b)

Figure 2. The experimental equipment for determining the hot deformability of the stainless steels: [10]
a) without the heating oven; b) with the heating oven

The specimens for hot torsions were mechanically taken from Φ20mm hot–rolled steel bars, having the form and dimensions presented in Figure 3. [10] The test specimens are typically cylindrical, with a calibrated small–diameter central portion, having the ration l/d = 5 in the point of deformation. The ends are screwed, and the specimen must have a shoulder in the continuation of the thread, to prevent further screwing during the torsion.

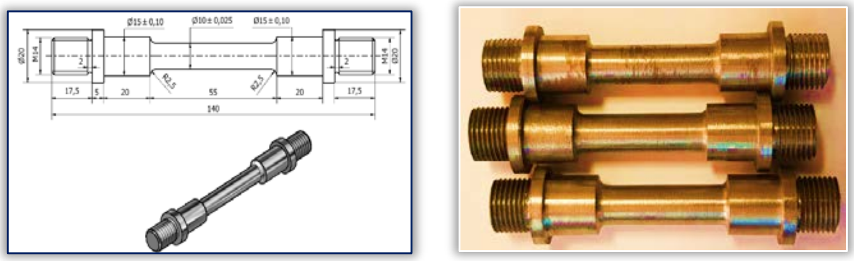

Figure 3. Sample for determining the hot deformability by torsion [10]

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.

5. RESULTS

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).

The martensitic stainless steel (hardenable stainless steel, grade X46Cr13) 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.

For the hot torsion test, we prepared 40 samples from each steel grade. They were subjected to torsional deformation by maintaining the deformation temperature in the experimental equipment, 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 up to breaking expresses the plasticity limit of that steel. The plasticity limit is expressed by the number of torsions up to breaking at a given temperature and deformation rate. Each point within the temperature range studied in the diagrams represents the arithmetic mean of four determinations.

Table 2. The results of the hot torsions tests conducted to find the plasticity and deformability characteristics of the martensitic stainless steel (grade X46Cr13) at the experimental heating temperature values (800–1250°C)

Experiments no.	Series no.	Testing temperature, [C]	Torque moment, [daN*cm]	Number of torsions up to breaking, [–]
Group I (at 800°C)	1.	800	274	6
	2.	800	300	5
	3.	800	240	7
	4.	800	250	5

Group II (at 850°C)	5.	850	242	5
	6.	850	268	7
	7.	850	250	10
	8.	850	280	10
Group III (at 900°C)	9.	900	266	9
	10.	900	276	10
	11.	900	258	8
	12.	900	269	9
Group IV (at 950°C)	13.	950	194	10
	14.	950	191	10
	15.	950	188	11
	16.	950	174	13
Group V (at 1000°C)	17.	1000	156	13
	18.	1000	158	11
	19.	1000	134	12
	20.	1000	134	12
Group VI (at 1050°C)	21.	1050	127	13
	22.	1050	121	13
	23.	1050	119	12
	24.	1050	118	13
Group VII (at 1100°C)	25.	1100	101	14
	26.	1100	83	13
	27.	1100	112	14
	28.	1100	112	13
Group VIII (at 1150°C)	29.	1150	90	7
	30.	1150	93	14
	31.	1150	98	14
	32.	1150	88	14
Group IX (at 1200°C)	33.	1200	59	8
	34.	1200	69	8
	35.	1200	60	8
	36.	1200	40	8
Group X (at 1250°C)	37.	1250	47	8
	38.	1250	48	9
	39.	1250	45	7
	40.	1250	45	7

