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Determination of the stability of retained austenite in TRIP-aided bainitic steel

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Materials

ABSTRACT

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

Design/methodology/approach: The heat treatment of the medium-carbon steel in order to obtain a bainitic structure with the retained austenite was realized. A range of the holding temperature of the steel under isothermal bainite transformation conditions was from 250 to 550°C. To investigate the structure, optical and transmission electron microscopy were employed. An amount of the retained austenite was determined using X-ray diffraction. The mechanical stability of retained austenite was determined by means of the tensile test.

Findings: It was found that after the optimum heat treatment the investigated medium-carbon steel has a structure of the ferritic bainite with a 19% fraction of retained austenite. Increasing the isothermal holding temperature results in obtaining the lower (350°C) and upper bainite (450°C). The retained austenite occurs as regular grains or thin foils between bainite laths. The steel is characterized by an excellent strength-ductility balance. A kinetics of the strain-induced martensitic transformation of the retained austenite has a two-stage character.

Research limitations/implications: To determine with more detail the stability of retained austenite the knowledge of the austenite carbon content as a function of the isothermal holding is required. Lattice parameter measurements with X-ray diffraction is planned for this purpose.

Practical implications: The established heat treatment conditions can be useful for manufacturing crash-related elements in the automobile industry.

Originality/value: It should be stressed that the developed conditions of the heat treatment concern the medium-carbon steel, compared with usually investigated low-carbon steels. The kinetics of the strain-induced transformation for TRIP-aided bainitic steel was determined, too.

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

1. Introduction

In recent years, there is a trend in the automobile industry to design vehicles of reduced weight. It leads to the reduced fuel consumption and exhaust emission reduction. On the other hand, the requirements concerning safety improvement and greater comfort result in increasing the automobile weight. For this reason, the steel is having to face up to the challenges of lower density materials, i.e. aluminium, magnesium and composite plastics. The special group of interest are structural microalloyed steels produced in integrated technological lines [1,2] and steels with a multiphase structure [3-5]. Plates and sheets manufactured of them have a various yield point and a high strength-density ratio. Moreover, in comparison with conventional steels and, especially, with Al and Mg-based alloys, the multiphase steels have a very good strength-ductility balance. The steels with a multiphase structure meet also different demands concerning deep drawing, welding, surface quality and cost efficiency. The specially important properties predestining multiphase steels to employ for different elements of cars are the outstanding work-hardening behaviour and the ability to absorb the high value of the energy during crash events [3,6,7].

The multiphase steels have a ferritic – bainitic structure with the retained austenite of the volume fraction between 5 to 15%. The strain-induced martensitic transformation of the γ phase occurring during technological forming of elements suppresses a localization of the plastic deformation increasing the ultimate tensile strength and uniform elongation (TRIP-effect – Transformation Induced Plasticity). The essential factor of obtaining optimum mechanical and technological properties for these steels is a stability of the retained austenite, depending mainly on the M_s temperature of the γ phase. A carbon content in the austenite increases, when the steel is coolled or annealed in a $\gamma+\alpha$ range as well as during isothermal holding in the bainitic range. Enrichment of the retained austenite in carbon should ensure to lower the M_s temperature of this phase below a room temperature. When the carbon concentration in the γ phase is to small, the retained austenite can transform into martensite during cooling from an isothermal holding temperature. It is not required, similarly to a sudden martensitic transformation occuring at low strains during technological forming of elements. On the other hand, the result of to much carbon concentration in the γ phase can be a lack of the martensitic transformation during straining or its very limited occurrence. For this reason, heat treatment parameters should be selected for a given chemical composition to ensure the continuous strain-induced martensitic transformation, favouring high uniform elongations of the steels.

Steels possessing a ferritic – bainitic structure with the retained austenite are produced by isothermal quenching from a temperature of intercritical annealing [8,9] or using an energy-saving thermo-mechanical processing [1,10]. These steels contain usually about 0.2%C and graphitizing elements Si and Al with a total concentration of up to 1.7% [11]. These elements should suppress carbide precipitation during the bainitic transformation. It was found [6,12] that changing the ferrite matrix into ferritic bainite can improve the stretch-flangeability of formed elements. It can be attained increasing a carbon concentration in the steels to about 0.5%. Deterioration of the ductility associated with a lack of soft ferritic matrix can be eliminate by the increase in the amount of the retained austenite in the structure of steel and more intensive TRIP-effect.

2. Experimental procedure

The structural medium-carbon 0.55C-Si-Mn-Cr steel (Table 1) was investigated. The steel was smelted using the secondary metallurgy and continuous casting of 100x100mm slabs. After solidification the slabs were hot-rolled in order to obtain the rods with a diameter of 12mm. The specimens for structure and mechanical properties investigations were prepared.

