

Heat treatment and mechanical stability behaviour of medium-carbon TRIP-aided bainitic steel

A. Grajcar *

Division of Constructional and Special Materials, Institute of Engineering Materials and Biomaterials, Silesian University of Technology, ul. Konarskiego 18a, 44-100 Gliwice, Poland

* Corresponding author: E-mail address: adam.grajcar@polsl.pl

Received 05.05.2008; published in revised form 01.09.2008

ABSTRACT

Purpose: The aim of the paper is to determine the influence of the isothermal holding conditions in a range of bainitic transformation on the mechanical stability of retained austenite for medium-carbon TRIP-aided steel.

Design/methodology/approach: The examinations were carried out on medium-carbon steel containing 0.55% C and 1.35% Si. The conditions of heat treatment consisted of isothermal quenching of the specimens to a temperature range of 250 to 550°C, where they were held for 600 and 1800 s. Tensile deformation of steel to the given strain equal 0.25, 0.5 and 0.75 of total elongation of samples was conducted in order to determine the kinetics of retained austenite transformation into martensite. The retained fraction of the γ phase was determined by the use of the quantitative X-ray phase analysis.

Findings: Increasing the carbon concentration to 0.55% in TRIP-type steels makes possible to obtain very high strength properties without a deterioration of the ductility. The retained austenite of the 19% volume fraction can be obtained after the isothermal quenching of the steel to a temperature of 250°C. In these conditions, the matrix of the steel is the ferritic bainite. The size of regular grains of retained austenite is equal up to 3 μm , while the rest of γ phase is present in a form of thin films between individual laths of bainite. Diversification of retained austenite form has a reflection in its mechanical stability, connected with two-stage kinetics of martensitic transformation of γ phase.

Research limitations/implications: To determine with more detail the stability of retained austenite the knowledge of lattice parameter changes with an isothermal holding temperature is needed.

Practical implications: The proposed heat treatment can be useful for manufacturing reinforced structural elements characterized by high strength and ductile properties in the automobile industry.

Originality/value: The developed conditions of the heat treatment concern the medium-carbon TRIP-type bainitic steel, offering higher product of UTS UEI compared with usually investigated TRIP-type ferritic-bainitic steels.

Keywords: **Metallic alloys; Heat treatment; TRIP-effect; Bainitic steel; Retained austenite; Mechanical properties**

MATERIALS

1. Introduction

Increasing demands of automotive industry concerning production of cars utilizing small quantity of fuel and emitting

limited amounts of exhaust gas into the environment as well as improvement of passive safety of passengers have led, in recent twenty years, to the development of several groups of steels which with success compete with more and more important light

metal alloys and polymer composite materials. The variety of cars and other vehicles produced determines the necessity of manufacturing the weldable plates, hot-rolled or cold-rolled sheets and other products, characterized by various tensile strength and formability depending on the structure. The end of twentieth century was characterized by substantial increase of use of microalloyed steels produced in integrated processing lines [1, 2]. Whereas, the answer of material engineers on the demands of automotive industry of the beginning of XXI century are multiphase steels [3-5]. These steels are used for production of sheets with diversified thickness for body parts and numerous reinforcing elements. Very important aspects of their usage are places in which controlled absorption of energy should occur during an accident. Advantageous mechanical and technological properties decide about suitability of these steels for mentioned parts. Profitable strength to density proportion and a very good combination of high strength and high ductility have crucial meaning. In the aspect of safety, particular significance has a high value of strain hardening coefficient, deciding about high ability of energy absorption in the conditions of dynamic load [3, 6, 7].

Multiphase steels strengthened through TRIP (Transformation Induced Plasticity) effect are a modern solution [8-15]. These steels are characterized with ferritic-bainitic microstructure with retained austenite, which undergoes martensitic transformation during technological forming of products, additionally contributing to the strengthening of a ready part. Steels strengthened through TRIP effect usually consist of around 0.2% C, 1-2% Mn and approximately 1.5% Si. Participation of retained austenite, usually being equal from 10 to 15%, has decisive meaning for obtaining high strength and ductility of these steels. It generally depends on carbon concentration in austenite, increasing in individual production stages of sheets made of this group of steels. Thermodynamic stability of retained austenite is defined by the temperature of martensitic transformation start M_s . The fact that M_s is decreasing in the individual stages of cooling should be taken into account during planning of cooling conditions. It's occurring during soaking of sheets in a range of $\gamma+\alpha$ or during slow cooling from the temperature of hot-working finish. A successive stage of M_s temperature decrease is soaking of sheets in the range of isothermal bainitic transformation during which further enrichment of γ phase in carbon proceeds. When the concentration of carbon in retained austenite is too low, martensitic transformation occurs already during cooling or in the early stage of technological deformation. Because of that, the conditions of heat treatment should be optimized every time for a specific grade of TRIP-type steels. It was found in [12, 13] that the size and arrangement of retained austenite, strength of matrix and state of stress have additional influence on initiation of martensitic transformation.

