CRYOGENIC SHEET METAL FORMING FOR AN ADVANCED MATERIAL BEHAVIOR

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Abstract. *The use of stainless steels in sheet metal parts is established in buses, subways and trains due to their low maintenance costs in combination with convincing material properties for a long term use. However, these steels are also increasingly becoming attractive for automotive applications. The combination of a perfect surface, the easy removal of graffiti, increasing fire-resistance and a good crash resistance explain the broad usage of this material. Considering the reduction in maintenance and the long-term usage of these steel grades, promising ways to cost reductions are opened. Moreover, it is also possible to realize a light-weight design by implementing metastable austenitic stainless steels with locally optimized material properties.*

The change in lattice during forming operations occurs in metastable austenitic steels caused by the strain-induced alpha'-martensite formation. Therefore, local high strength martensitic reinforcements can be produced in this austenitic ductile material. Temperatures below room temperature enforce the effect of the phase transformation while the transformation from fcc to bcc can be avoided above 60°C. In one project at the IFUM, martensitic reinforcements were applied to increase the crash energy absorption of sheet parts in transportation vehicles. Moreover, a positive influence regarding the folding behavior as well as the force-distance-progression could be determined. The implementation of the martensitic reinforcements enables a reduction of additional material weight for e.g. patches or the increase in sheet thickness.

For an advanced usage of strain-induced phase transition in deep drawing processes, a thermomechanical forming tool was developed. Thus, it is possible to realize low temperatures down to -20°C within the tool to increase the martensite content in defined areas of the blank by providing a constant true strain. Further investigations show that the alpha'-martensite content is also depending on the rolling direction and the state of stress.

To optimize the existing process, additional investigations are carried out considering the stainless steel EN 1.4301. The flow curves of tensile tests are accomplished at different strain rates applied at a test temperature of about T = -10°C to ascertain the influence of the temperature and alpha'-martensite on the material behavior. The martensite evolution for tensile stress loads is characterized by means of eddy-current measurements using a Feritscope. These investigations with respect to the material behavior aim at determining the optimum parameters to increase the martensite content in thermomechanical sheet metal forming processes. One intention is the modification of the existing forming tool regarding a liquid nitrogen (LN_2) cooling in combination with the forming velocity.

Keywords: *phase transition, alpha'-martensite formation, deep drawing, low forming temperatures*

1. INTRODUCTION

Stainless steel grades are well established in diverse industrial applications due to their good forming behavior, excellent ductility and corrosion resistance. These grades can be distinguished into ferritic, martensitic, austenitic and duplex stainless steel grades. Metastable austenitic stainless steels can transit from an austenitic lattice into an alpha'-martensitic microstructure, leading to a local increase in strength and stiffness. Caused by this martensitic transition, an increase of the flow curve is obvious. The change of microstructure can be suppressed by forming temperatures above T = 60°C. However, it is also possible to increase this martensite growth at room temperature and below. In order to realize a concerted content of alpha'-martensite to increase local material properties, tensile tests were carried out at a temperatures of about T = -10°C at the material EN 1.4301. To analyze the influence of different strain rates on the martensite evolution, tests were accomplished at three different velocities.

2. EXPERIMENTAL INVESTIGATIONS

2.1. Tensile tests at temperatures of about T = -10°C

To analyze the strain-induced alpha'-martensite evolution caused by uniaxial strain loads, tensile test are carried out at temperatures of about T = -10°C. The cooling of the specimen made of 1.4301 was realized by liquid nitrogen, with a boiling point at T = -195.8°C at an ambient pressure of p = 1.013 bar.

To realize the cooling of the specimens, a Dewar vessel, established for the transportation and short time storage of liquid gases, was used [Fig.1].

The tensile test specimen was dipped directly into the liquid within the Dewar vessel. At the beginning of the dipping, a boiling of the nitrogen is observed which also includes an increase in volume. Caused by this fact, a sufficient air ventilation is mandatory to reduce the risk of working accidents due to the asphyxiant properties of nitrogen.

Figure 1. Cooling of specimen in a Dewar vessel filled with liquid nitrogen.

The cooled tensile tests specimens were tested in the universal testing machine at the IFUM. To ensure reproducible thermal conditions during material characterization, the test is supervised by application of a tactile thermocouple element and an infrared camera.

