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COLD-FORMING EFFECT ON MECHANICAL PROPERTIES OF STAINLESS STEEL SECTION – MATERIAL TESTING

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Abstract: *An experimental investigation of the cold-forming effect on mechanical properties of several grades of stainless steel is presented. The research is focused on basic grades of stainless steel, namely austenitic (1.4404), ferritic (1.4003), duplex (1.4462) and lean-duplex (1.4162) as correctly described cold-forming effect implies a possible strong increase of resistance. The test programme includes set of coupon tests of the material with various levels of induced plastic deformation. Measurement results serve to further modelling of stress-strain response and predicting of mechanical properties of cold-formed stainless steel. The general properties (0.2% proof tensile strength, ultimate tensile strength, ductility and nonlinearity) of cold-formed material were evaluated as well as values of the unformed material. In addition, other material properties were also described, such as the degree of stress-strain diagram non-linearity or anisotropy, modulus of elasticity of cold-formed or cold-worked stainless steel etc.*

Keywords: Cold-forming, Stainless steel, Stress-strain diagram, 0.2% proof strength, Mechanical properties.

1. Introduction

In structural design of stainless steel elements, in comparison with common carbon steel, the different material behaviour often demands more sophisticated design and offer possibilities how to prosper from specific material properties. The general investigated benefit for all stainless steel grades is the significant increase of 0.2% proof strength due to the cold-working within a fabrication process of structural elements. In the past, several proposals were developed (Van der Berg, Van der Merwe, 1992; Cruise, Gardner 2008; Rossi, Jaspart, 2010). Nevertheless, the design standards usually require tests for proving the increased strength properties and none of the proposal was established in the design rules with an exception of the British National Annex to EN 1993-1-4 using the method of Cruise and Gardner (2008). Generally, the proposed material models use various parameters and give different material strength. Some of them show good agreement in the range of strain expected in load-bearing structures. Other ones are in good agreement at higher strains. Results obtained from the recent investigations (Afshan et al. 2013; Rossi et al. 2013) demonstrate also different values for basic material characteristics, especially for modulus of elasticity, 0.2% proof strength, ultimate tensile strength or ductility. Especially, stainless steel in cold worked conditions can exhibit material properties with high scatter of the values among the steel grades and products. Current and extensive research of (Afshan et al. 2013) shows slightly different hardening exponent n depending on a grade of stainless steel, i.e. austenitic, ferritic, and duplex as opposed to recent European design standard. The same paper recommends also a lower modulus of elasticity for design purposes which may be assumed for the global analysis and in determining the resistances of members. Thus it is important to analyse more experimental data to establish generally valid relations for enhanced strength of cold-formed stainless steel.

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This article presents test results of coupons made of a cold rolled sheet from the austenitic (1.4404), ferritic (1.4003), duplex (1.4462) and lean-duplex (1.4162) grade. Apart from a classic tensile test, coupon tests were also performed on cold-worked specimens respecting different behaviour parallel and transverse to the rolling directions, either parallel or transverse to the previous plastic strain induction. The results of the research might lead to more accurate material characteristics and material models of a cold-formed material appropriate for FEM modelling and structure design.

2. Experimental programme

The section describes set of experiments executed at the Czech Technical University in Prague. The testing programme is aimed on the establishment of stress-strain diagram of a cold-formed stainless steel section made of all kinds of stainless steel grades, i.e. ferritic (1.4003), austenitic (1.4404), duplex (1.4462) and a relatively new lean-duplex grade (1.4162). The project involved especially tensile coupon tests. All specimens were prepared of a cold-rolled steel sheet of 1.5 mm respectively 2.0 mm thickness. First of all, material tensile tests of all grades were performed, both for direction transverse and parallel to the rolling direction. Strain was measured by foil strain gauges attached to both sides of the specimens (see Fig. 1) for the best accuracy of the initial part of the stress-strain diagram and by an extensometer for higher strain ranges.