Depending on required sheet thickness and specific application, TRIP-type steels are manufactured through intercritical annealing of cold rolled sheet with successive isothermal holding in the range of bainitic transformation [11, 12, 14] or through energy-saving method of thermo-mechanical processing [7-10]. The latter requires a strict control of time-temperature conditions during cooling after rolling is finished. It was stated in [6, 15] that the steel sheets with ferritic matrix show low stretch-flangeability under conditions of tensile stresses,

especially in case of application for some parts of chassis. Hence the interest in steels with bainitic matrix with increased concentration of carbon, in which the lack of plastic ferritic matrix can be levelled through increase of retained austenite portion and more effective usage of gradual transformation of γ phase into martensite during cold plastic deformation. Results of the determination of the stability of retained austenite for low-carbon steels are reported by many authors [6, 12-14]. There are not many works concerning the mechanical stability of the γ phase for medium-carbon steels [15].

The aim of the paper is to determine the influence of the isothermal holding temperature and time in a bainitic range of medium-carbon steel on the stability of retained austenite.

2. Experimental procedure

The examinations were carried out on medium-carbon steel containing 0.55% C, 1.35% Si, 0.59% Mn and 0.59% Cr (Table 1). The steel was subjected to secondary metallurgy in a liquid state and successively continuous cast into slabs with 100x100 mm section. The final result of hot-rolling were 12 mm diameter bars. They were used for preparation of samples for structural examinations and static tensile test.

Table 1.
Chemical composition of the investigated steel

Mass contents in percentage (%)								
C	Si	Mn	Cr	Ni	Cu	S	P	Al
0.55	1.35	0.59	0.59	0.07	0.13	0.010	0.015	0.027

The conditions of heat treatment for investigated steel were selected in consideration of A_{c3} and M_s critical temperatures determined basing on Andrew's dependence [16]. They are equal: $A_{c3}=818^\circ\text{C}$ and $M_s=280^\circ\text{C}$, respectively. After austenitizing of samples in temperature of 840°C for 18 min, they were cooled in oil till the temperature of isothermal bainitic transformation even from 250 to 550°C . The purpose of applied cooling rate was to eliminate the possibility of transformation of part of austenite into ferrite or pearlite. The specimens were held in the temperature of bainitic transformation for 600 and 1800 s. The final stage of the heat treatment was cooling the samples to room temperature with a rate of approximately 1°C s^{-1} . The scheme of performed heat treatment is presented in Fig. 1.

In order to reveal microstructure of the steel, giving particular consideration to retained austenite, etching in LePera reagent was performed [17]. Microscopic observations were conducted on Leica MEF4a microscope, at 1000x magnification. Microstructure observations of thin foils were performed in JEM-200CX transmission electron microscope at 120 kV of accelerating voltage. The identification of retained austenite was additionally achieved using X-ray qualitative and quantitative phase analysis. Examinations were done using DRON2.0 diffractometer and cobalt anode. In order to evaluate the participation of retained austenite, Averbach-Cohen method was implemented [18].

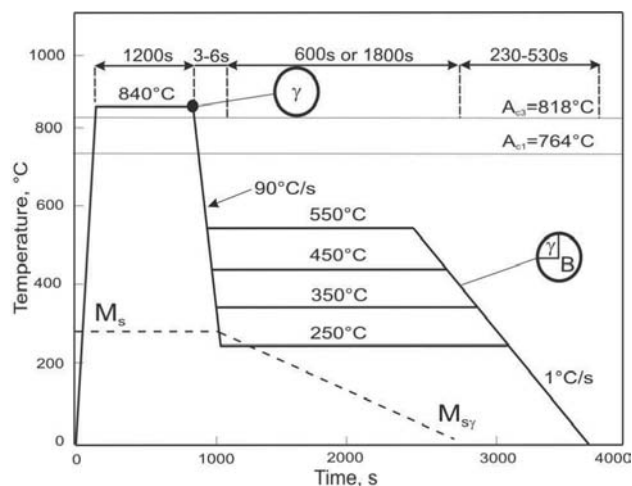


Fig. 1. Heat treatment of the investigated steel; M_s – martensite start temperature of the steel, M_{sy} – martensite start temperature of the austenite with increased carbon concentration

Static tensile test was performed on 6 mm diameter quintuple specimens using Zwick Z/100 testing machine. Deformation of steel to the given deformation equal 0.25, 0.5 and 0.75 of total elongation of samples was conducted in order to determine the kinetics of retained austenite transformation into martensite. The retained fraction of the γ phase was again determined by the use of the quantitative X-ray phase analysis.