2.2. Flow curves of the EN 1.4301 for different strain rates

The tests were carried out at a constant start temperature of about T = -10°C for three different strain rates. In addition to the standard test strain rate of 0.0083 1/s (according to DIN EN 10130 and DIN EN 10002), further strain rates of 0.0416 1/s and 0.0016 1/s were chosen.

Considering the stress-strain- curve progression of the material EN 1.4301, specimen tested at 0.0416 1/s differentiate at higher strain values from the ones tested at different strain rates, mainly. The shown ductility level at those strain rates cannot be reached at higher strain rates. Tested specimens exhibited an increase in ultimate strain of about 9 %. The tensile strength delivers increasing data, as well.

Tab. 1 presents the different material properties for the different strain rates of the material EN 1.4301 at a test temperature of about T = -10°C.

Table 1. Experimental results for the tensile tests at start temperatures of about T = -10°C for three different strain rates.

Strain rate [1/s]	0,0016	0,0083	0,0416
Tensile strength R_m [MPA]	868.9	856.3	820.6
Elastic limit $R_{p0.2}$ [MPA]	313.6	312.5	313.3
Ultimate strain A_{80} [%]	37.8	28.8	28.0

While gained data for the elastic limit $R_{p0.2}$ do not diversify for different strain rates, tensile strength properties exhibit different R_m values for the tested material. Higher strain rates are leading to a decrease in tensile strength. The material behavior is contrary to ultimate strains. Higher A_{80} values are resulting from slower strain rates.

The flow curves for these tests are shown in Fig. 2. The similar material behavior of all specimen is evident. At a true strain of about φ = 0.13, all specimens show an identic level. But by the starting point of plastic deformation, the flow curve with the lowest strain rate delivers the lowest curve progression till cracking occurs.

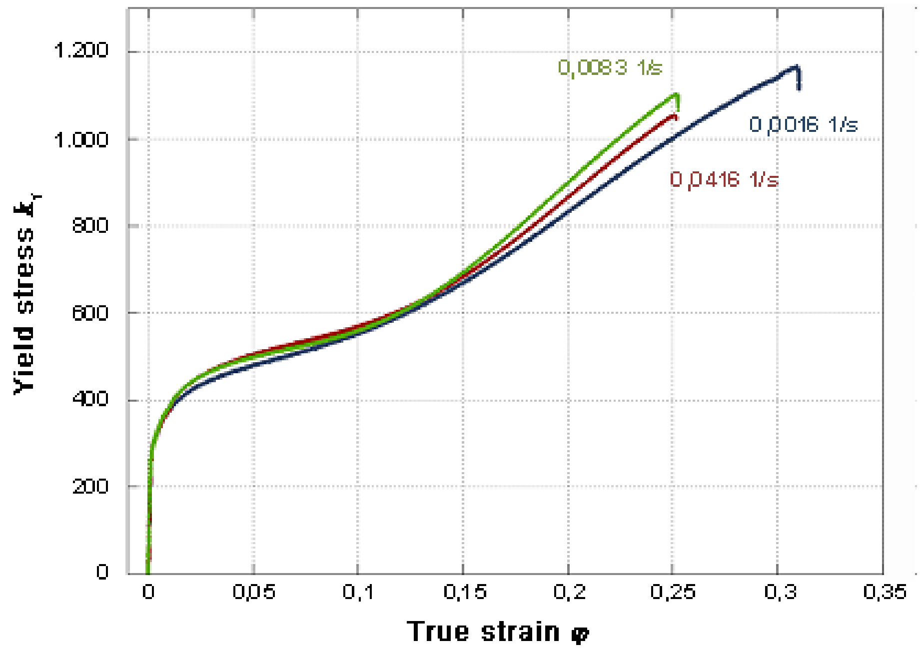

Figure 2. Flow curves for the tested material under different strain rate conditions.

2.3 alpha'-martensite evolution for different strain rates

The strain-induced alpha'-martensite content which was gained during the uniaxial forming process was evaluated by using the eddy-current testing system Feritscope from Fischer. After the transition of lattice the paramagnetic austenite changes into strain–induced martensite containing ferromagnetic material properties. By this probe, the ferromagnetic fraction of the transformed alpha'-martensite in the metastable austenitic specimen was measured before and after the test under consideration of the local sheet thickness. Applying these values, it is possible to calculate the local alpha'-martensite content percentage according to Springub 2005 [Fig. 3].

