Effect of rolling strain on transformation induced plasticity of austenite to martensite in a high-alloy austenitic steel

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ABSTRACT

Current studies show a growing interest on transformation induced plasticity (TRIP) in austenitic steels. Most researches are based on inducing plasticity via tensile stresses, so it seems interesting to accomplish these researches by compressive stresses. Rolling process is a suitable choice to make compressive stresses. In present work, the effects of a wide range of rolling strains (5%–60%) at 0 and 24 °C on the austenite to martensite transformation were investigated on high-alloy austenitic steel. For this purpose, XRD, hardness test and magnetic measurements were used. Results show that by increasing the amount of rolling strain, transformation of austenite to martensite generally increases. The regime of this increase depends on the amount of the plastic deformation and temperature.

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1. Introduction

Austenitic steels are well-known because of their excellent formability even at room temperature. This type of steel can be highly strengthened with cold work processes (Fourlaris and Gladman, 1997; Davis, 1994; Byun et al., 2004). Austenitic steels are inherently paramagnetic but since martensite is a ferromagnetic phase the transformation of austenite to martensite makes them ferromagnetic (Spencer et al., 2004; Jacques, 2004). Plasticity may prepare driving force of this transformation in some austenitic steels. These steels are known as TRIP steels which is an acronym of transformation induced plasticity (Tsuchida and Tomota, 2000; Radu et

al., 2005). This transformation mainly depends on two factors (Fahr, 1971):

 (i) free energy difference between austenite and martensite,
(ii) external applied stress.

By decreasing deformation temperature, free energy difference between austenite and martensite increases. Consequently, smaller amounts of stresses are enough to occur martensitic transformation (Fahr, 1971; Perlade et al., 2003).

Volume fraction of transformed austenite shows the progress of TRIP phenomenon. It can be determined with various methods (Nagy et al., 2004; Berrahmoune et al., 2004; Zhao

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Table 1 – The chemical composition of the investigated austenitic steel

	Element							
	C	Cr	Ni	Mo	Mn	Si	Cu	V
Wt.%	0.17	10	7.8	4.8	2	2	0.1	0.07
	Element							
	Nb	Al	Co	Ti	P	S	Fe	
Wt.%	0.06	0.05	0.03	0.01	0.02	0.02	Rem	

Table 3 – Hardness of the samples

Sample	HV$_{(20)}$	Sample	HV$_{(20)}$
24TR5	479	0TR5	487
24TR10	508	0TR10	529
24TR20	572	0TR20	608
24TR30	593	0TR30	665
24TR40	632	0TR44	692
24TR50	661	0TR50	728
24TR60	666	–	–

et al., 2001; Seong et al., 2004; Van Dijk et al., 2005). Among these methods XRD is very common. Also, since martensite is ferromagnetic and austenite is paramagnetic, magnetic measurements can be used to determine the amount of the reaction progress.

TRIP phenomenon in austenitic steels have been highly investigated using tensile stresses (Byun et al., 2004; Spencer et al., 2004; Jacques, 2004; Tsuchida and Tomota, 2000; Radu et al., 2005; Fahr, 1971; Perlade et al., 2003; Nagy et al., 2004; Berrahmoune et al., 2004; Tsakiris and Edmonds, 1999; Wang et al., 2004; Wasilkowska et al., 2004; Lee et al., 2004; Jacques et al., 2001; De Cooman, 2004) but there is a little information about studying TRIP phenomenon under compressive stresses (Mumtaz et al., 2004). In this research we used rolling to apply compressive stresses to high-alloy TRIP steel in order to see the relationship between the amount of plasticity (rolling strain) and volume fraction of transformed austenite via TRIP phenomenon. Also, another purpose was to consider the hardness variation of the alloy with rolling strain at 0 and 24 °C.

2. Experimental procedure

The composition of the metastable austenitic stainless steel used in this study is presented in Table 1. Several bars of this alloy are produced under Argon atmosphere using an induction furnace. The bars were then homogenized at 1200 °C for 2 h. Then they were hot rolled at 450 °C in order to gain a 50% thickness reduction in one pass. The rolled samples were heat treated at 450 °C for 1 h. Then the samples were rolled from 5% to 60% (thickness reduction) at 0 and 24 °C. The conditions of samples are presented in Table 2. For this steel, in practice, it was impossible to continue rolling for more than 60% at mentioned temperatures.

In order to investigate the formation of martensite after rolling, magnetic measurement and XRD methods were used.