3. Results and discussion

The temperature of isothermal bainitic transformation has decisive meaning for bainite morphology, formed during cooling of samples from the temperature of 840°C. Cooling down of steel to the lowest temperature applied equal 250°C results in obtaining ferritic bainite in the conditions close to martensitic transformation. Application of temperature slightly lower than M_s temperature causes that apart from laths of bainite, also a certain portion of martensite can be observed in microstructure (Fig. 2). Applied conditions allowed for thermal stabilization of over 19% of retained austenite to room temperature. Such an amount of the γ phase was obtained due to a lack of carbide particles in the structure of steel. Increasing the isothermal holding time in a bainitic range to 1800 s resulted in carbide precipitation and decreasing a fraction of the retained austenite to 15.5% (Fig. 3). The retained austenite has a various morphology. A part of the retained austenite occurs as multi-angular grains with a size of up to 3 μm . Their boundaries are packets of ferritic bainite laths. Another part of the γ phase has a shape of thin plates located between bainite laths. The refinement of the retained austenite grains for the specimens held at a temperature of 250°C for 1800 s was observed.

Increasing the isothermal holding temperature of the steel to 350°C results in a change from the ferritic bainite to lower bainite, even for specimens held at the bainitic transformation

temperature for 600 s (Fig. 4). However, a fraction of the retained austenite is still high amounting 17.7%. In the previous investigations [19], it was found that under these conditions is possible to obtain even to 24% of the γ phase. Further increasing the holding temperature of the steel in a bainitic range to 450°C results in a further change of the bainite morphology. For this temperature, it is the upper bainite (Fig. 5). A fraction of the retained austenite decreases to 13.6%. Increasing the isothermal holding temperature of the steel to 550°C causes decreasing of the γ phase fraction to 7% due to cementite precipitation, being locally a part of pearlite (Fig. 6). It is in agreement with the works of other authors [20, 21]. Results of the decreasing volume fraction of retained austenite with increasing the isothermal holding temperature and time are summarized in Table 2.

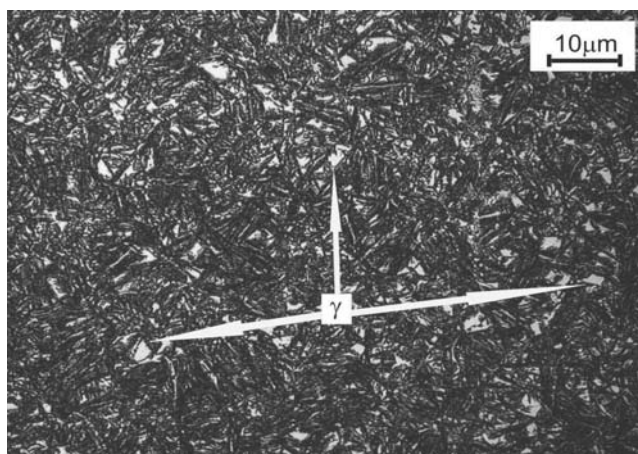


Fig. 2. Structure of the ferritic bainite with the retained austenite for the steel quenched to a temperature of 250°C (holding time: 600 s)

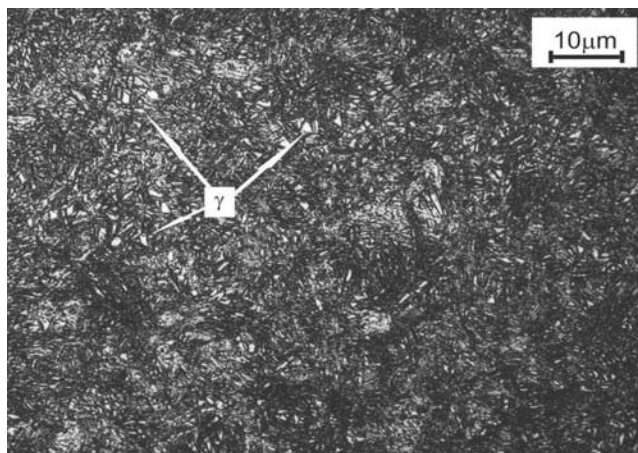


Fig. 3. Structure of the lower bainite with the retained austenite for the steel quenched to a temperature of 250°C (holding time: 1800 s)

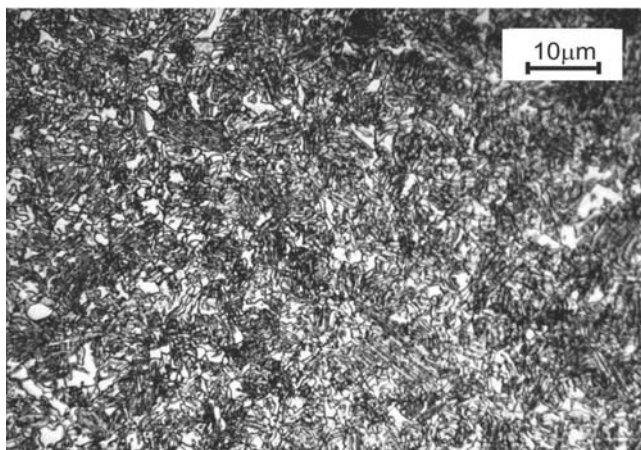


Fig. 4. Structure of the lower bainite with the retained austenite for the steel quenched to a temperature of 350°C (holding time: 600 s)

