

# Study on the Deformation behaviour of Non–Hardenable Ferritic Stainless Steel (grade X6Cr17) by Hot Torsion Tests

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**Abstract:** The knowledge about the characteristics of deformability (deformation resistance and plasticity) 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. The chemical composition of the material influences the plasticity and its deformation resistance both by the nature and distribution of the alloying elements and by the phase transformations they produce. In this paper, through "deformability", we cover all properties characterizing the deformation behaviour of alloys. In this sense, "deformation resistance" 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. Plasticity, being the ability of metallic materials to deform plastic under the action of external forces, is influenced by a number of material characteristics (chemical composition, structure) and other factors characteristic of the deformation (temperature, degree and speed of deformation, applied mechanical scheme). Plasticity is characterized, in the torsion test, by the number of rotations made by the specimen until breakage. A number of methods have already been used for the study of deformability. This study includes the results of hot torsion tests conducted to find the plasticity and deformability characteristics of ferritic stainless steel (non–hardenable stainless steel, grade X6Cr17), which is a flexible grade of the stainless steel family with properties closely matching those of the more popular and expensive austenitic grade.

**Keywords:** deformability (plasticity and deformation resistance); ferritic stainless steel; hot torsion tests; grade X6Cr17; stainless steel grades

## 1 ABOUT FERRITIC STAINLESS STEELS

The fundamental criterion in the selection of stainless steel is generally that it can survive with virtually no corrosion in the environment in which it is to be used [1, 2]. The choice among the stainless steels that can be used in that environment is then based on the alloy from which the component can be produced at the lowest cost, including maintenance, over the intended service life [1, 2].

The main factor in the selection process for stainless steels is corrosion resistance [1–8]. Careful consideration of the application should be done to enable the choice of a grade with suitable corrosion resistance whilst keeping the costs on an economic minimum [1–5, 10]. Other considerations such as mechanical properties (strength and toughness), physical properties (magnetic permeability) and forming, fabrication and the joining methods available should be secondary in any material selection process [1–3]. Good engineering practice sometimes requires that materials be selected for sufficient, but finite, service life [3–9]. This is especially true for high–temperature service, for which creep and oxidation lead to a limited life for all materials [3, 9, 10].

Because of the stainless steel's corrosion–resistant properties, the material is often used in the fabrication of components used in the food and pharmaceutical manufacturing [1, 2]. Typical applications for ferritic stainless steels include petrochemical, automotive exhaust systems, heat exchangers, components for furnaces and food equipment, to name a few. With a greater strength than that of carbon steels, ferritic stainless steels provide an advantage in many applications where reduced weight are necessary, such as automotive emission control systems [4–8]. As with any engineered material, it is up to the user to specify what is needed for the application not over–engineered, which will cost more, or under–engineered, which exposes some degree

of risk during usage [3–5]. Knowing the limitations and constraints associated with the many choices is a good step in determining the optimum material for each application.

Ferritic stainless steels are less expensive for the same corrosion resistance [1–3, 11]. Ferritic stainless steels are classified in the 400 series, usually with 10–30% Chromium content, and are often chosen for their excellent corrosion resistance and elevated temperature oxidation resistance. Standard ferritic stainless steels contain 10–27% Chromium, usually 16–20%, and are Nickel–free. Because ferritic stainless grades do not have Nickel, they are generally of lower cost than the 300 series grades [2–4]. Because of their low Carbon content (less than 0.2%), they are not hardenable by heat treatment and have less critical anticorrosion applications, such as architectural and auto trim [1, 7, 9]. Even though austenitic grades typically have better general corrosion resistance, formability, and weldability, some applications use ferritic stainless steels too [9–12, 16]. In elevated–temperature applications, ferritic grades provide better tensile–property stability and thermal fatigue resistance. They have lower thermal expansion and higher thermal conductivity than austenitic grades [2, 9–13, 16]. The standard ferritic stainless steel's chemical composition of corrosion–resistant high–temperature steel, grade X6Cr17, is presented in Tab. 1 [11, 14, 15].

