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ADVANCED MATERIAL CHARACTERIZATION OF FORMED METASTABLE AUSTENITIC STEELS TO ANALYSE THE PHASE TRANSFORMATION[1]

Kathrin Voges-Schwieger[2]
Philipp Olle[2]
Sven Hübner[2]
Bernd-Arno Behrens[3]

Abstract

Material characterization becomes more and more important for the description of material behavior in numerical modeling. To specify the fractions of strain-hardening due to the change of microstructure from austenite into α'-martensite and work-hardening considering the forming process in metastable austenitic steels, a new approach of material characterization is necessary. Therefore, the influence of different forming temperatures is investigated. The present paper deals with various analyses of the phase transformation in deep drawn parts and their characterization in order to examine the formation process at temperatures below the room temperature. Several (residual-) austenitic steels, e.g. stainless steels and TRIP-steels are investigated. One goal of the investigations is the stress-dependent description of strain-induced martensite formation.

Key words: α'-martensite; Phase transformation; Material characterization.

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[2] *Research Assistant, Institute for Metal Forming and Metal-Forming Machines, Leibniz Universität Hannover, Germany.*

[3] *Head of the Institute, Institute for Metal Forming and Metal-Forming Machines, Leibniz Universität Hannover, Germany.*

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1 INTRODUCTION

The formation of strain-induced α'-martensite in metastable austenitic sheet metals is well known, but a concerted use of this effect is just since a few years under research. One part of this project is the local compensation of imperfections e.g. cataphoretic drain holes by using deep drawn martensitic reinforcements. This leads to a concerted material behavior during quasi-static and dynamic loads. The effect of local α'-martensitic reinforcements enables an advanced crash behavior for especially crash relevant parts. Forming temperatures below T = -20°C enforce the phase transformation while temperatures beyond T = 60°C can suppress this change of lattice.[1,2] One goal of research is the characterization of the transformation process for different forming temperatures. Therefore, the determination of hardness distribution in correlation to the martensite content is carried out. Another topic is the analysis of the life cycle behavior and the determination of residual stresses in reinforcements formed at different temperatures. Finally, the description of martensite formation can be formulated for different temperatures for the stainless steels EN 1.4301, EN 1.4318 and EN 1.4372.

2 MATERIALS AND METHODS

The examined metastable austenitic steels are the CrNi stainless steels EN 1.4301, EN 1.4318, EN 1.4372 and the residual austenitic steel TRIP780. The metastable phase of the CrNi steels is caused by the alloy elements chromium and nickel. Nickel enlarged the γ-area of the austenitic phase and enables this as a present phase at room temperature. Due to this, the material wants to change in a stable phase. The forming operation allows the formation of strain-induced martensite by bracing and fastening. Lower temperatures abet the phase transformation conditioned by the free enthalpy. The considered stainless steels are differing in their metastable phase due to their alloy elements.[3,4] Table 1 shows the alloy elements of the three materials.

Table 1. Alloy elements of the considered stainless steels

	Cr [%]	Ni [%]	C [%]	N [%]	Mn [%]
EN 1.4301	18,1	8,3	0,04	-	-
EN 1.4318	17,7	6,5	0,02	0,14	-
EN 1.4372	17,0	5,0	0,05	0,15	6,5

In addition, the steel TRIP700 shows also a metastable character. The microstructure consists of ferrite, bainite and residual austenite. At a temperature of about T = 20°C, the stability of the residual austenite concerning the transformation into a martensite-lattice is effectuated by the alloy elements carbon and manganese. Due to local strain hardening and martensite evolution, the elongation modifies to higher strain values.[5]

The local reinforcements are implemented by using a temperable deep drawing tool for the temperature range T = -20°C up to T = 100°C. Additional forming elements function as punches for a concerted stretch-out of material, locally. In Figure 1, an example for the arrangement of these additional forming elements is given. Every single structure shows a martensite content $f^{\alpha'}$ of about 8 %.