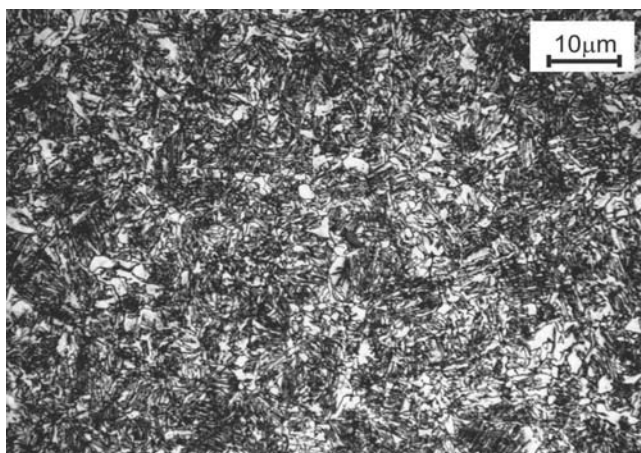


Fig. 5. Structure of the upper bainite with the retained austenite for the steel quenched to a temperature of 450°C (holding time: 600 s)

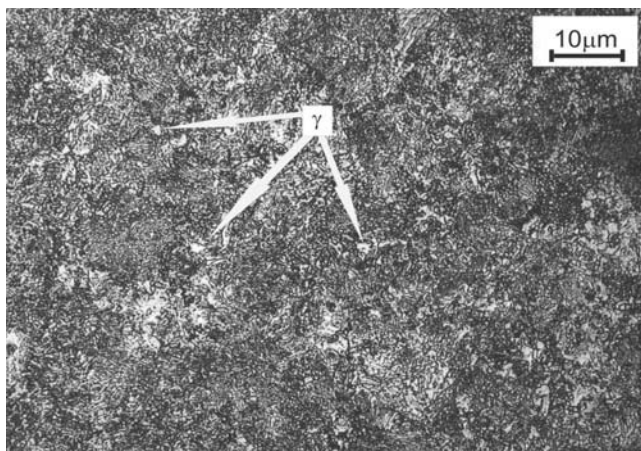


Fig. 6. Structure of the upper bainite with the retained austenite for the steel quenched to a temperature of 550°C (holding time: 600 s)

Table 2.

Volume fraction of retained austenite for various temperature – time conditions

Isothermal holding temperature, °C	Isothermal holding time, s	Volume fraction of retained austenite, %
250	600	19.2
	1800	15.5
350	600	17.7
	1800	12.7
450	600	13.6
	1800	6.8
550	600	7.1
	1800	4.2

Confirmation of diversified morphology of retained austenite was achieved in examinations of thin foils in transmission electron microscope. Retained austenite is present most often in a form of films between individual laths of bainite (Fig. 7) or as bigger polygonal grains. Temperature increase of isothermal bainitic transformation to 350°C leads to a change of morphological characteristics of retained austenite. The γ phase still occurs as thin films between laths of the lower bainite or as elongated grains located between packets of bainite laths (Fig. 8). The size of the largest regular grains is up to 3 μm (Fig. 9). The regular multi-angular shape of the retained austenite particles is probably a result of the influence of growing diffusionless products of the supercooled austenite on boundaries of the γ phase. Increasing the isothermal holding temperature to 450°C results in obtaining the upper bainite with apparent precipitations of carbides on the boundaries of particular laths (Fig. 10). It influences a drop of the retained austenite stability displaying in the decrease of the γ fraction to 13.6% for an isothermal holding temperature of 450°C. The further drop of the stability of the γ phase is caused by extending the isothermal holding time. Decreasing of the retained austenite fraction to 6.8% is associated with the Fe_3C precipitation. For the temperatures of 350°C and 450°C the carbides have a shape of fine spherical particles or plates (Fig. 10). For a temperature of 550°C the steel has a structure of the upper bainite with distinct lamellar carbide particles located between particular laths (Fig. 11).

It is apparent from Figure 12 that considerably higher amounts of retained austenite are associated with the lower bainite transformation temperatures of 250 and 350°C. In contrast, at the high temperatures of 450 and 550°C the fraction of retained austenite decreases to 13.6% and 7.1%, respectively. This behaviour can be attributed to the faster bainite transformation kinetics at higher isothermal holding temperatures. Pietrzyk et al. [20] observed that depending on the temperature and time of bainitic transformation, a kinetics of the austenite decomposition can have 1, 2 or 3 stages. At the lowest transformation temperatures (250°C) two stages of the transformation are occurred. In the first stage, the austenite transforms into athermal martensite. It is confirmed by the structure in Figure 2. At the second stage of the transformation the bainitic ferrite is formed. In a temperature range of 350–450°C the austenite decomposition have three stages. Initially the bainitic ferrite is formed and then the transformation is partially or completely stopped. At the third stage the precipitation of carbides after the time dependent on a chemical composition of steel is started. The precipitation process results in

decreasing a fraction of retained austenite as well as a drop of its stability. Similar results are reported by Liu et al. [21], too.