For XRD test Bruker D4 diffractometer with Cu Kα radiation was used. Alternating gradient force magnetometer (AGFM) with a sensitivity of 0.5 Orsted (1 Oe = $10^3/(4\pi)$ A/m) was used for estimating volume fraction of martensite. The magnetometer was calibrated for a 100% magnetization saturation using a martensitic structure obtained by quenching a CK45 steel from 850 °C in cold water, so that its microstructure was approximately 100% martensitic. Then various samples with different amounts of martensite were subjected to the test in order to measure the magnetization saturation (M_{sat}) from hysteresis loop of each sample. The volume fraction of martensite (f_α) was determined as follows (Zhao et al., 2001; Mumtaz et al., 2004):
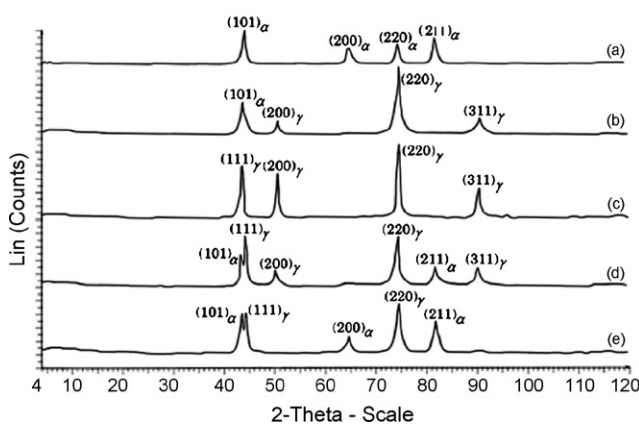
$$\%f_\alpha = \frac{M_{sat}(100\% \text{ mar}) - M_{sat}(x\% \text{ mar})}{M_{sat}(100\% \text{ mar})} \times 100 \tag{1}$$

$$\%f_\alpha = 100 - \%f_\gamma \tag{2}$$

The intensity of magnetic field was increased up to a maximum of 20000 Oe until it reached a saturation value. Finally the hardness of each samples determined using Vickers hardness test (20 kg load). The reported values in Table 3 are the average amounts of five records. For microstructure evolution, SEM study of the samples was performed using after the metallographic samples were electrolytically etched in Fry's reagent.

3. Results and discussion

The results of X-ray diffraction studies obtained for each of the samples are presented in Fig. 1. Spectrum(c) in Fig. 1 related to the sample that was heat treated at 450 °C for 1 h. This sample was approximately fully austenitic, but when it was rolled the intensity of austenite peaks gradually decreased and martensite peaks appeared in the spectrums (a, b, d, e). These spectrums show the higher the amount of thickness reduction the more the numbers and the intensity of martensite peaks.

Table 2 – Sample codes

Code of the samples tested at 24 °C	Thickness reduction (%)	Code of the samples tested at 0 °C	Thickness reduction (%)
24TR5	5	0TR5	5
24TR10	10	0TR10	10
24TR20	20	0TR20	20
24TR30	30	0TR30	30
24TR40	40	0TR44	44
24TR50	50	0TR50	50
24TR60	60	–	–

Fig. 1 – **Typical XRD spectra of the samples. (a) 0TR44, (b) 0TR10, (c) Heat treated sample at 450 °C, (d) 24TR10 and (e) 24TR40.**

So for the same amount of thickness reduction, martensitic transformation was more for the samples rolled at 0 °C. This means that the transformation rate of the material at 0 and 24 °C was different.

The amount of martensite formation not only depends on the amount of applied strain but also on the density of dislocations and area percentage of austenite grain boundaries (Spencer et al., 2004; Tsuchida and Tomota, 2000; ASM, 1995). So by increasing the amount of deformation the dislocation density increased within the austenite matrix which in turn caused an increase in the stability of austenite. This reduced the transformation rate of austenite to martensite. Therefore, although an increase in the amount of deformation increases the volume fraction of transformation, it seems that this increase occurred with a reducing rate.

The average hardness of the heat treated sample at 450 °C before cold rolling was 450 HV. Table 3 and Fig. 2 show the variation of hardness versus percentage of thickness reduction of the samples. Table 3 also shows the difference of hardness between samples which were rolled at 0 and 24 °C. This figure indicates that by increasing the amount of deformation, the rate of increase in hardness reduces. This phenomenon occurred due to lower rate of martensitic transformation at higher strains.