**Table 1** Chemical composition of corrosion–resistant high–temperature steel for grade X6Cr17 [14, 15]

C (%)	Mn (%)	Si (%)	S (%)	P (%)	Cr (%)
max. 0.12	max 0.8	max 0.8	max 0.025	max 0.035	16 – 18

Plasticity, being the ability of metallic materials to deform plastic under the action of external forces, is influenced by a number of material characteristics (chemical composition, structure) and other factors characteristic of

deformation (temperature, degree and speed of deformation, applied mechanical scheme) [3, 9–13, 16].

The chemical composition of the material (ferritic stainless steel / non-hardenable stainless steel) influences the plasticity and its deformation resistance both by the nature and distribution of the alloying elements and by the phase transformations they produce [10–12].

## 2 RESEARCH AREA

As we mentioned above, the processing of 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 [9–13]. 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 occur due to equipment imperfection, processing takes place without any removal of material [3, 11].

The deformability of 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 [2–5].

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 [3, 9–12]. 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 [9–12, 16]. In view of this, deformability is the ability of a material to be plastically deformed without the occurrence of undesired conditions (cracking of material during the plastic deformation, inadequate quality of surface, wrinkling or curling of stamped steel sheets, coarse structure, difficulty of material flowing when filling the moulds, or other commercially-imposed conditions) [9–12, 16].

Bearing in mind that different plastic deformation processes have specific mechanical deformation schemes and as different factors have a different influence on the plasticity and deformation resistance of metallic materials subject to deformation, until at the moment it has not been able to find a universally valid method of determining absolute values directly applicable for the calculation of plasticity and resistance to deformation [3, 9–12, 16]. Because of this, different indirect simulation methods are today used for the study of deformability. The values thus obtained can only be used to compare the behaviour relative to the deformation of the analyzed metal materials [3, 9–12, 16].

To date, a number of methods have already been experienced for the study of deformability, including the torsion, compression, bending or rolling of specimens of various shapes and sizes [9–12, 16]. There are several methods for determining deformability, such as:

- by compression, rolling or forging (taking into account friction) [9–12,16];
- by tensile, bending or torsion (without taking into account friction) [9–12,16].

The above-mentioned methods make it possible to study – besides the determination of deformability characteristics (plasticity and deformation resistance, depending on temperature) – 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.) [9–12, 16].

## 3 METHODOLOGY

Currently, the hot torsion test, which is an effective means of studying the plastic deformation skills of metals and alloys, seems to be considered, as a result of experience, as one of the best deformability tests. The main advantage of a torsion attempt lies in the possibility of obtaining important deformations made at constant speeds at a given point of the specimen, without disturbances in the flow of a deformed metallic material [9–12,16]. Moreover, the rate of deformation, the degree of deformation and deformation temperature can be imposed.

Thus, the torsion test allows the simulation of a thermomechanical cycle to be completed to a continuous blade and for the mechanical aspect and the metallurgical aspect of one or more deformations to be analyzed. The hot torsion test allows for the plasticity of the analyzed alloy and resisting deformation to be directly studied.

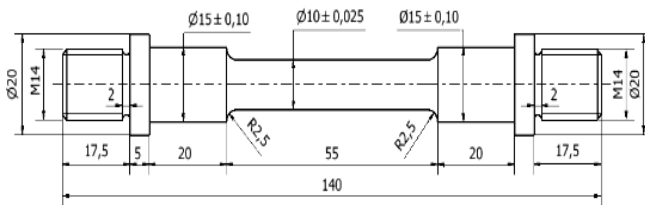
The determination of stainless steel deformability by torsion is the only one that makes it possible to obtain large deformations along the length of the specimen, which is why it is mainly used to determine the characteristics at large deformations [3, 9–12, 16].

Since shear strains play 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 [3, 11, 12, 16]. Via this method, the hot deformability of stainless steel is determined by subjecting to torsion a cylindrical specimen maintained at the deformation temperature in a tubular oven [11, 12, 16]. The size of the required moment for the torsion of the specimen expresses the resistance to deformation, and the number of torsions before failure expresses the plasticity limit of that steel [11, 12, 16].

The laboratory equipment used to study the deformation behaviour of non-hardenable ferritic stainless steel by hot torsion belongs to the Faculty of Engineering Hunedoara, University Politehnica Timișoara [9–12, 16]. The specimens for hot torsions were mechanically taken from  $\varnothing 20$  mm hot-

rolled steel bars, having the form and dimensions presented in Fig. 2 [9–12, 16].