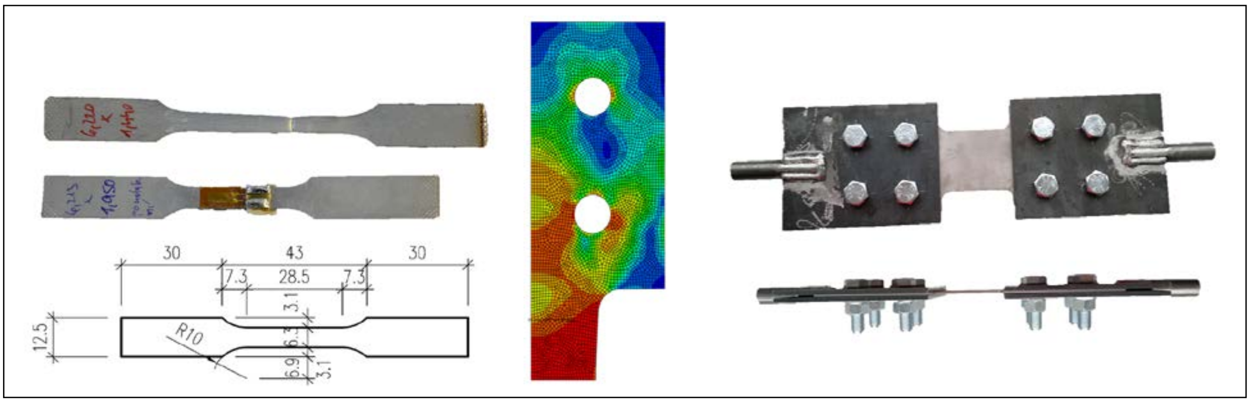


Fig. 1: Coupon before and after a tensile test including its initial geometry; stress distribution in the numerical model (quarter of the sample – symmetric conditions) and the test device with stainless steel plate attached.

The next step included tensile plastic deformation induction on the coupons or a special wide specimen from which the coupons were subsequently machined. A device able to induce uniform plastic deformation through the whole width of the wide specimen was used. That provides the desired (uniform) strain distribution in the area which the new coupon was created from (neck of the specimen) as it is shown in Fig. 2. The geometry of the specimen was based on a simple Abaqus 2D model presented as well. The device consists of 2 parts in which the sample was connected by 4 bolts M16 of 8.8 quality. There were two shear planes (represented by two plates and the sample) to minimalize the eccentricity in the connection. The device was able to clamp into a testing machine by a round bar which eliminated eventual moment influence. The middle part of the specimen served for extensometer set with gauge length of 50 mm at maximum. The device allowed load of the specimen over 100 kN.

Levels of the induced plastic strain varied significantly. Plastic strain equal to 1%, 3%, 5%, 10%, 15% and for other than ferritic grades also 20% or 50% (austenitic grade only) was used. From these “cold-worked” specimens where the plastic strain was induced, coupons were machined and tested. The cold-worked specimens are shown in Fig. 3, as well as the directions of the forming and the subsequent testing. The experimental set consisted of 5 or 6 specimens with various level of the induced plastic strain. The set was tested for each grade, in respect to the sheet rolling direction and in respect to the induced plastic strain direction. Coupon tests were executed in about four weeks after the plastic forming. In total, 92 coupons were prepared and tested in accordance with the recent European standard (EN ISO 6892-1:2009).