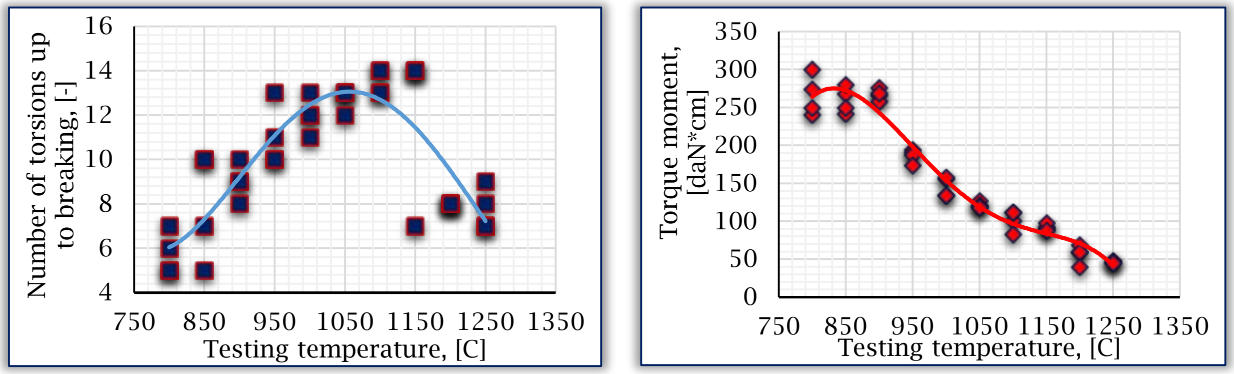

Figure 4. Correlations: Testing temperature Vs. Number of torsions up to breaking and Testing temperature vs Torque moment of the martensitic stainless steels (hardenable stainless steel, grade X46Cr13), at the experimental heating temperature values (800–1250°C)

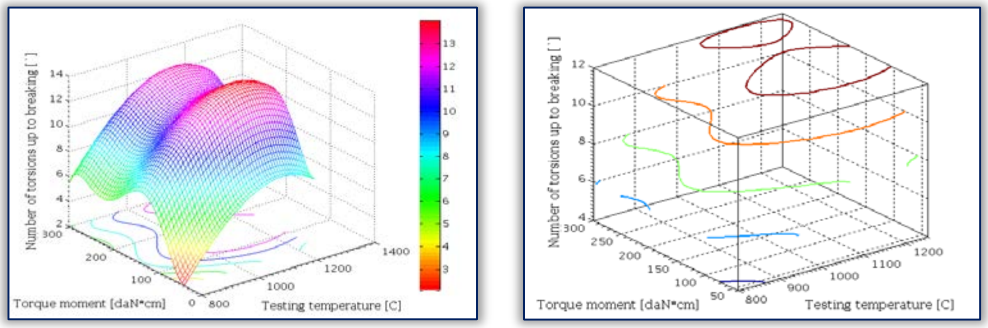

Figure 5. Number of torsions up to breaking, vs. Torque moment and Testing temperature of the martensitic stainless steels (hardenable stainless steel, grade X46Cr13), at the experimental heating temperature values (800–1250°C) [equation type: $z_1 = a_1+a_2x+a_3x^2+a_4x^3+a_5y+a_6y^2+a_7y^3+a_8y^4+a_9y^5$, standard deviation: $r^2 = 0.8685$]

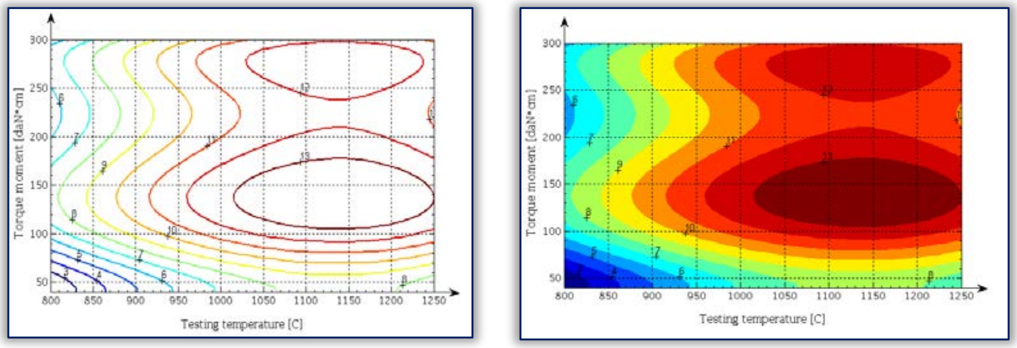

Figure 6. Correlation diagrams for technological domains area of Deformability: Testing temperature vs Torque moment of the martensitic stainless steels (hardenable stainless steel, grade X46Cr13), at the experimental heating temperature values (800–1250°C)

