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Effect of plastic deformation on the magnetic properties of selected austenitic stainless steels

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Abstract
Austenitic stainless steels are materials, that are widely used in various fields of industry, architecture and biomedicine. Their specific composition of alloying elements has got influence on their deformation behavior. The main goal of this study was evaluation of magnetic properties of selected steels, caused by plastic deformation. The samples were heat treated in different intervals of temperature before measuring. Then the magnetic properties were measured on device designed for measuring of magnetism. From tested specimens, only AISI 304 confirmed effect of plastic deformation on the magnetic properties. Magnetic properties changed with increasing temperature.

1. Introduction

The austenitic stainless steels are ternary alloys of Fe-Cr-Ni. They contain high percentage of Cr and Ni, but also other elements such as Mb, Ti, Al, Nb, Cu, N, S, P and Se may be added to increase corrosion resistance. A selection of added elements depends on the required properties of a final product and specific environments, too. Their microstructures consist of very clean FCC crystals in which all the alloying elements are held in a solid solution. Such kinds of steel are called austenitic because of their final structure. It is austenitic at room temperature. Austenitic stainless steel is applied in chemical, petrochemical and nuclear industry, architecture, food processing and many others. They are also used in medicine as biomaterials. In this case, it is necessary, that the used material must be biocompatible, biofunctional, bioadhesive and corrosion resistant.

The most widely used austenitic stainless steel is AISI 304. This material belongs to the type called high-alloy TRIP steels. This types of steels contains a large number of alloying elements such as Cr and Ni, which improve pitting and corrosion resistance (RODRÍQUEZ-MARTÍNEZ J.A. ET AL. 2011, JAKOBSEN P.T., MAAHN E. 2001). AISI 304 contains essentially 18% Cr and 8% Ni. The content of C is limited to maximum of 0,08% (TOURKI Z. et al. 2005). 100% austenitic steel AISI 304 is non-magnetic and it has got a cubic closed γ-phase. After plastic deformation, the phase is transformed to a BCC α'-martensite phase. The steel becomes ferromagnetic after plastic deformation. Many reports refer, that the magnetic effects of martensite content in AISI 304 is caused by progressive cold rolling (YAMASAKI T. ET AL. 1996).

Effective tools to monitor the influence of the deformation behavior are magnetic techniques. Magnetic measurements are suitable for non-destructive testing, detection and characterization of modification and defects in materials (VÉRTESY G. ET AL. 2005). These techniques include measurement of magnetic hysteresis loop and magnetic Barkhausen emissions measurement (MITRA A. ET AL. 2006). A hysteresis loop shows the relationship between the induced magnetic flux density and the magnetizing force. The loop is generated by measuring the magnetic flux of a ferromagnetic material while the magnetizing force is changed. From hysteresis loop one can determine several primary magnetic properties of the material, such as retentivity, residual magnetism, permeability etc. The Barkhausen noise means that when an external magnetizing field through the ferromagnetic material is changed, the magnetization of material changes in series of discontinuous changes. It causes jumps in the magnetic flux through the material. These jumps of magnetization are interpreted as discrete changes in a size or a rotation of ferromagnetic domains. The jumps can be detected by winding a coil of wire around the bar, which is attached to an amplifier and a loudspeaker. When the amplifier produce sound in the loudspeaker, the unexpected transitions in the magnetization produce current pulses in a coil (O'SULLIVAN D. ET AL. 2004).

2. Experimental material and procedure

Three types of austenitic stainless steel- AISI 304, Cr-Ni-Mo low-carbon steel AISI 316 L and Cr-Ni-Mo steel stabilized with Ti AISI 316 Ti were chosen for magnetic measurements. The 316 grades steels are non-magnetic with good resistance to acids (NOVÝ F. ET AL. 2014). The non-magnetic steel was chosen for better comparison with magnetic properties of AISI 304. Chosen materials are standard commercially available stainless austenitic steel. The testing specimens were small blocks with dimensions 10x10x20 mm.

The samples were heat treated in furnace before measuring their magnetic properties. The first set of samples was marked by letter (A). It was initial state of materials. There were chosen values of temperatures at 100 °C (B), 400 °C (C), 800 °C (D), where the samples were heated for 15 minutes and temperature 1050 °C (E), where they were heated for 30 minutes. The last temperature was 700 °C (F), where the samples were heated for 10 hours.

Differences in microstructure after heat treatment were observed by means of a light microscope. In microstructure of AISI 304 in initial state, austenitic grains, α'-martensite phase, deformation twins were visible (Fig.1.). The structure has changed after solution annealing. There were mainly polyhedral austenitic grains and annealing twins (Fig.2.).