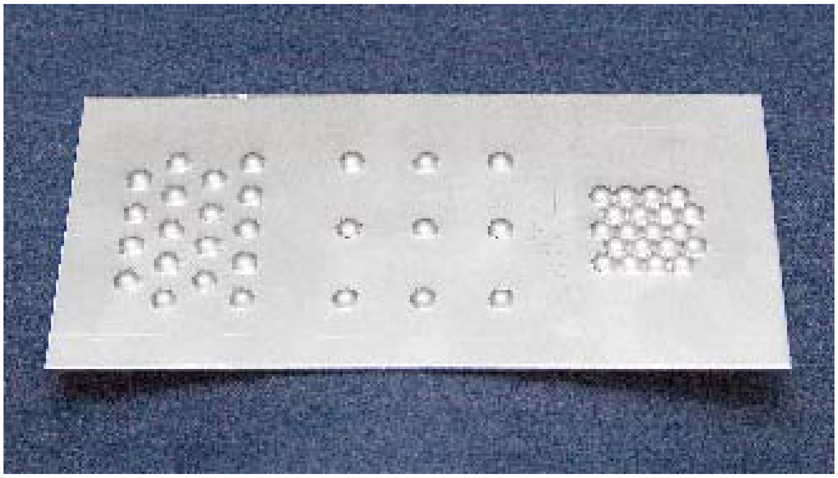


Figure 1. By additional forming elements generated structures in material EN 1.4301.

3 RESULTS AND DISCUSSION

To investigate the correlation of forming temperature, martensite content and hardness increase, different methods of material characterization are used. The following investigations improve a great benefit for the material behavior by using temperatures below room temperature. Moreover, strain-induced martensite in metastable austenitic steels can enhance the local material behavior regarding load-adaption and hardness.

3.1. Connection between the Hardening-Process and the Solidity under Consideration of Temperature Effect

Within the scope of the experiments, new questions arose regarding the complex hardening concept of hardening as a result of forming (work hardening) and phase transformation. Extensive preliminary analyses were carried out in order to quantify the work hardening part and the transformation induced α'- martensite formation via differing temperature control systems. The focus lay particularly on the steel materials EN 1.4301 and TRIP780. The selection of these two materials arose from their metastable (and remaining) austenitic structure, there is now wide theoretical knowledge regarding the material behavior at room temperature. The hardening concept of the stainless steel is based on the loading of the alloyed proportions of chromium and nickel. The TRIP780 contrasts the latter with a remaining austenite share of approximately 15%, imbedded within a matrix compiled of ferrite and bainite, whereupon the principle of phase conversion lies upon the carbon and manganous alloyed elements. Upon the basis of the correlation between hardness and solidity, micro-hardness measurements were evaluated regarding round structures, at a forming degree of $\varphi = 0.12$. The structuring was carried out at differing forming temperatures from $T = -20°C$, $T = 20°C$ as well as $T = 100°C$. In regards to the reference and quantification of the work hardening effect, micro-hardening data was examined on the basis of unformed source material. With the aid of this data, the temperature impact on the phase conversion became particularly apparent. Based on this experiment, a qualitative impact of increased hardening, being a result of forming, as well as phase conversion become possible.