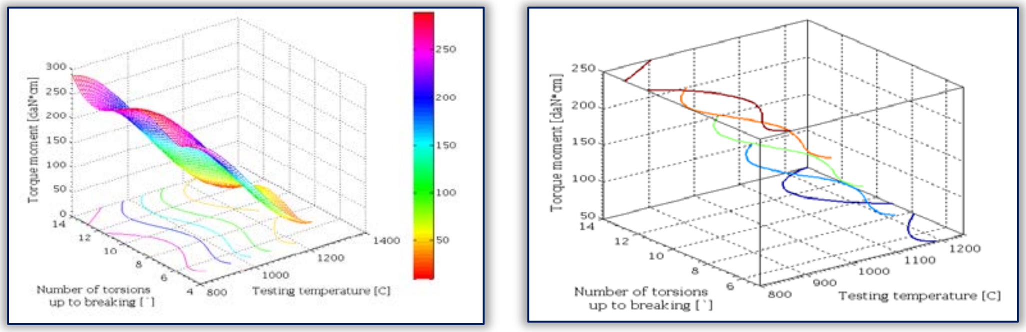

Figure 7. Torque moment vs. Number of torsions up to breaking and Testing temperature of the martensitic stainless steels (hardenable stainless steel, grade X46Cr13), at the experimental heating temperature values (800–1250°C) [equation type: $z_1 = a_1+a_2x+a_3x^2+a_4x^3+a_5y+a_6y^2+a_7y^3+a_8y^4+a_9y^5$, standard deviation: $r^2 = 0.9836$]

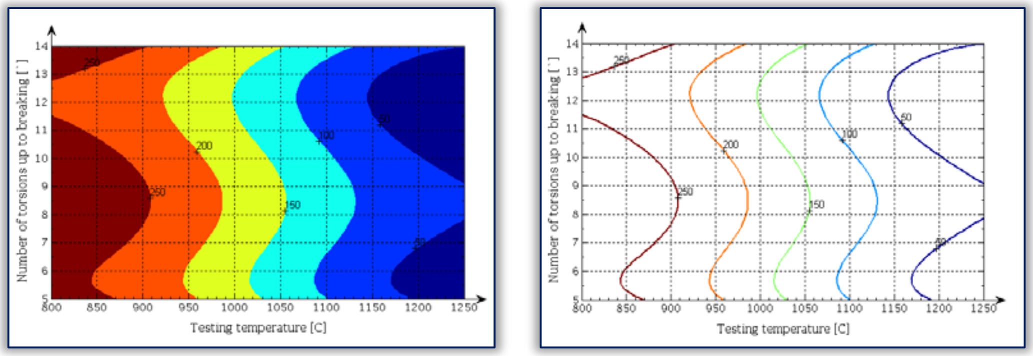

Figure 8. Correlation diagrams for technological domains area of Deformability: Testing temperature vs Number of torsions up to breaking of the martensitic stainless steels (hardenable stainless steel, grade X46Cr13), at the experimental heating temperature values (800–1250°C)

6. DISCUSSIONS

In the graphical representation of the experimental tests results, presented above in the Figures 4–8, we have the following technological remarks:

— the number of torsions up to breaking (i.e. the variation of plasticity) and the torque moment (i.e. the deformation resistance) are plotted in the Figure 4. The variation, as shown in the above mentioned figure, indicate that:
  - # the upper limit of the optimum range of heating temperatures applied for deforming the martensitic stainless steel, (grade X46Cr13), results clearly from the plasticity – temperature diagrams, being 1050–1100°C (Figure 4a);
  - # the deformation resistance of a martensitic stainless steels (grade X46Cr13) decreases with increasing the heating temperature (Figure 4b);

— the regression surface of plasticity and deformability characteristics of the martensitic stainless steels (grade X46Cr13), described by the number of torsions up to breaking, are shown in Figure 5 – Number of torsions up to breaking vs. Torque moment and Testing temperature of the martensitic stainless steels (grade X46Cr13), at the experimental heating temperature values (800–1250°C), respectively in Figure 7 – Torque moment vs. Number of torsions up to breaking and Testing temperature of the martensitic stainless steels (grade X46Cr13), at the experimental heating temperature values (800–1250°C),

- Figure 6 and Figure 8 presents the correlation diagrams for technological domains area of deformability of the martensitic stainless steels (grade X46Cr13), at the same experimental heating temperature values. These can be interpreted as deformability diagrams, which are typical for the martensitic stainless steel (grade X46Cr13);
- regarding the end heating temperature, for the hot deformation of the studied martensitic stainless steel (grade X46Cr13), we have the following experimental ranges: 900–950°C; it has a lower limit due to the high deformation resistance and the cracking hazard;
- 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);

7. CONCLUSIONS

The indications regarding the variation of plasticity with the temperature, using the hot torsion method, allowed to 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°C, the martensitic stainless steel (grade X46Cr13) have a sufficient plasticity, but the value of the deformation resistance is still high up to the temperature of 950°C. The growth dynamic of the plasticity characteristics is continuous, reaching the maximum value at the temperature of 1250°C, 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 analysed steels is found within the temperature range 950–1250°C.

Acknowledgement

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