Increase in hardness in this type of transformation can either be due to increase in dislocation density within the austenitic matrix which provides better conditions for transformation of austenite to martensite or by increasing in twin boundaries. In addition, by increasing the amount of deformation, the hardness of the matrix increases because of higher formation of dislocation and their interaction with each other, but this causes more stability in austenite which in turn causes a lower rate of martensitic transformation. So, at higher amounts of strain it is expected that the rate of increasing of hardness reduces as a result of the reduction in the rate of martensite formation.

Fig. 2 also shows that the average hardness values of the samples rolled at 0 °C are higher than those rolled at 24 °C. According to Table 3, the difference in hardness between the
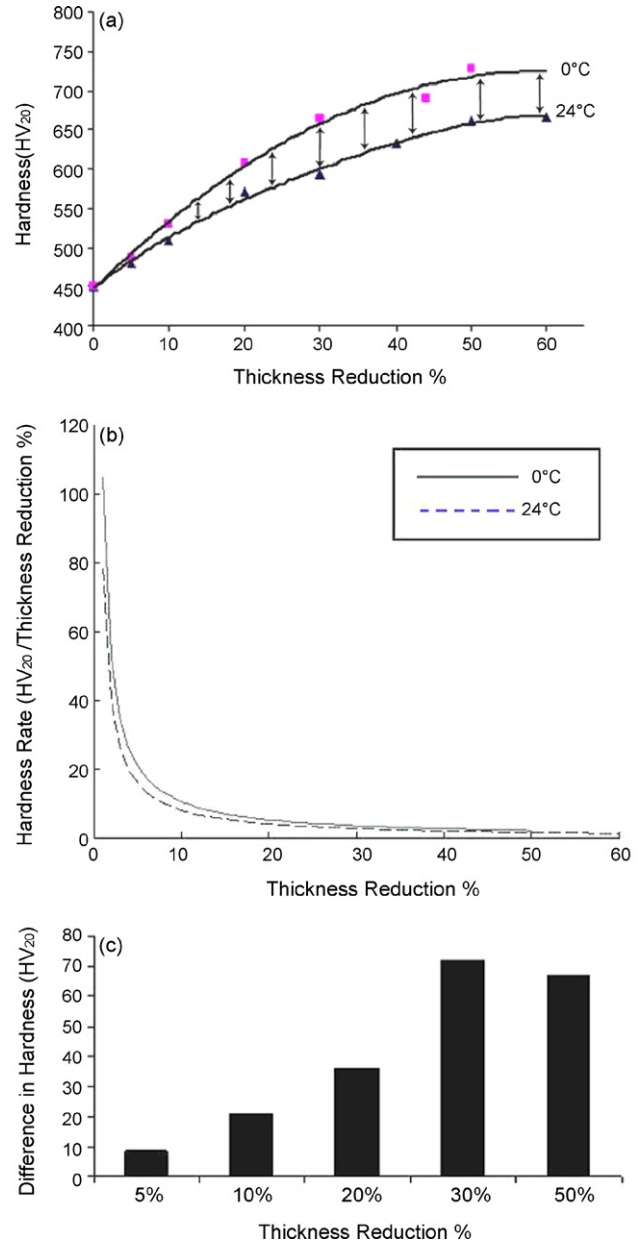
Fig. 2 – **(a) Hardness of the samples as a function of their thickness reductions at 0 and 24 °C, (b) hardness rate as a function of thickness reduction and (c) hardness difference between 0 and 24 °C samples at different thickness reductions.**

samples rolled at 0 and 24 °C for up to about 30% reduction increased, while for higher reduction it remained approximately constant. This might be due to a balance in dislocation density and the rate of martensite formation on the hardness of the samples after 30% reduction, while below this amount of reduction, the effect of martensite formation rate on hardness was more than dislocation density effect. So, according to Fig. 2 higher rate of martensite formation on the samples rolled at 0 °C leads to higher amounts of hardness of these samples compared to those rolled at 24 °C. Therefore, this might be an indication that the influence of martensite forma-
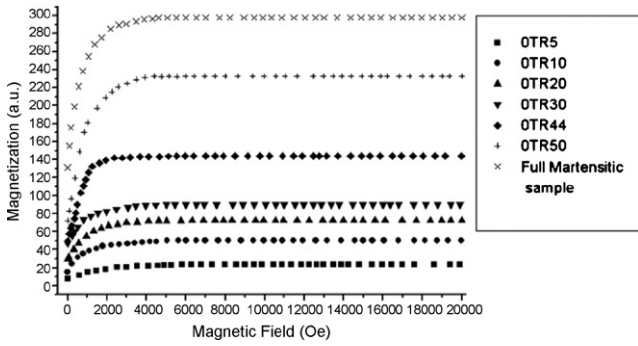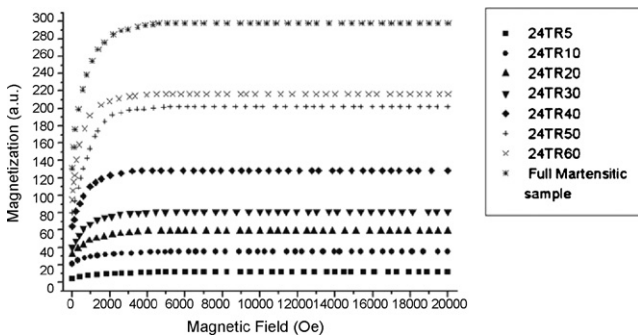
Fig. 3 – Magnetization plotted versus magnetic field for approximately full martensitic sample and samples with 10% to 50% thickness reductions at 0 °C.