The test specimens are typically cylindrical, with a calibrated small-diameter central portion, having the ratio  $l/d=5$  in the point of deformation (Fig. 1) [11, 12, 16]. The ends are screwed, and the specimen must have a shoulder in the continuation of the thread, to prevent further screwing during torsion (Fig. 1) [11, 12, 16].



**Figure 1** The test specimens used for the study of the deformation behaviour of non-hardenable ferritic stainless steel by hot torsion

#### 4 RESULTS AND DISCUSSION

For experimental tests, we used several stainless steel grades. This study includes the results of the tests conducted to find the deformability characteristics (plasticity and deformation resistance) of ferritic stainless steel, grade X6Cr17 (Tab. 2) [11, 15].

Ferritic stainless steel (non-hardenable stainless steel, grade X6Cr17) is resistant to corrosion in most environments. The grade of X6Cr17 is characterized by its good corrosion resistance and is displayed in immoderately corrosive environments. Stainless heat-resistant steels are always in demand when extreme technical requirements are imposed on the material, due to their outstanding chemical corrosion and mechanical properties [1, 3, 11].

For the hot torsion test, we prepared 40 samples from each steel grade (according to the experiments presented in Tab. 2). They were subjected to torsional deformation by maintaining the deformation temperature in the experimental equipment, from 50 to 50 °C, within the range of 800–1250 °C [11, 12, 16]. Each point within the temperature range studied in the two diagrams (Fig. 2 and Fig. 3) represents the arithmetic mean of four determinations.

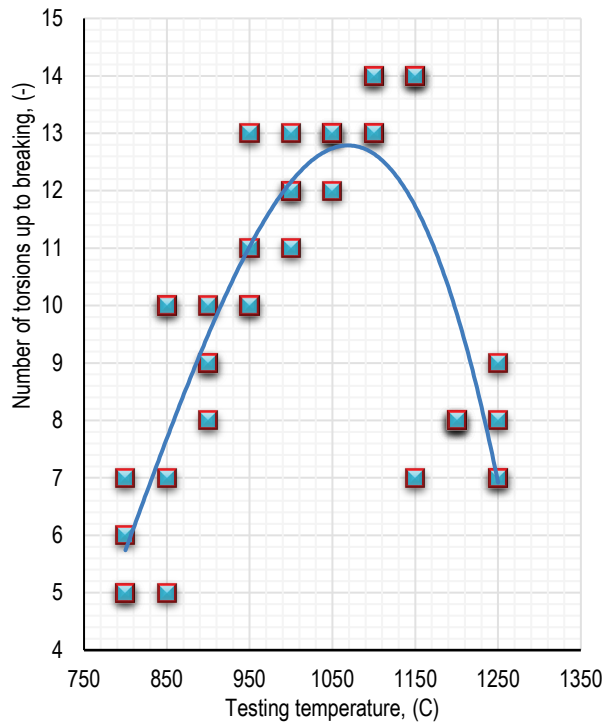
The magnitude of the torque required for the specimen's torsion expresses the resistance to deformation, and the number of torsions to failure expresses the plasticity limit of

that steel (Fig. 2). The plasticity limit is expressed by the number of torsions to failure at a given temperature and deformation rate (Fig. 3) [3, 9–12, 16].

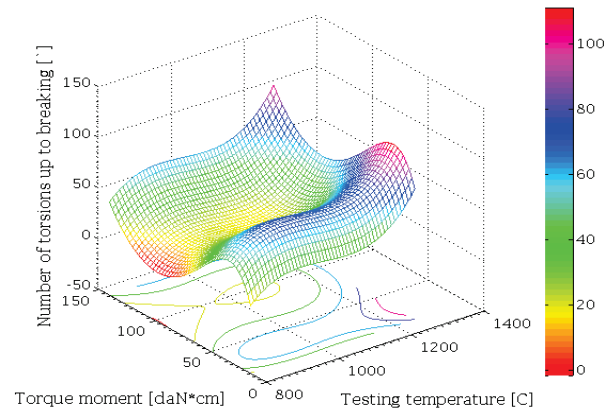
Deformation resistance is the resistance posed by metal plastic deformation materials under the concrete conditions of the plastic processing process (friction conditions, temperature, degree and deformation speed, and mechanical deformity scheme) [11, 12].