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

Conditions for isothermal quenching of the specimens were selected on the basis of A_{c3} and M_s temperatures, calculated using Andrews' equations [13]. The calculated temperatures of the investigated steel are: A_{c3} = 818°C, M_s = 280°C. In order to obtain a fine-grained structure of austenite, the specimens were austenitized at a temperature of 840°C for 18min. After austenitizing, the steel was oil cooled to a bainite transformation temperature in a range of between 250 to 550°C. The isothermal holding time of the specimens at a given temperature was 600s, and a cooling rate to the room temperature was about 1°Cs^{-1}. The heat treatment conditions for the specimens are shown in Figure 1.

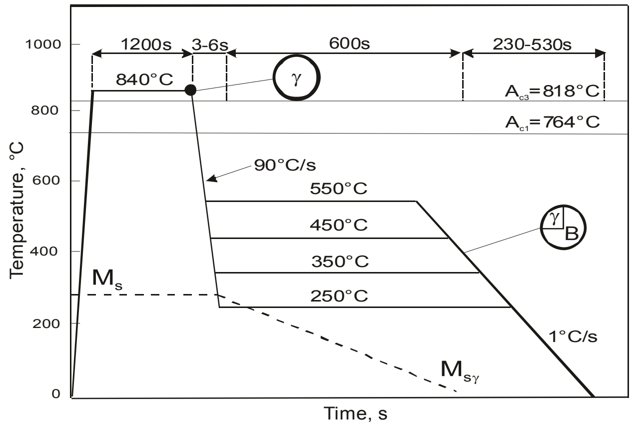

Fig. 1. Heat treatment of the investigated steel; M_s – martensite start temperature of the steel, $M_{s\gamma}$ – martensite start temperature of the austenite with increased carbon concentration

Investigations of steel structure after the heat treatment were performed by means of optical microscopy using LePera etching [14]. The structure observations were carried out by the use of the Leica MEF4a light microscope and observations of thin foil structure were carried out in the JEM-200CX transmission electron microscope using an accelerating voltage of 120 kV. The type and phase fractions in the structure of the heat-treated steel were determined by means of qualitative and quantitative X-ray phase analyses using the DRON2.0 X-ray diffractometer with CoK_α radiation. The volume fraction of retained austenite was quantitatively measured applying Averbach-Cohen's method [15].

Mechanical properties of the heat-treated steel were determined by means of the tensile test using the Zwick Z/100 machine and specimens with a diameter of 6mm and a gauge length of 30mm. To investigate the mechanical stability of retained austenite, a part of the specimens were stretched to rupture and another part to a given strain amounting 0.25, 0.5 and 0.75 of absolute elongation.

3. Results and discussion

Based on the structural investigations of the specimens isothermally quenched from a temperature of 840°C, it was found that the medium-carbon steel has a bainite structure of the morphology dependent on an isothermal holding temperature. After quenching the steel to a temperature of 250°C, it is the ferritic bainite of the evident acicular character with a small fraction of martensite (Fig. 2). The presence of the martensite is due to applying the isothermal holding temperature 30°C lower than the M_s temperature of the investigated steel. It was found that a fraction of the austenite stable to the room temperature is over 19%. A part of the retained austenite occurs as multi-angular grains with a size of up to 3 μm. Another part of the γ phase has a shape of thin plates located between ferritic bainite laths. Increasing the isothermal holding temperature of the steel to 350°C results in obtaining the lower bainite and the amount of the retained austenite decreases to 17.7%.

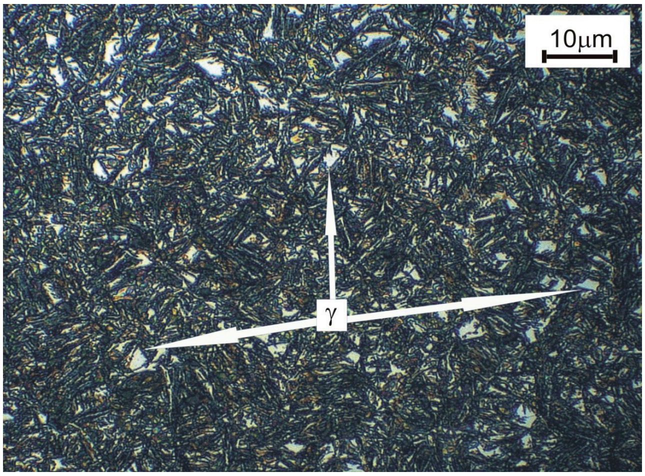

Fig. 2. Structure of the ferritic bainite with the retained austenite for the steel isothermally quenched to a temperature of 250°C

The stabilization of such a fraction of the retained austenite to room temperature indicates a high carbon enrichment of the austenite during the isothermal γ→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 during the bainite transformation. 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 [16,17]. Increasing the holding temperature of the steel in a bainitic range to 450°C results in a change of the bainite morphology. For this temperature, it is the upper bainite (Fig. 3). A fraction of the retained austenite of dual morphology decreases to 13.6%. Further increasing the isothermal holding temperature of the steel to 550°C causes decreasing of the γ phase fraction to 7% due to cementite precipitation [17].

The structure investigations of thin foils in a transmission electron microscope confirmed a various morphology of the retained austenite. It occurs as films located between rectilinear laths of the ferritic bainite (Fig. 4) or as regular grains of larger size. 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. It influences a drop of the retained austenite stability displaying in the decrease of the γ fraction to 13%.