The results demonstrated above, concern low-carbon steels containing about 0.2%C. However, the carbon content in the austenite increases up to 0.6-0.8% after intercritical annealing. It is close to a carbon concentration for the investigated medium-carbon steel. For this reason, the analogy concerning a similarity of the austenite decomposition under conditions of the isothermal bainite transformation can be applied. On the other hand, the higher carbon content in the steel can be a reason of some essential differences concerning the kinetics of the austenite decomposition. It seems to be that the ferritic bainite occurs only for the lowest isothermal holding temperature of 250°C. At the higher temperature of 350°C the carbon supersaturated in the ferritic bainite is partitioned into the retained austenite soon after a diffusionless transformation. However, carbide precipitation in the bainite intervenes to slow down the carbon diffusion to austenite. It was observed that a precipitation of fine carbides occurs for shorter times compared with TRIP-aided low-carbon steels.



Fig. 7. Retained austenite as films between the laths of the ferritic bainite (isothermal holding temperature: 250°C)

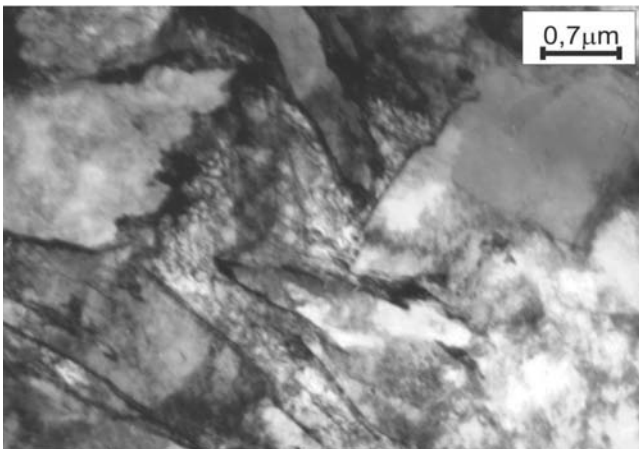


Fig. 8. Retained austenite as an elongated grain between packets of the lower bainite laths (isothermal holding temperature: 350°C)

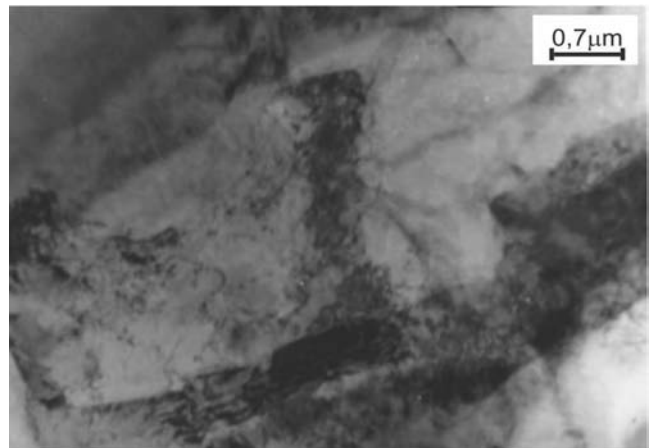


Fig. 9. Retained austenite as a regular grain (isothermal holding temperature: 350°C)



Fig. 10. Structure of the upper bainite with carbide particles on boundaries of particular laths (isothermal holding temperature: 450°C)

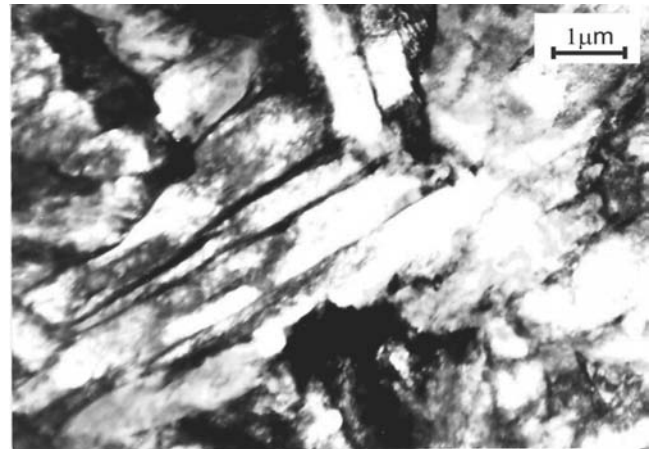


Fig. 11. Structure of the upper bainite with lamellar carbide particles between particular laths (isothermal holding temperature: 550°C)

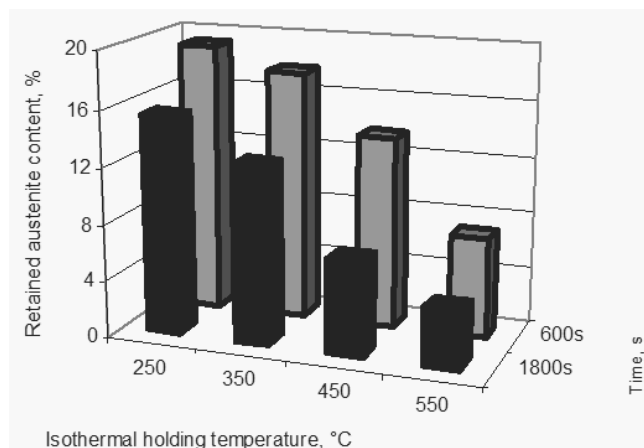


Fig. 12. Change in the retained austenite fraction as a function of temperature and time of the isothermal holding