**Table 2** The results of the tests conducted to find the deformability characteristics of ferritic stainless steel (non-hardenable stainless steel, grade X6Cr17), at the experimental heating temperature values (800–1250 °C)

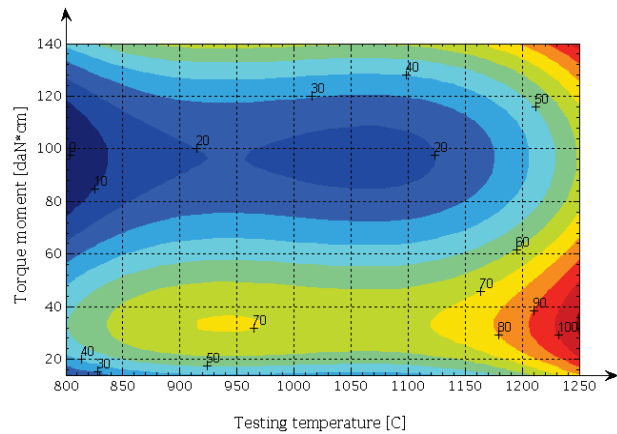
Experiments no.	Series no.	Heat-testing temperature, (°C)	Torque moment, (daN·cm)	Number of torsions up to breaking, (–)
Ferritic stainless steel – I	01.	800	135	31
	02.	800	133	34
	03.	800	140	42
	04.	800	138	40
Ferritic stainless steel – II	05.	850	126	29
	06.	850	126	22
	07.	850	123	26
Ferritic stainless steel – III	08.	850	122	24
	09.	900	108	27
	10.	900	112	17
Ferritic stainless steel – IV	11.	900	111	29
	12.	900	112	29
	13.	950	94	34
Ferritic stainless steel – V	14.	950	73	33
	15.	950	77	28
	16.	950	75	27
	17.	1000	63	35
Ferritic stainless steel – VI	18.	1000	57	36
	19.	1000	57	48
	20.	1000	58	48
Ferritic stainless steel – VII	21.	1050	26	62
	22.	1050	22	58
	23.	1050	38	68
	24.	1050	28	62
Ferritic stainless steel – VIII	25.	1100	83	15
	26.	1100	36	71
	27.	1100	41	75
	28.	1100	41	72
Ferritic stainless steel – IX	29.	1150	29	78
	30.	1150	28	69
	31.	1150	29	94
	32.	1150	28	94
Ferritic stainless steel – X	33.	1200	21	43
	34.	1200	21	57
	35.	1200	20	64
	36.	1200	20	67
Ferritic stainless steel – X	37.	1250	18	82
	38.	1250	16	89
	39.	1250	14	97
	40.	1250	14	93



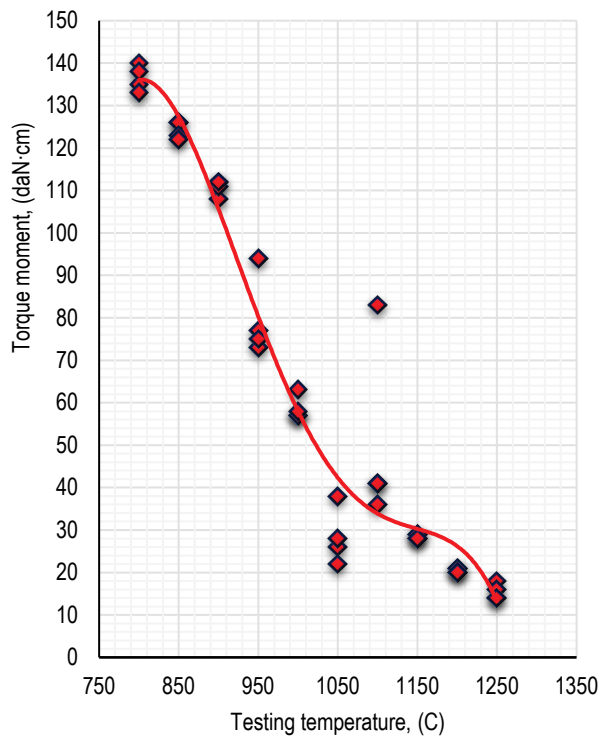
**Figure 2** Correlations: Testing temperature vs. Number of torsions up to the breaking of ferritic stainless steel (non-hardenable stainless steel, grade X6Cr17), at the experimental heating temperature values (800–1250 °C)