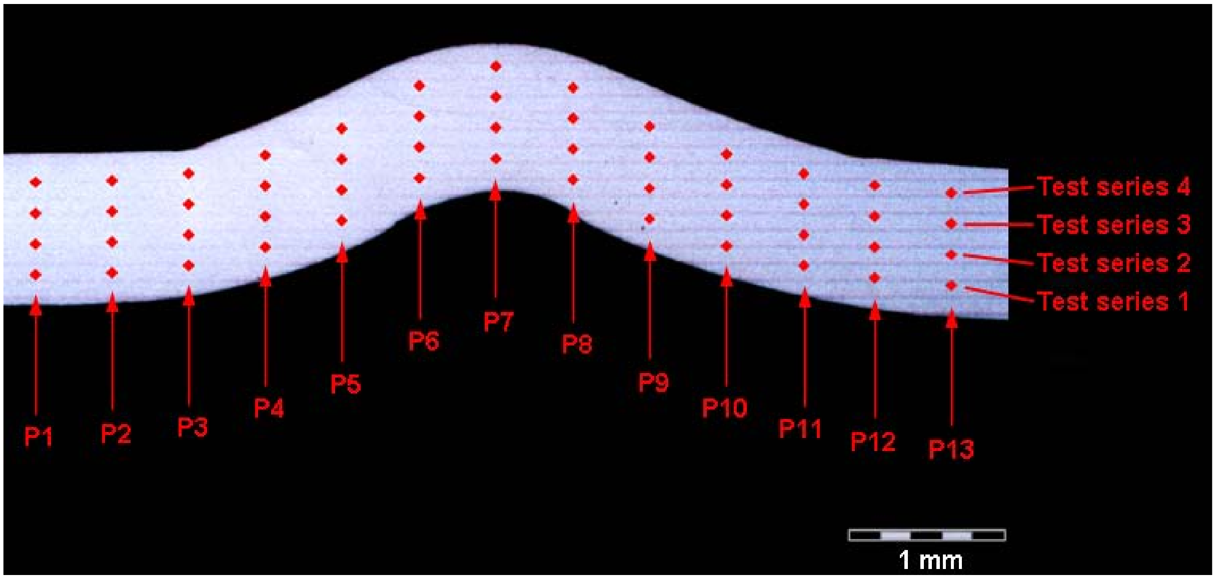
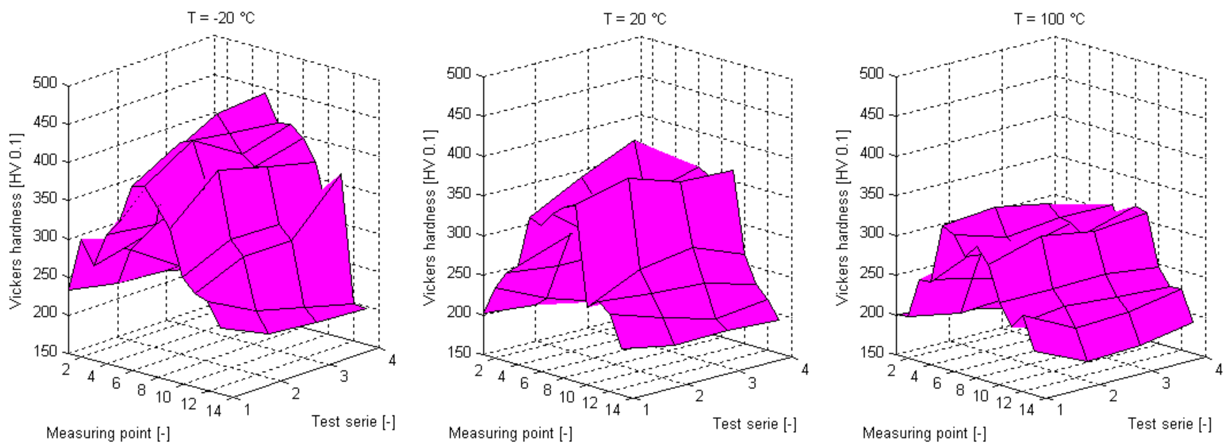


Figure 2. Sketch of the Principle of measurement of hardness on a polished specimen.

The micro-hardness measurements follow the grindings of the additionally forming-element's round structures (Figure 2). Thirteen measuring points were distributed in four different measuring-rows over the sheet-metal thickness and measured, whereby the measuring point P7 presents the center of the vaulting. The distance between the separate measuring rows amounts to a = 0.2 mm.



a) T = -20 °C b) T = 20 °C c) T = 100 °C

Figure 3. Measurements of micro-hardness for the material EN 1.4301 at varying forming temperatures.