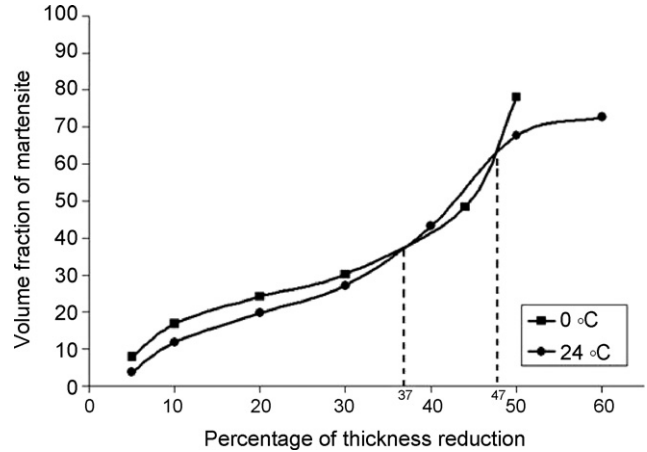**Fig. 5 – Volume fraction of martensite versus thickness reduction of the samples.**

tion at a thickness reduction below 30% was more than that of dislocation density. However, for a thickness reduction more than 30%, due to decrease in the rate of martensite formation, it seems that the role of dislocation in hardness increased, so that the differences between the hardness values, Fig. 2, reduced substantially.

AGFM test was performed to find out the percentage of martensite volume fraction in various conditions. Quarters of hysteresis loops obtained for samples at two temperatures are presented in Figs. 3 and 4. These figures show the magnetization (M_{sat}) of the samples as a function of the applied magnetic field for samples deformed at 0 and 24 °C. The analyzed results of AGFM test are presented in Fig. 5. It shows that by increasing the amount of reduction, the amounts of austenite transformed to martensite increased and the amount of martensite formed in the samples rolled at 0 °C was more than those rolled at 24 °C up to 37% of reduction.

According to Figs. 2 and 5, in spite of increasing hardness in all rolled samples with increasing the amount of reduction, the rate of increasing martensite was non linear. Volume fraction of martensite as a function of thickness reduction for the samples rolled at 24 °C apparently changed in four regimes. Up to 10% reduction, the rate of increase in volume fraction of martensite decreased, then it became linear up to 30% of reduction, then, increased up to 50% and finally it decreased substantionally. Similar behavior was observed in the sam-

ples rolled at 0 °C with a difference shown in Fig. 5. The rate of martensite formation up to 10% reduction decreased, and then it minimized between 10% and 30% of reduction and increased sharply for more reduction. Despite uniformity in hardness, increased by thickness reduction percentage, the rate of formation of martensite changed in a non-uniform mood. In the other word, increase in volume percentage of martensite and dislocation density balanced each other in such a way that resulted in a uniform increase in hardness.