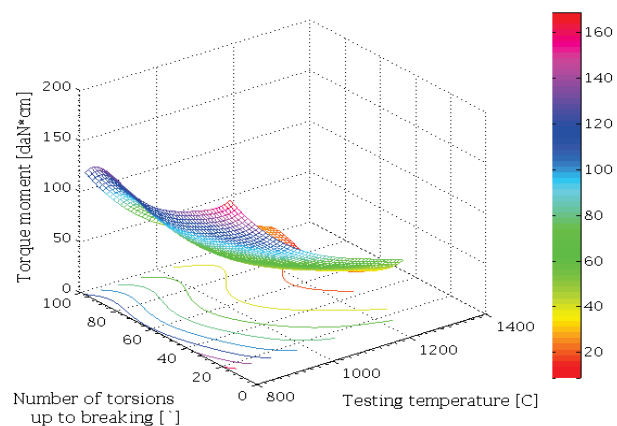
**Figure 4** Number of torsions up to breaking vs. Torque moment and Testing temperature of ferritic stainless steel (non-hardenable stainless steel, grade X6Cr17), at the experimental heating temperature values (800–1250 °C) (equation type:  $z_1 = a_1 + a_2x + a_3x^2 + a_4x^3 + a_5y + a_6y^2 + a_7y^3 + a_8y^4 + a_9y^5$ , standard deviation:  $r^2 = 0.9078$ )



**Figure 5** Correlation diagrams for the technological domains' area of deformation resistance: Testing temperature vs Torque moment of ferritic stainless steel (non-hardenable stainless steel, grade X6Cr17), at the experimental heating temperature values (800–1250 °C)

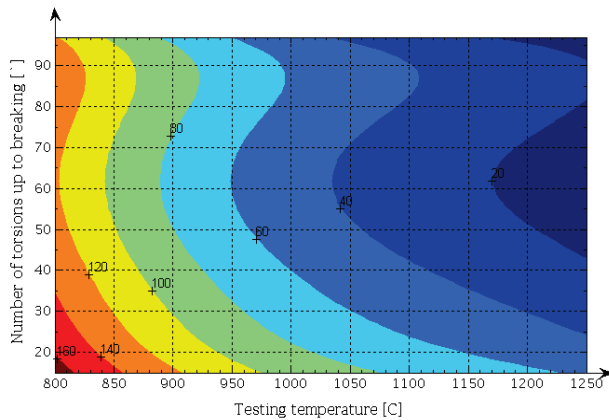


**Figure 3** Correlations: Testing temperature vs. Torque moment of ferritic stainless steel (non-hardenable stainless steel, grade X6Cr17), at the experimental heating temperature values (800–1250 °C)



**Figure 6** Torque moment vs. Number of torsions up to breaking and Testing temperature of ferritic stainless steel (non-hardenable stainless steel, grade X6Cr17), at the experimental heating temperature values (800–1250 °C) (equation type:  $z_2 = a_1 + a_2x + a_3x^2 + a_4x^3 + a_5y + a_6y^2 + a_7y^3 + a_8y^4 + a_9y^5$ , standard deviation:  $r^2 = 0.9869$ )





**Figure 7** Correlation diagrams for the technological domains' area of plasticity: Testing temperature vs. Number of torsions up to the breaking of ferritic stainless steel (non-hardenable stainless steel, grade X6Cr17), at the experimental heating temperature values (800–1250 °C)

In the graphical representation of the experimental tests' results (Figs. 2–7), we have the following comments and remarks:

- the variations of plasticity and the deformation resistance (expressed by the number of torsions to failure, respectively the maximum torque moment) of ferritic stainless steel (grade X6Cr17) are plotted in the Fig. 2 and Fig. 3;
- the upper limit of the optimum range of heating temperatures applied for deforming the studied steel (ferritic stainless steel, grade X6Cr17) clearly results from the plasticity – temperature diagrams (Fig. 2), being 1050 °C;
- based on the practical skills acquired in the rolling industry, it can be noticed that the heating 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);
- regarding the end-heating temperature, the plasticity – temperature diagrams (Fig. 2), for the hot deformation of the studied stainless steel grade (ferritic stainless steel, grade X6Cr17), we have the following experimental values: 800 °C;
- based on the practical experience of the rolling industry, sometimes it is recommended that the last two passes (processing stages of rolling) be carried out at temperatures below 800 °C, for the completion of granulation;
- the variation of the torque moment with the heating temperature, as shown in Fig. 3, indicates that the deformation resistance of ferritic stainless steel (grade X6Cr17) generally decreases when the heating temperature increases;
- the regression surfaces of the plasticity and deformability characteristics of ferritic stainless steel (grade X6Cr17), described by the number of torsions before failure, respectively the maximum torque moment, in correlation with the experimental testing

temperature (heating in the 800–1250 °C range of temperature), are shown in Fig. 4 and Fig. 6;

- these regression surfaces (expressed by the equation type:  $z = a_1 + a_2x + a_3x^2 + a_4x^3 + a_5y + a_6y^2 + a_7y^3 + a_8y^4 + a_9y^5$ , having standard deviations  $r^2 = 0.9078$ , respectively  $r^2 = 0.9869$ ) can be plotted in Fig. 5 and Fig. 7, and interpreted as correlation diagrams for the deformability characteristics (for the technological domains' area of deformation resistance – Fig. 5, respectively for the technological domains' area of plasticity – Fig. 7), which are typical for ferritic stainless steel, grade X6Cr17;
- the knowledge related to the steel's deformability characteristics (deformation resistance and plasticity) have for the technologist, as well as for the researcher, a great practical significance. The knowledge of the technological domains' area of plasticity and of deformation resistance is very important in the rolling practice because they are important elements in establishing a correct technological rolling process;
- the results of the hot torsion testing of ferritic stainless steel (grade X6Cr17) show that the resistance to deformation increases at deformation speed, being dependent on the nature of the stainless steel and the temperature, while the resistance to deformation decreases with a rise in temperature.

## 5 CONCLUSIONS

The choice of the heating regime is currently mostly based on the practical experience of the rolling industry. 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. The indications regarding the variation of plasticity with the temperature, using the hot torsion method, allowed the establishing of the temperature range within which steel plasticity is optimal and in which, in general, it is recommended to perform the entire hot plastic deformation.

The diagrams shown above (Fig. 5 and Fig. 7) show that the hot deformability characteristics of ferritic stainless steel (grade X6Cr17) vary as follows:

- hot plasticity increases when temperature increases in the field of 900–1200 °C.
- starting from 900 °C, they have sufficient plasticity, but the value of the deformation resistance is still high – up to 950 °C.
- it decreases after reaching the range of 1050–1150 °C, when the deformation speed increases. This adverse effect of a high rate of deformation is increased by a rise in temperature.
- the growth dynamic of the plasticity characteristics is continuous, reaching the maximum value at 1150 °C, while reducing the resistance to deformation.

Therefore, we can conclude that an increased level of the deformation temperature increases the plasticity within the

950–1150 °C temperature range and that it decreases the resistance to deformation of these types of stainless steel.

Thus, from the torsion tests carried out to determine the hot deformability, it results that the optimal plasticity of the analysed ferritic stainless steel (grade X6Cr17) is found within the temperature range of 950–1200 °C, preferably within the range of 1000–1150 °C.

### Acknowledgement

The laboratory equipment used to study the stainless steel deformability by hot torsion is subject to a patent registered with the State Office for Inventions and Trademarks (OSIM–Romania) under the number 439/17.05.2010, entitled "Equipment adapted for experimental determination of the resistance to thermal fatigue of samples placed tangentially on the generator of support discs", No. 54/2011. Additional information about the equipment (description, method, pictures etc.) are available in the studies [11], [12] and [16], according to the below-presented reference list.

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