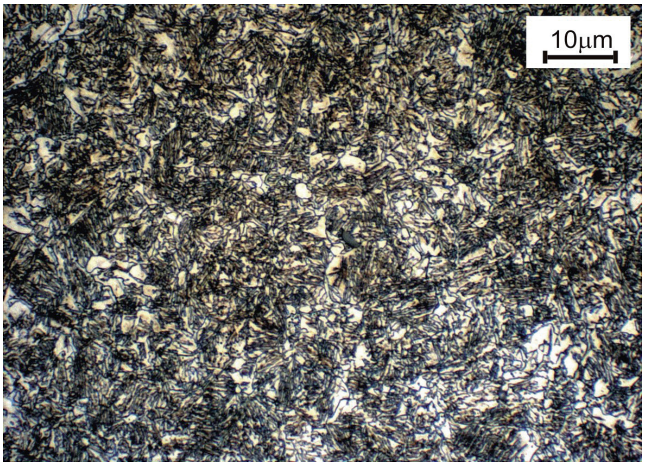

Fig. 3. Structure of the upper bainite with the retained austenite for the steel isothermally quenched to a temperature of 450°C

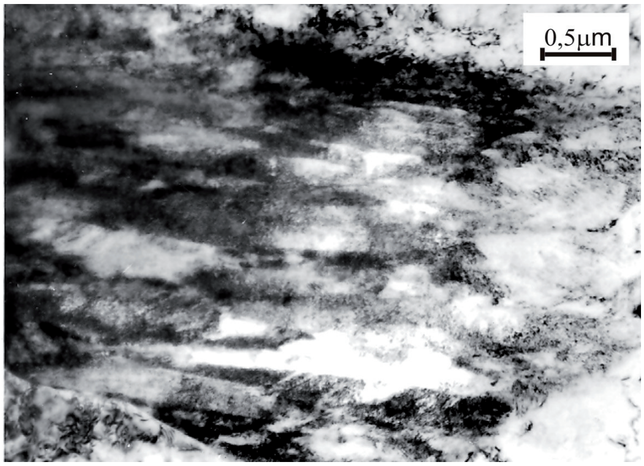

Fig. 4. Retained austenite as films between laths of the ferritic bainite

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 medium-carbon steel possesses a very good balance between strength and ductile properties. The proof stress of the steel is YS = 960MPa and ultimate tensile strength UTS = 1210MPa. The high value of the ultimate tensile strength and beneficial YS/UTS 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 UEl = TEl = 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.

The 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 5 that at the initial stage of the plastic deformation, a sudden drop in the amount of the retained austenite is occurred. It is due to the low mechanical stability of the γ phase. A further course of the curve indicates that the mechanical stability of the austenite increases. A similar character of the curve for a medium-carbon steel with a similar chemical composition was observed [18]. The two-stage course of the curve of the retained austenite transformation can be associate with a various morphology of the γ phase. Authors of the work [19] suggest, that at the initial stage of the plastic deformation the equiaxed grains of lower carbon concentration are transformed. At the further stage of deformation the transformation of thin films of the retained austenite is occurred.

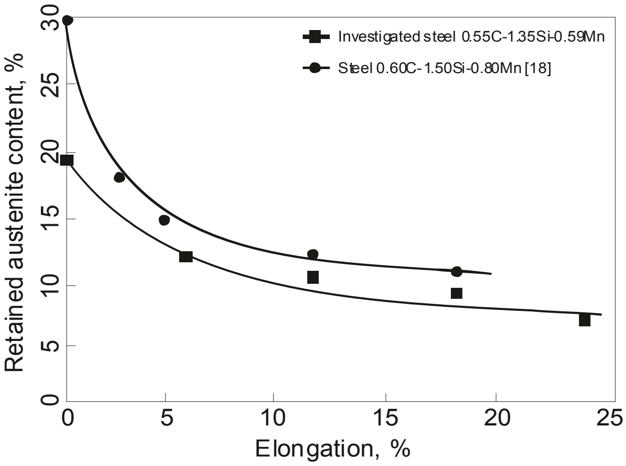

Fig. 5. A change in the retained austenite fraction as a function of the elongation of the specimen

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. The retained austenite of the 19% volume fraction can be obtained after the isothermal quenching of the steel to a temperature of 250°C, at which the matrix of the steel is the ferritic bainite. Increasing the isothermal holding temperature up to 550°C results in a change of the morphology, from the ferritic bainite to lower and upper bainite and a drop of the retained austenite stability asscociated with carbide precipitations.

It was found that the retained austenite occurs as regular grains and as films located between bainite laths. A various morphology of the retained austenite influences the mechanical stability of this phase. A kinetics of the strain-induced martensitic transformation has a two-stage character. The low stability of the γ phase at the initial stage of the plastic deformation is associated with a transformation of regular grains of the retained austenite. Together with an increase in the amount of deformation the stability of the retained austenite increases.

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