The analyzed measurements of micro-hardness in the metastable austenite stainless steel EN 1.4301 on the structure have been produced in

Figure 3 for three different tests as 3D diagrams. Diagram a) presents the hardening-process over the four measuring rows for all measuring points at a forming

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temperature of T = -20°C. In contrast to this, diagram b) exhibits lower hardening values, at a forming temperature of T = 20°C, which accompanies the low α'-martensite content. In diagram c) a forming temperature of T = 100°C was actualized, in order to suppress the α'-martensite formation, which is reflected in the low Vickers hardening rates. The highest values were achieved in the measuring rows 3 and 4.

The solidity can be deduced based on the presented hardening-process. An increase of the solidity, as a result of the promotion of the phase transformation at low temperatures, but also thru the effect of the forming in contrast to the unformed material, becomes very clear. The micrographs were used in order to document the forming history and, as a consequence, evaluate the martensite formation at a forming temperature of T = -20°C (Figure 4). It becomes clear that the increase of solidity results accompanies the phase conversion with the forming degree and the degree of strain.

However, an exact separation of the effect of work-hardening is not possible by this method. Moreover, it lacks an allocation of the effects of phase conversion as a result of differing strain conditions, as for example the deep drawing and extension.

Such experiments were carried out for the remainder of the austenitic steel TRIP780. In Figure 5, the results of the micro hardening readings after Vickers are presented, in the case of this material, at forming temperatures of T = -20°C, T = 20°C and T = 100°C. Similar to the experiments on EN 1.4301, the emergence of the maximal values are exhibited within the measuring rows 3 and 4 and on the specimen's undersurface. A comparison of these measuring rows shows that the highest hardness values were exacted at room temperature, while at low temperatures of T = -20°C, little data developed, which were nevertheless higher than the original value of the unformed material.

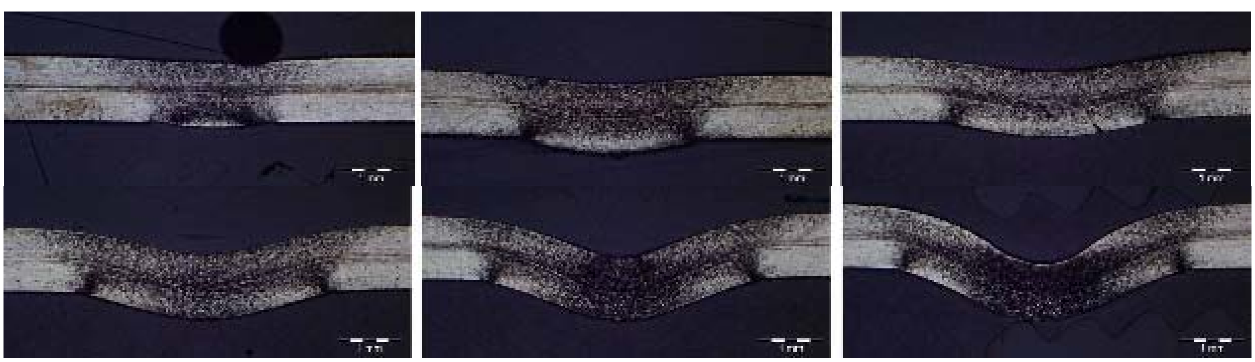

Figure 4. Deformation history and the α'-martensite formation accompanying it within the material EN 1.4301, at a forming temperature of T = -20°C.

Based on these results, the different concepts of solidification become distinct once more, within the examined materials. The temperature-dependent solidification concept of the remainder of the austenitic steel in combination with the work-hardening solidification is to be examined in detail.