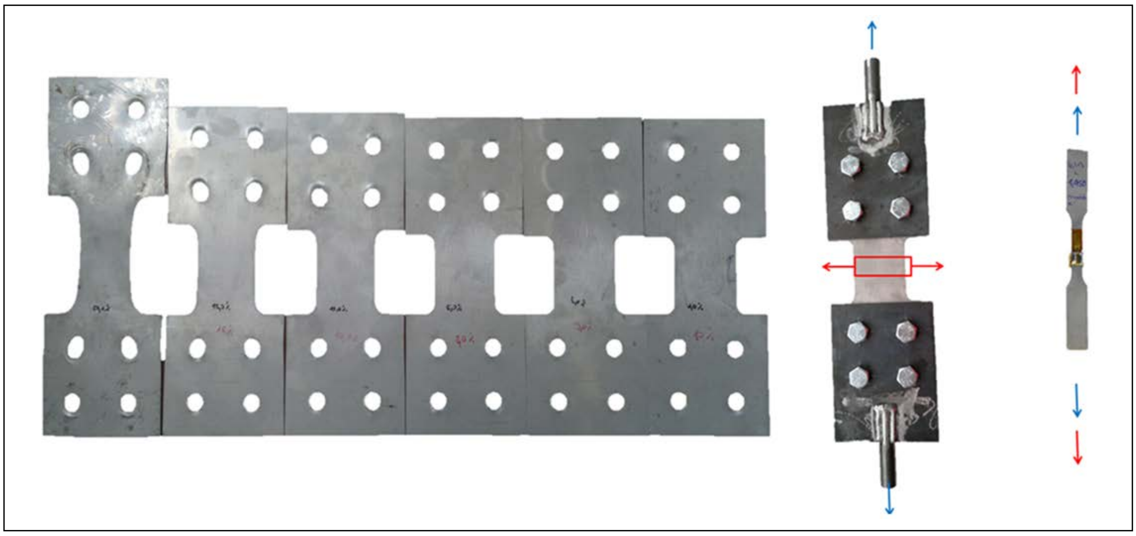
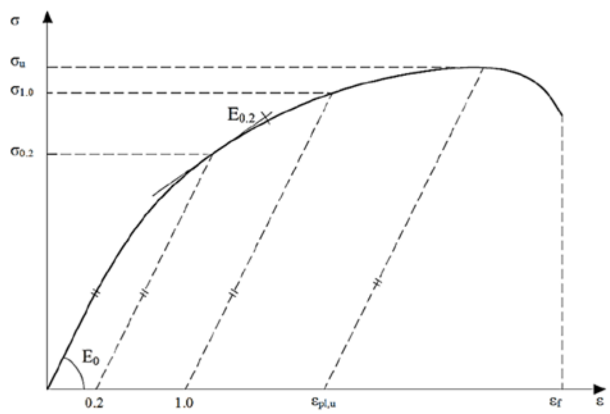


Fig. 2: Specimens after the plastic strain induced transversally (left) and along the tensile test direction (right).

All tests were performed using the MTS Qtest 100 kN electromechanical testing machine with all data recorded at 5 Hz using the SPIDER data acquisition system with CATMAN32 data acquisition software. The tests were strain controlled. The accepted strain rate for testing up to 1.5% strain was 0.007% s^{-1} and followed by 0.2% s^{-1} until fracture. The value of 1.5% strain ensured the lower stress rate for both 0.2% and 1.0% proof strength measurements. Both values are often used for stress-strain diagram description.



$$\varepsilon = \frac{\sigma}{E_0} + 0.002\left(\frac{\sigma}{\sigma_{0.2}}\right)^n \qquad (1)$$

$$n = \frac{\ln(\varepsilon_{p2}/\varepsilon_{p1})}{\ln(\sigma_2/\sigma_1)} = \frac{\ln(20)}{\ln(\sigma_{0.2}/\sigma_{0.01})} \qquad (2)$$

Fig. 3: Stress-strain behaviour description; Ramberg-Osgood model for a nonlinear metallic material.

3. Results and discussions

Figure 4 shows stress-strain diagrams for coupons of selected grades tested in the rolling direction. Stress-strain behaviour of the coupons tested transversally to the rolling direction was almost identical (as well as for other grades).