There are many devices for measuring magnetic properties. This experiment was realized on a device called Magnet Physik, which is used for measuring of hysteresis loops. It makes it possible to determine magnetic quantities (remanence, coercivity), to make measurements with surrounding coils to determine the magnetic mean values and measure at temperatures up to 200 °C.

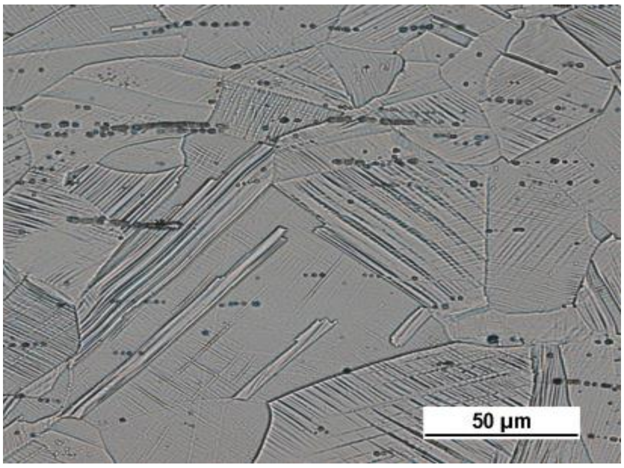

Fig. 1. Microstructure of AISI 304 in initial state

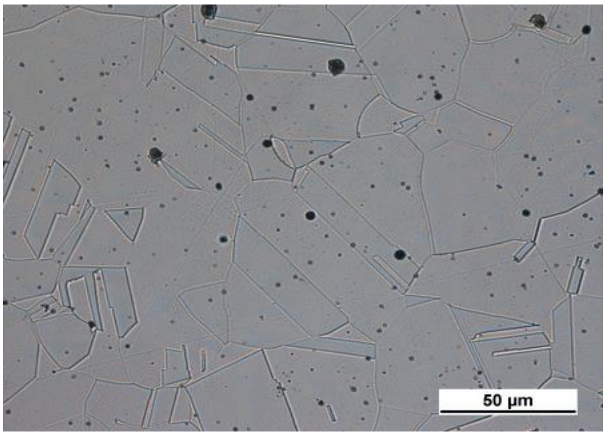

Fig. 2. Microstructure of AISI 304 after solution annealing

The measurement was performed under normal conditions at room temperature. The temperature of samples was 21 °C. The magnetic excitation fields that are necessary to record a hysteresis loop were generated by the electromagnet EP 3. In the case of AISI 304 the maximum current of the electromagnets power supply was set to ±10 A and time of increasing of current to maximum to 40 s. For AISI 316 L and AISI 316 Ti I_{max} was ±5 A and increasing time was 60 s. Different input values do not have influence on the shape of magnetization curves, as shown in Fig.3. During all the measurements, the demagnetization was on.

3. Results and discussions

Austenitic steel is, generally, a paramagnetic material. AISI 304 showed highest values of magnetism. It is caused by α'-martensite phase emergent by previous forming of material. It is included mainly in this type of steel. The presence of α'-martensite phase was proven by checking of microstructure on light microscope (Fig.1). Another factor that could affect magnetic behavior of austenitic steel is δ-ferrite. It causes that paramagnetic material turns its magnetic properties from paramagnetic to ferromagnetic, as mentioned in article (MARTÍNKOVÁ J. 2010). However, the presence of δ-ferrite in initial status was not proven.

AISI 316 L and AISI 316 Ti include higher percentage of alloying elements. Different chemical composition is the reason why steel change its primary deformation mechanism from twining (in 304 grades) to slipping typical for 316 grades (CORREA SOARES G. ET AL. 2017). These two types of steels did not create hysteresis loops at neither temperature in contrast with AISI 304. That is reason why this research was more focused on AISI 304 and its magnetic behavior. The difference between magnetic properties of materials in initial state is obviously visible in Fig.3.

In this research, it was confirmed that from all tested austenitic stainless steel only AISI 304 has got significant magnetic properties. Detail of measured values for this material is shown in Fig.4. This steel created hysteresis loop in interval of temperatures from initial state to 400 °C. It means that material is ferromagnetic and contains α'-martensite phase caused by the plastic deformation. After heat-treatment at higher temperatures the curve did not connect at neither point, so did not create hysteresis loop. The steel has lost its magnetic properties. It is caused by structure elements decay. The α'-martensite phase is not contained in structure anymore.