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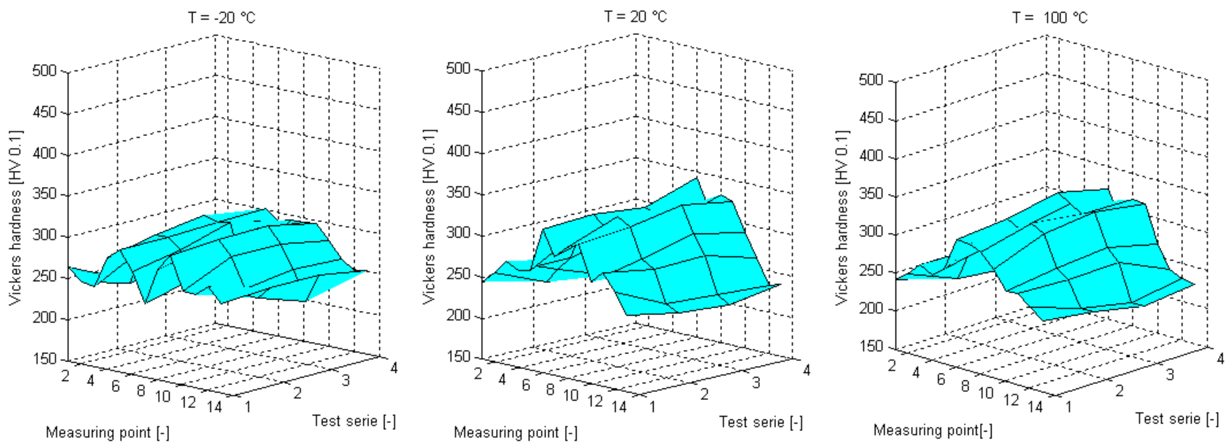

a) T = -20 °C b) T = 20 °C c) T = 100 °C

Figure 5. Measurements of micro-hardness for the material TRIP780 at different forming temperatures.

3.2. Residual stresses for different deep drawing temperatures

The structures inserted during the forming were analyzed particularly regarding their internal stresses. The examination of the tensions was carried out at the Institute for Manufacturing Technology and Tool Machinery at the Leibniz Universität Hannover, within an X-ray diffractometer. The material TRIP780 and EN 1.4301 were analyzed. In Figure 6, a part of the results for the structures is exemplarily presented. Internal stresses were measured in longitudinal and cross direction for various parameters. It can be gathered from the results that the structures primarily cause the contribution of compressive stress. Negative internal stresses can work against the emerging of cracks. At a temperature control within the region of T = 80°C and T = 100°C, the compressive internal strain can be increased. In the case of the metastable stainless steel EN 1.4301, no increase in internal stress can be achieved despite the forming temperature of T = -20°C and despite the promotion of α'-martensite formation.