The stabilization of high fractions of the retained austenite for the isothermal holding temperatures of 250°C and 350°C indicates a high carbon enrichment of the austenite during the isothermal $\gamma \rightarrow$ bainite transformation. It caused a lowering of the M_s temperature of the γ phase below room temperature. Of great importance is that a 1.35% Si content hampers the precipitation of carbides. It is in agreement with the SDLE hypothesis (Solute Drag-Like Effect) concerning the decreasing of the carbon activity in the austenite by segregating nearby the α/γ boundary silicon atoms. It results in decreasing the propelling force of the transformation and its hampering [20]. Lowering of the M_s temperature below room temperature in TRIP-aided steels with a ferritic – bainitic structure is possible due to the enrichment of the austenite in carbon during the $\gamma \rightarrow \alpha$ transformation and holding in a bainitic range. The enrichment of the γ phase in carbon in the investigated steel is only in progress under isothermal bainite transformation conditions. The calculations according to Andrews' equation [16] concerning the M_s temperature exhibited that a thermal stabilization of the retained austenite to room temperature requires the enrichment in carbon of the γ phase at least to a concentration of about 1.2%. It is in agreement with results of some works [5, 15], where the carbon concentration in the retained austenite in steels of similar chemical composition was investigated.

To summarize the influence of heat treatment conditions on a structure of the investigated steel it should be stressed that products of the transformation of austenite are strongly dependent on the temperature and time of the isothermal holding in a bainitic range. A matrix of the steel for a temperature of 250°C was the ferritic bainite. However, extending the holding time to 1800 s or increasing the isothermal transformation temperature to 350°C resulted in forming the classical lower bainite instead of the ferritic bainite. The conclusion is that the isothermal holding time for the investigated steel can not be too long. On the other hand when the extent of transformation to bainite is not sufficient, the retained austenite can transform to martensite during cooling to room temperature. The holding time should be precisely chosen for a given chemical composition and a temperature of isothermal holding. Increasing the isothermal holding temperature to 450°C

results in forming the upper bainite with distinct spherical or lamellar carbides on the boundaries of particular laths. Further increasing the isothermal holding temperature to 550°C enhances the precipitation process due to the progress of the bainite transformation having a detrimental influence on the stability of retained austenite. To determine with more detail the stability of retained austenite the knowledge of the variation of the austenite carbon content as a function of the bainitic isothermal transformation temperature and time is required. Lattice parameter measurements with X-ray diffraction is planned in the future for this purpose.

The tensile test was carried out for the specimens isothermally quenched to a temperature of 250°C, i.e. containing the highest fraction of the γ phase. It was found that the investigated steel possesses a very good balance between strength and ductile properties (Table 3). The proof stress is $Y_S = 960$ MPa and ultimate tensile strength $U_{TS} = 1210$ MPa. The high value of the ultimate tensile strength and beneficial Y_S/U_{TS} ratio are associated with a transformation of the retained austenite into martensite. The strain-induced martensitic transformation is confirmed by a fact that the uniform elongation equals to total elongation $U_{EI} = T_{EI} = 24\%$. The work-strengthening and progressing volume changes of the steel due to the martensitic transformation of the γ phase prevent a localization of the plastic deformation and necking in stretched samples.

Table 3. Mechanical properties of the investigated TRIP-aided bainitic steel quenched to a temperature of 250°C

	Y_S , MPa	U_{TS} , MPa	T_{EI} , %	U_{EI} , %	Y_S/U_{TS}	$U_{TS} \cdot U_{EI}$, MPa·%
Medium value	960	1210	24.3	23.7	0.79	28677
Standard deviation	± 10.5	± 25.8	± 1.2	± 1.2	± 0.02	± 1463

Investigations of the influence of plastic deformation to a given strain made possible to determine a mechanical stability of the retained austenite. It is apparent from Figure 13 that at the initial stage of the plastic deformation, a sudden drop in the amount of the retained austenite from 19% to 12% is occurred. It is due to the low mechanical stability of the γ phase. A further course of the curve indicates that a transformation rate of the austenite decreases. It was found that even after rupture, the fraction of the γ phase in the structure of the steel is about 7%. A similar character of the curve for a medium-carbon steel with a similar chemical composition was observed [22]. In spite of a higher initial fraction of the austenite, its amount decreases rapidly at the initial stage of the plastic deformation and then the character of the curve changes analogical to the investigated steel behaviour. A kinetics of the strain-induced martensitic transformation for low-carbon TRIP-aided steels with a ferritic – bainitic structure with the retained austenite is similar [14]. The two-stage course of the curve of the retained austenite transformation can be associated with a various morphology of the γ phase. Authors of the works [23, 24] suggest, that at the initial stage of the plastic deformation the equiaxed grains of the larger size and probably lower carbon concentration are transformed.