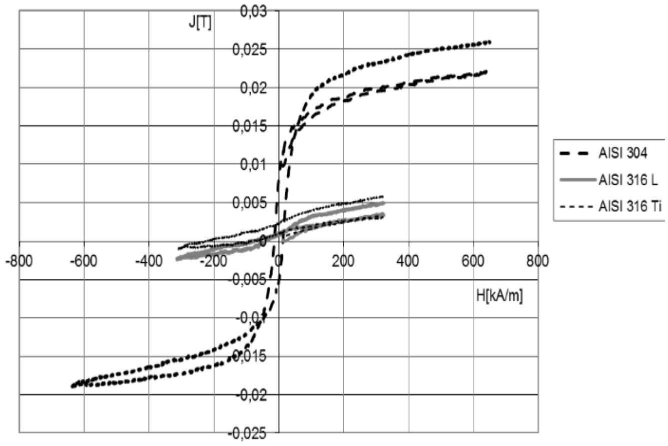

Fig. 3. Comparison of magnetic properties in initial state
Source: own study

In Table 1 are listed explanatory notes to curves from Fig.4. At the temperature of 100 °C the investigated material has got a top of internal damping, at 400 °C shape memory is canceled and at the temperature of 800 °C recrystallization is occurred. Heating of material at 1050 °C for 30 minute causes solution annealing. The heat treatment at 700 °C for 10 hours causes sensitization of material.

Table 1. Explanatory notes for Fig.4.

Number of curve	1	2	3
Temperature/Time	Initial state	100 °C/ 15 min	400 °/ 15 min
Number of curve	4	5	6
Temperature/Time	800 °C/ 15 min	1050 °C/ 30 min	700 °C/ 10 hours

Source: own study

4. Summary and conclusions

The influence of plastic deformation on the magnetic properties of austenitic stainless steel by measurement of magnetic properties was proven. From three chosen materials, only one has got a significant magnetic behavior- AISI 304. It is caused by the presence of plastic deformation after previous forming. It was necessary to choose suitable interval of temperatures for heat treatment before measurement of magnetic properties. Conventional austenitic steels are creep and corrosion resistant, but their use at high temperatures may be limited by the intergranular corrosion susceptibility that results from chromium depletion adjacent to grain boundaries due to carbide precipitation in the 450 °C-850 °C range (YAE KINA A. ET AL. 2008). This measurement has shown that magnetic properties change with increasing temperature. The reason of this change is the structure elements decay. Issues of anomalous evolution of martensitic phase caused by heat treatment are more precise described in article written by Gauzzi et al. (GAUZZI F. ET AL. 2006).

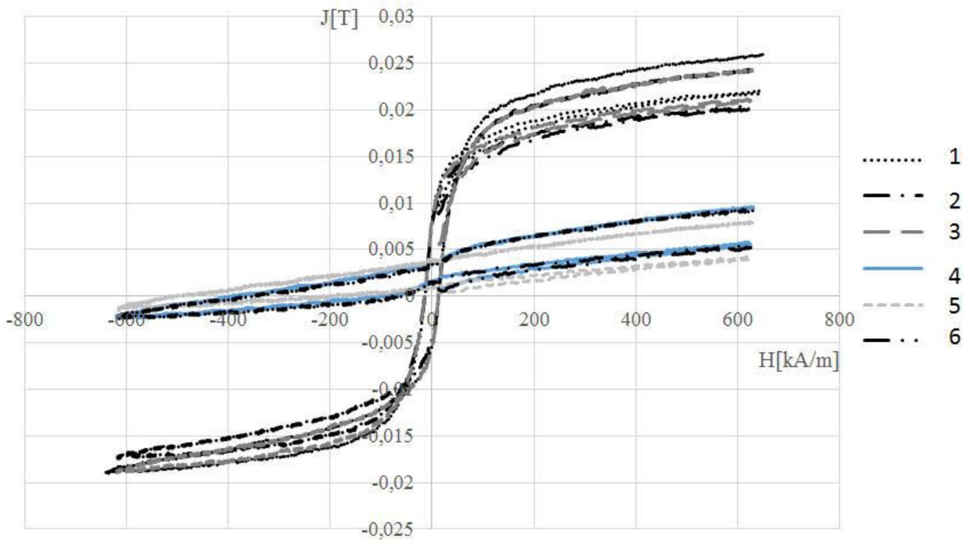

Fig. 4. Comparison of magnetic properties of AISI 304

Source: own study

Acknowledgements

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塑性變形對選擇的奧氏體不銹鋼的磁性能的影響

關鍵詞
塑性變形，奧氏體，
不銹鋼，
磁性能

摘要
奧氏體不銹鋼是廣泛用於工業，建築和生物醫學的各個領域的材料。
它們的合金元素的具體組成對它們的變形行為有影響。
這項研究的主要目標是評估所選擇的鋼的磁性能，由塑性變形引起。
在測量之前，樣品在不同的溫度間隔進行熱處理。
然後在設計用於測量磁性的裝置上測量磁性能。 從測試樣品，只有AISI 304證實塑性變形對磁性能的影響。 磁性隨溫度的升高而變化。