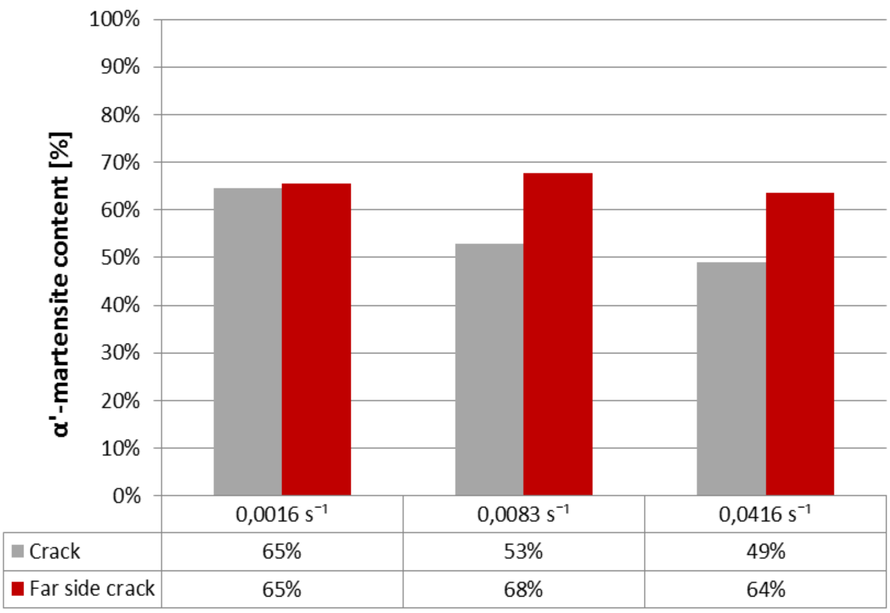

Figure 3. Martensite contents at crack and far side crack (average) for different strain rates at T = -10°C.

In order to analyze the martensite formation at different areas of the specimens, the martensite contents were analyzed at the very crack location. Additionally, an averaged value on the measuring length on the tensile test specimen's far side of the crack was determined. According to the investigations of Hecker et al., considering the martensite evolution at different strain rates at room temperature, the martensite fraction increases with lower strain rates. One discussed reason was the suggestion that higher strain rates may promote more irregular shear band arrays compared to the low strain rate.

In Fig. 3, the gained martensite contents are shown. All averaged values of the measuring lengths far side crack are at the same level, while a difference of the martensite content at the place of crack is obvious. At a strain rate of about 0.0016 1/s, the martensite content of crack and measuring length is nearly identical; whereas those values clearly differ for higher strain rates of about 15%. One reason for the different martensite contents at crack may be the differing material behavior considering the ultimate strain A_{80}, which shows higher values at lower strain rates.

3. CONCLUSION

In the progression of the yield stress a characteristic increase in flow curves at $\varphi \approx 0.13$ for the standard strain rate 0.0083 1/s and higher strain rate 0.0416 1/s is evident. This leads to the assumption that high forming velocities abet the strain-induced phase transformation. Thus, all tensile strength values for higher strain rates are decreasing in comparison to slower strain rates. In addition to the alpha'-martensite formation, several mechanisms affect the increase in strain-hardening and the influence the material behavior. Most of these mechanisms proceed with a limited velocity inside the microstructure. Caused by this fact, such mechanisms cannot proceed at higher strain rates or fast forming operations. Based on this assumption, tensile tests with a strain rate of about 0.0416 s^{-1} are resulting in a lower tensile strength than at a standard strain rate of about 0.0083 s^{-1}, representing a five times slower velocity.

Considering the specimen cooling, an increase in alpha'-martensite can be achieved. While standard tensile tests at room temperature often show average measuring length martensite contents of about 23%, a considerable raise could be realized. For reinforcement applications mentioned above, the use of liquid nitrogen enables an advanced realization of optimized local material properties in metastable austenitic stainless steels.

4. ACKNOWLEDGEMENTS

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