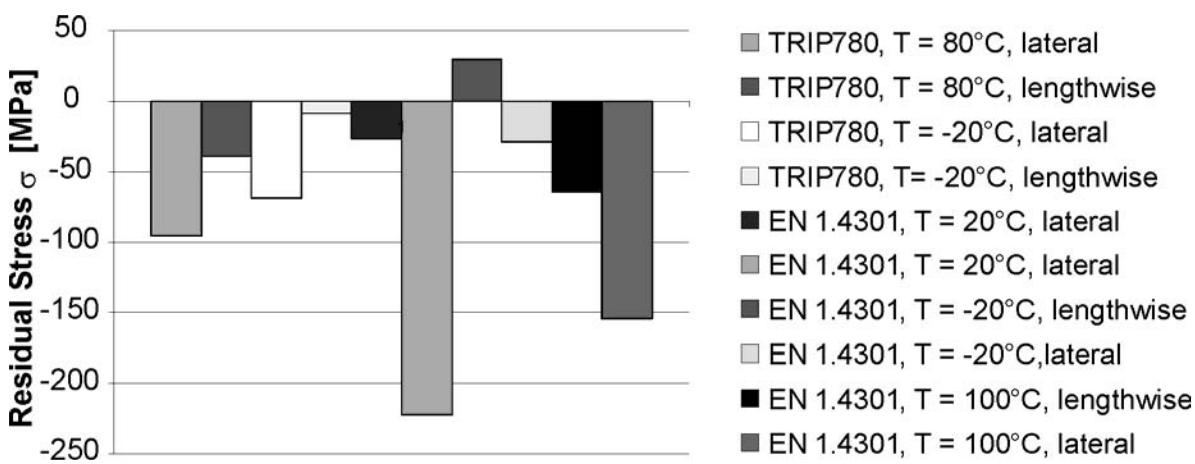

Figure 6. Exemplary presentation of the internal stress measurements for reinforcements of steels materials TRIP780 and EN 1.4301.

3.3. Investigations of fatigue strength for different deep drawing temperatures

The presented structures were also investigated regarding their fatigue strength for different forming temperatures. Therefore, specimens with structures, deep drawn at different forming temperatures, for life cycle tests were analyzed. Depending on the forming temperature, an increase in life cycle could be accomplished (Figure 7). For a forming temperature of T = 100°C, the formation of martensite content could be suppressed. The fatigue strength is diminishing than at a forming temperature at room temperature. At a temperature of about T = 20°C, the corresponding life cycle is assumed of 100%. At these forming parameters, the change of lattice into α'-martensite takes place. In comparison to reinforcements, drawn at T = -20°C, the corresponding life cycle behavior shows better results. At these cold temperatures, the phase transformation could be enforced. The martensite content in the specimen shows for these forming parameters the highest amount. These results show the positive effect of cold temperatures during the deep drawing process.

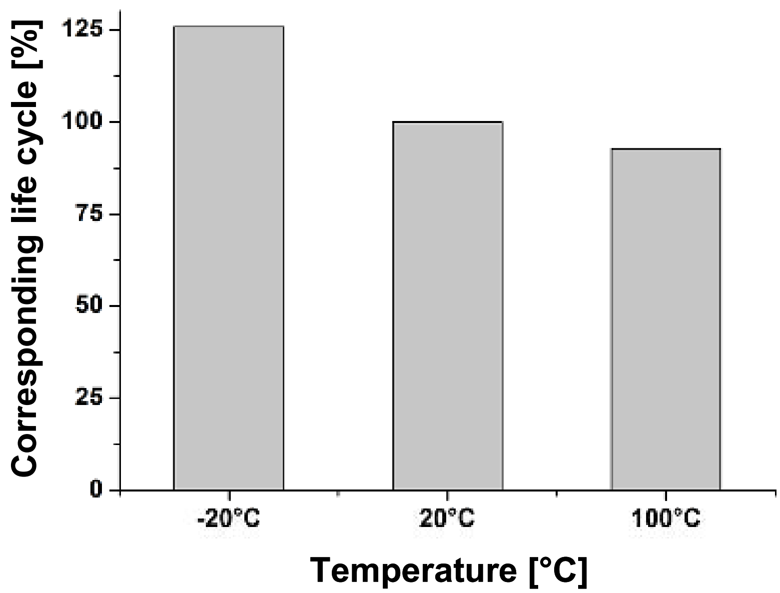

Figure 7. Increase in corresponding life cycle for cold forming temperatures.

3.4. Martensite content for different forming temperatures

For the different stainless steels EN 1.4301, EN 1.4318 and EN 1.4372 the martensite content of the reinforcements was determined by the eddy-current testing system Feritscope. Caused by the different metastable phases of the stainless steels, various martensite contents could be realized in the materials.

In Figure 8 is the correlation of the martensite content against forming temperature displayed. The trend lines show exponential curves with highest martensite contents at cold temperatures below room temperatures. For these steels, the dependency of martensite formation on the forming temperature could be described in the following functions.