In contrast to the 0.2% proof strength increase, ultimate tensile strength increase is significant only when the engineering values are compared. For the true values of the ultimate strength, the “cold-formed” samples showed no important increase. Significant decrease of ductility and Ramberg-Osgood nonlinearity parameter n is typical for all grades.

Ductility decrease is significant for all investigated grades. The largest decrease is exhibited by ferritic grade in contrast to the austenitic grade with the smallest effect of cold-working affecting the ductility. Values for duplex and lean duplex grade lie within the area bounded by the ferritic grade from the bottom and the austenitic grade from the top. The fact reflects the ductility of the virgin material. Ferritic grades exhibit the lowest values, following by duplex and lean duplex grades. Austenitic grades are well-known for their ability to be cold-formed due to high ductility in general and they exhibit the highest ductility among all tested grades.

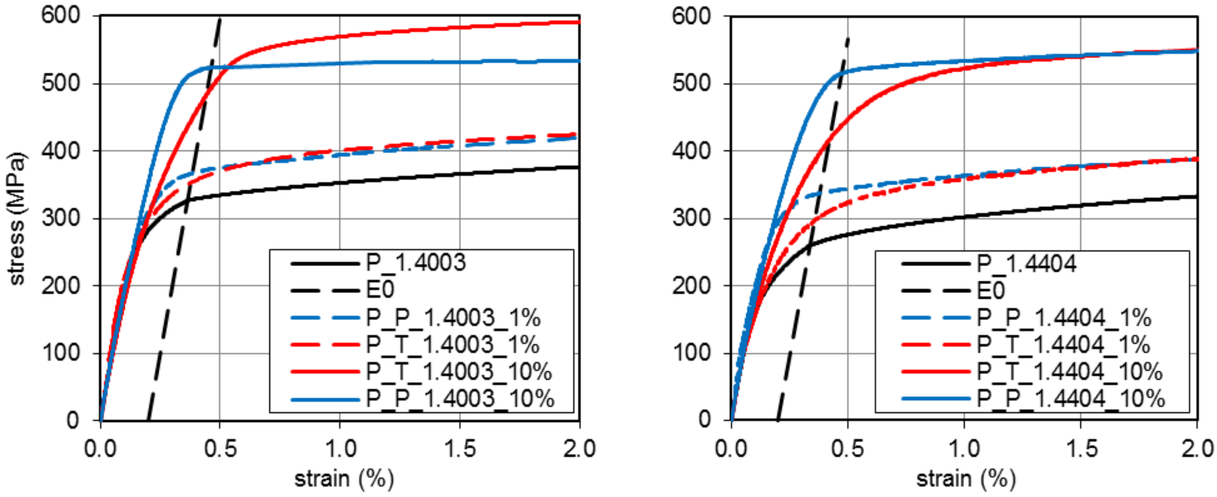


Fig. 4: Stress-strain diagram of selected 1.4003 and 1.4404 samples manufactured parallel to the rolling direction (P) with different direction and level of plastic strain induction (P – parallel, T –transverse).

4. Conclusions

The testing programme on 116 coupons was performed and its results presented. The main material characteristics and stress-strain curves were shown. Values of non-linearity parameters n, 0.2% proof strength, 1.0% proof strength, ultimate tensile strength, ductility and modulus of elasticity were evaluated and may be used for further research on cold-formed sections. The presented strength increase shows that the influence of cold forming is important not just for the austenitic grades, but also for the other stainless steel grades. However for the ferritic grade, the ductility could be limiting. After the plastic strain induction in a specimen corresponding to the level of strains induced during section cold-forming (in corners typically exceeding ten percent), the 0.2 proof strength increase typically reaches 30 to 90 %. Ultimate strength increase, when the true value is calculated, is almost none. The higher the plastic strain induced in the specimen the higher the values of Ramberg-Osgood nonlinearity parameter and the lower ductility. Material parameters also differ in respect to the forming direction and the anisotropy is evident.

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