At the further stage of deformation the transformation of thin films is occurred. Another theory explains that the films of the retained austenite are not so susceptible to the strain-induced martensitic transformation due to the vicinity of hard bainite plates [25]. However, this problem for TRIP-aided steels with a bainitic matrix requires further detailed investigations.

To summarize, it was found that the mechanical stability of retained austenite is dependent on its morphology and size. Apostolos et al. [12] and Pietrzyk et al. [23] observed that together with increasing the isothermal holding temperature and time the mechanical stability of retained austenite is lower. The drop in austenite stability is attributed to carbide precipitation in the bainite making the austenite leaner in carbon. The conclusion for the investigated medium-carbon steel is that for the lowest bainite transformation temperature of 250°C the holding time in a bainitic range should be sufficient for an optimum enrichment of the retained austenite in carbon. For the higher temperatures of the bainite transformation the times should be shorter depending on a given chemical composition of the steel.

Apostolos et al. [12] indicate that apart from the morphology of the γ phase the mechanical stability of retained austenite is also dependent on the size of austenite particles. They observed that the stability rises at longer isothermal holding times due to the refinement of the retained austenite. As the bainite transformation progresses, the amount of retained austenite is decreased but the austenite dispersion becomes progressively finer. It is in agreement with the results obtained for the investigated steel isothermally quenched to a temperature of 250°C. Extending the holding time to 1800 s results in the initiation of carbide precipitation but the considerable refinement of the retained austenite particles is occurred simultaneously (Fig. 3), having a positive influence on the stability of the γ phase. In spite of the carbide precipitation the fraction of the γ phase decreases about 4% only, compared with the specimens held at a temperature of 250°C for 600 s (Fig. 12). The influence of the refinement of austenite particles on the mechanical stability of retained austenite for the medium-carbon steel requires further detailed investigations.

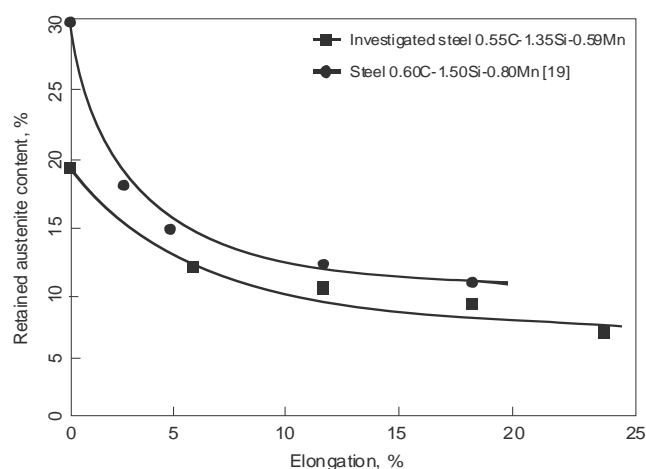


Fig. 13. Change in the retained austenite fraction as a function of elongation of the specimens

4. Conclusions

The carried out investigations showed that increasing the carbon concentration to 0.55% in TRIP-type steels makes possible to obtain very high strength properties without a deterioration of the ductility, compared to most often used steels containing about 0.2%. The retained austenite of the 19% volume fraction can be obtained after the isothermal quenching of the steel to a temperature of 250°C. In these conditions, the matrix of the steel is the ferritic bainite. Increasing the isothermal holding temperature to 350°C or holding time to 1800 s results in forming the lower bainite due to the initiation of carbide precipitation. Further increasing the bainite transformation temperature up to 550°C is a reason of a change in the morphology of the matrix, from the lower bainite to upper bainite and a drop of the retained austenite stability associated with faster precipitations of spherical or lamellar carbides.

The size of regular grains of retained austenite is equal up to 3 μm , while the rest of γ phase is present in a form of thin films between individual laths of bainite. Diversification of retained austenite form has a reflection in its mechanical stability, connected with two-stage kinetics of martensitic transformation of γ phase. Lower mechanical stability of retained austenite in a range of small deformations should be ascribed to transformation of large regular grains of γ phase into martensite. Together with the increase of strain rate, the rate of retained austenite transformation considerably decreases, what should probably be connected with transformation of thin films of retained austenite located between laths of bainite.