For the materials, the following equations could be ascertained for the description of the transformation mechanism:

$$y_{EN1.4301}(x) = 10.46\ e^{-0,0226x}$$
$$y_{EN1.4318}(x) = 17.607\ e^{-0,0107x}$$
$$y_{EN1.4372}(x) = 3.8406\ e^{-0,0229x}$$

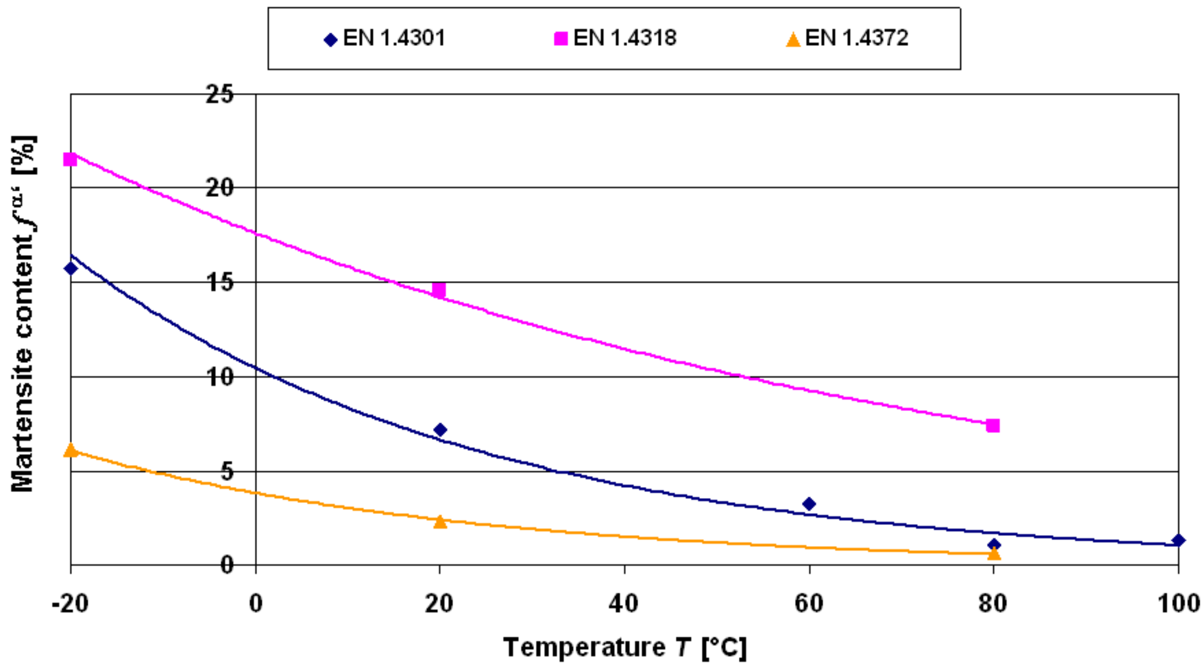

Figure 8. Diagram of the determined martensite content against the temperature at constant strains and stresses for the materials EN 1.4301, EN 1.4318 and EN 1.4372.

It can clearly be seen, that the martensite content due to the strain-induced phase transformation can be increased by lower temperatures. For the material EN 1.4301, the martensite content can be redouble, comparing the forming temperatures *T* = 20°C and *T* = -20°C. At a temperature of *T* = 80°C, it is possible to suppress nearly the martensite transformation in the stainless steels EN 1.4301 and EN 1.4372.

4 CONCLUSIONS

The presented results are leading to the conclusion, that a higher martensite content and therefore an increase in phase transformation can be achieved caused by forming temperatures below room temperature. Moreover, this accompanied with an increase in hardness and strength in local reinforcements. The increase in α'-martensite does not effect the residual stresses and the life cycle behavior negatively. Moreover, an advanced life cycle behavior for forming temperatures of about *T* = -20°C is determined.

Investigations regarding the metastable phase of three stainless steel grades, results in a description of the exponential trends of phase transformation.

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