A typical microstructure image of sample 24TR50 is shown in Fig. 6. This figure shows stress regions induced by the nano-scale martensite laths appeared in the form of bands
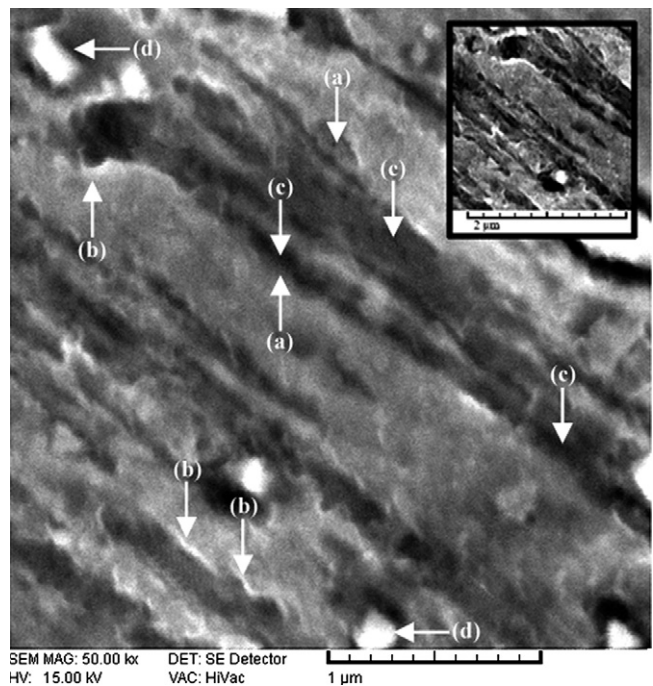

Fig. 4 – Magnetization plotted versus magnetic field for approximately full martensitic sample and samples with 10% to 60% thickness reductions at 24 °C.
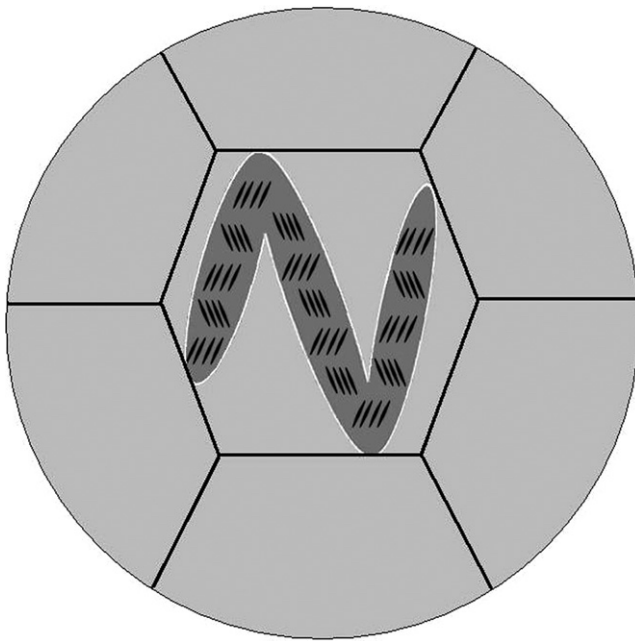

Fig. 6 – SEM micrograph of sample 24TR50 (a) stress induced zone, (b) interface of stress induced zone and matrix, (c) transformed austenite and (d) residual carbides.

White: Interface of Matrix and stress induced zone   Black: Transformad Austenite
Dark Gray: Stress induced zone   Gray: Austenitic Matrix

Fig. 7 – Schematic presentation of the stress induced zone, nano-scaled martensite and interface of stress induced and matrix within a grain.

within the austenite matrix. Fig. 7 schematically illustrates the microstructural changes of Fig. 6. This type of behavior was also reported by Zaefferer et al. (2004) that due to small size of martensite laths, their direct observation by SEM is very difficult but their stress field can be observed much easier via SEM.

4. Conclusions

1. The amount of martensite formation due to plastic deformation for the austenitic steel rolled at 0 °C was higher than that rolled at 24 °C for up to 37% thickness reduction.
2. Volume fraction of martensite obviously increased up to 50% thickness reduction at 24 °C. Higher amounts of thickness reduction had no considerable effects on martensite volume fraction.
3. The hardness of the samples rolled at 0 and 24 °C continuously increased with thickness reduction but with a reducing rate.
4. The hardness of the samples rolled at 0 °C was more than those rolled at 24 °C for the same amount of thickness reduction. However, it seems the effect of cold rolling at 0 °C on increasing the hardness of the sample was more than the amount of austenite transformed to martensite within the thickness reduction of 37%–47%.

REFERENCES

ASM, 1995. Martensitic Structure, ASM Handbook, vol. 9., ninth ed, pp. 668–675.

Berrahmoune, M.R., Berveiller, S., Inal, K., Moulin, A., Patoor, E., 2004. Analysis of the martensitic transformation at various scales in TRIP steel. Mater. Sci. Eng. A 378, 304–307.

Byun, T.S., Hashimoto, N., Farrell, K., 2004. Temperature dependence of strain hardening and plastic instability behaviors in austenitic stainless steels. Acta Mater. 52, 3889–3899.