References

- [1] J. Adamczyk, Engineering of Metallic Materials, The Silesian University of Technology Publishers, Gliwice, 2004 (in Polish).
- [2] T. Gladman, The Physical Metallurgy of Microalloyed Steels, The University Press, Cambridge, 1997.
- [3] B. Ehrhardt, T. Berger, H. Hofmann, T.W. Schaumann, Property related design of advanced cold rolled steels with induced plasticity, Steel Grips 2 (2004) 247-255.
- [4] A.K. Lis, B. Gajda, Modeling of the DP and TRIP microstructure in the CMnAlSi automotive steel, Proceedings of the 11th International Scientific Conference „Contemporary Achievements in Mechanics, Manufacturing and Materials Science”, CAM3S'2005, Gliwice – Zakopane, 2005, 585-591.
- [5] A. Basuki, E. Aernoudt, Influence of rolling of TRIP steel in the intercritical region on the stability of retained austenite, Journal of Materials Processing Technology 89-90 (1999) 37-43.
- [6] K. Sugimoto, T. Iida, J. Sakaguchi, T. Kashima, Retained austenite characteristics and tensile properties in a TRIP type bainitic sheet steel, ISIJ International 9 (2000) 902-908.
- [7] J. Adamczyk, A. Grajcar, Structure and mechanical properties of DP-type and TRIP-type sheets, Journal of Materials Processing Technology 162-163 (2005) 267-274.

- [8] A. Grajcar, Effect of hot-working in the $\gamma+\alpha$ range on a retained austenite fraction in TRIP-aided steel, *Journal of Achievements in Materials and Manufacturing Engineering* 22/2 (2007) 79-82.
- [9] A. Grajcar, Hot-working in the $\gamma+\alpha$ region of TRIP-aided microalloyed steel, *Archives of Materials Science and Engineering* 28/12 (2007) 743-750.
- [10] A. Grajcar, Determination of the stability of retained austenite in TRIP-aided bainitic steel, *Journal of Achievements in Materials and Manufacturing Engineering* 20 (2007) 111-114.
- [11] B. Gajda, A.K. Lis, Thermal processing of CMnAlSi steel at ($\alpha+\gamma$) temperature range, *Journal of Achievements in Materials and Manufacturing Engineering* 18 (2006) 355-358.
- [12] N. Apostolos, A. Vasilakos, K. Papamantellos, G. Haidemenopoulos, W. Bleck, Experimental determination of the stability of retained austenite in low alloy TRIP steels, *Steel Research* 11 (1999) 466-471.
- [13] K. Eberle, P. Cantinieaux, P. Harlet, M. Vande Populiere, New thermomechanical strategies for the realization of multiphase steels showing a transformation induced plasticity effect, *Iron and Steelmaker* 26/2 (1999) 23-27.
- [14] A. Wasilkowska, P. Tispouridis, A. Werner, A. Pichler, S. Traint, Microstructure and tensile behaviour of cold-rolled TRIP-aided steels, *Proceedings of the 11th Scientific International Conference „Achievements in Mechanical and Materials Engineering” AMME’2002, Gliwice–Zakopane, 2002, 605-610.*
- [15] K. Sugimoto, R. Kikuchi, S. Hashimoto, Development of high strength low alloy TRIP-aided steels with annealed martensite, *Steel Research* 73 (2002) 253-258.
- [16] K.W. Andrews, Hardenability of steels, *Journal of the Iron and Steel Institute* 7 (1965) 721-727.
- [17] E. Girault, P. Jacques, Ph. Harlet, K. Mols, J. Van Humbeeck, E. Aernoudt, F. Delannay, Metallographic methods for revealing the multiphase microstructure of TRIP-assisted steels, *Materials Characterization* 40 (1998) 111-118.
- [18] B. Averbach, M. Cohen, X-ray phase analysis, *Trans. AIME* 176 (1948) 60-70.
- [19] J. Adamczyk, A. Grajcar, Heat treatment of TRIP-aided bainitic steel, *Proceedings of the 11th International Scientific Conference „Contemporary Achievements in Mechanics, Manufacturing and Materials Science”, CAM3S’2005, Gliwice – Zakopane, 2005, 1-6.*
- [20] J. Pietrzyk, W. Osuch, G. Michta, The isothermal decomposition of the austenite obtained at a temperature between A_3-A_1 in a steel containing 0.2%C, 1.5%Mn and 1.5%Si, *Materials Engineering* 19 (1998) 18-23 (in Polish).
- [21] S.K. Liu, L. Yang, D.G. Zhu, J. Zhang, The influence of the alloying elements upon the transformation kinetics and morphologies of ferrite plates in alloy steels, *Metallurgical and Materials Transactions* 25A (1994) 1991-1996.
- [22] Y. Tomita, K. Morioka, Effect of microstructure on transformation-induced plasticity of silicon-containing low-alloy steel, *Materials Characterization* 38 (1997) 243-250.
- [23] J. Pietrzyk, G. Michta, W. Osuch, A. Kruk, Low-carbon steels with the TRIP effect, *Materials Engineering* 24 (2002) 154-156 (in Polish).
- [24] A. Barbarki, E. Mikołajki, M. Popławski, The application of austempering in the formation of microstructure and mechanical properties of medium carbon constructional steels, *Archives of Machine Technology and Automatization* 24 (2004) 9-16 (in Polish).
- [25] H.K.D.H. Bhadeshia, *Bainite in Steels, Transformations, Microstructure and Properties, Second Edition, The University Press, Cambridge, 2001.*