Davis, J.A., 1994. Carbon and Alloy Steels: ASM Specialty Handbook, first ed. ASM, pp. 1–12.

De Cooman, B.C., 2004. Structure-properties relationship in TRIP steels containing carbide-free bainite. Curr. Opin. Solid State Mater. Sci. 8, 285–303.

Fahr, D., 1971. Stress- and strain-induced formation of martensite and its effects on strength and ductility of metastable austenitic stainless steels. Metall. Trans. 2, 1883–1892.

Fourlaris, G., Gladman, T., 1997. Microscopical characterisation of martensite formation in a metasteble austenitic stainless steel. J. Phys. IV 7, 423–428.

Jacques, P.J., 2004. Transformation-induced plasticity for high strength formable steels. Curr. Opin. Solid State Mater. Sci. 8, 259–265.

Jacques, P., Furnemont, Q., Pardoen, T., Delannay, F., 2001. On the role of martensitic transformation on damage and cracking resistance in TRIP-assisted multiphase steels. Acta Mater. 49, 139–152.

Lee, C.G., Kim, S.-J., Lee, T.-H., Lee, S., 2004. Effects of volume fraction and stability of retained austenite on formability in a 0.1C–1.5Si–1.5Mn–0.5Cu TRIP-aided cold-rolled steel sheet. Mater. Sci. Eng. A 371, 16–23.

Mumtaz, K., Takahashi, S., Echigoya, J., Kamada, Y., Zhang, L.F., Kikuchi, H., Ara, K., Sato, M., 2004. Magnetic measurements of martensite transformation in austenitic stainless steel after room temperature rolling. J. Mater. Sci. 39, 85–97.

Nagy, E., Mertinger, V., Tranta, F., Solyom, J., 2004. Deformation induced martensitic transformation in stainless steels. Mater. Sci. Eng. A 378, 308–313.

Perlade, A., Bouaziz, O., Furnemont, Q., 2003. A physically based model for TRIP-aided carbon steels behaviour. Mater. Sci. Eng. A 356, 145–152.

Radu, M., Valy, J., Gourgues, A.F., Le strat, F., Pineau, A., 2005. Continuous magnetic method for quantitive monitoring of martensitic transformation in steels containing metastable austenite. Scr. Mater. 52, 525–530.

Seong, B.S., Shin, E.J., Han, Y.S., Lee, C.H., Kim, Y.J., Kim, S.J., 2004. Effect of retained austenite and solute carbon on the mechanical properties in TRIP steels. Phys. B 350, 467–469.

Spencer, K., Embury, J.D., Conlon, K.T., Veron, M., Brechet, Y., 2004. Strengthing via the formation of strain-induced martensite in stainless steels. Mater. Sci. Eng. A 387–389, 873–881.

Tsakiris, V., Edmonds, D.V., 1999. Martensite and deformation twinning in austenitic steels. Mater. Sci. Eng. A 273–275, 430–436.

Tsuchida, N., Tomota, Y., 2000. A micromechanic modeling for transformation induced plasticity in steels. Mater. Sci. Eng. A 285, 345–352.

Van Dijk, N.H., Butt, A.M., Zhao, L., Sietsma, J., Offerman, S.E., Wright, J.P., van der Zwaag, S., 2005. Thermal stability of retained austenite in TRIP steels studied by synchrotron X-ray diffraction during cooling. Acta Mater. 53, 5439–5447.

Wang, Z.C., Kim, S.J., Lee, C.G., Lee, T.H., 2004. Bake-hardening behavior of cold-rolled CMnSi and CMnSiCu TRIP-aided steel sheets. J. Mater. Process. Technol. 151, 141–145.

Wasilkowska, A., Tsipouridis, P., Werner, E.A., Pichler, A., Traint, S., 2004. Microstructure and tensile behaviour of cold-rolled TRIP-aided steel. J. Mater. Process. Technol. 157–158,633–636.

Zaefferer, S., Ohlert, J., Bleck, W., 2004. A study of microstructure, transformation mechanisms and correlation between

microstructure and mechanical properties of a low alloyed TRIP steel. Acta Mater. 52, 2765–2778.

Zhao, L., Van Dijk, N.H., Bruck, E., Sietsma, J., Van der Zwaag, S., 2001. Magnetic and X-ray diffraction measurements for the determination of retained austenite in TRIP steels. Mater. Sci. Eng. A 313, 145–152.