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Modelling of the DP and TRIP micro-structure in the CMnAlSi automotive steel

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Analysis and modelling

ABSTRACT

Purpose: The CMnAlSi steel is a new grade of TRIP steels with 1wt % of Al and Si. It is important to determine the usability of the CMnAlSi for production of sheets for automotive applications.

Design/methodology/approach: The effect of cooling rate and austenitization temperature on phase transformations was investigated. The dilatometric experiments of the steel were done for the full austenitization temperature 1200°C, and for ($\alpha+\gamma$) temperature ranges: 1100°C, 1000°C, 900°C and 800°C. Steel was also processed to achieve TRIP grade by continuous annealing with modeled vertical hot dip galvanizing line. The microstructures were investigated by light optical microscopy and SEM with EDX attachment. The amount of retained austenite in the obtained microstructures was investigated with X-ray diffraction

Findings: There is possibility to produce "dual-phase" CMnAlSi steel grade with controlled rolling at finishing temperature below 900°C to 800°C and fast cooling. Steel CMnAlSi is well suited for production of TRIP grade via heating cycle which correspond to vertical hot dip galvanizing process.

Practical implications: This steel is suitable for production of automotive applications.

Originality/value: The new procedure of control rolling from the ($\alpha+\gamma$) temperature range of CMnAlSi steel was presented.

Keywords: Automotive steel; CCT; SEM; TRIP; HDG line

1. Introduction

Dual phase (DP) and transformation induced plasticity (TRIP) steels are very promising approach to increase the ductility of high strength steels for automotive applications.

In low alloyed DP and TRIP steels, the retained austenite is mainly stabilized by carbon. Thus carbon enrichment in the austenite and the prevention of precipitation of iron carbides, are achieved by lowering the activity of carbon in cementite, by addition of alloying elements such as Si and appropriate heat treatment of the cold-rolled strips [1]. Addition of aluminum accelerates formation of ferrite in the ($\alpha+\gamma$) temperature range thus enables creation of bainite-martensite islands from retained austenite when fast cooling is applied [2-8]. Synergetic effect of alloying elements on phase transformation occurrence is shown in Figure 1.

In order to succeed in car-body weight reduction, it is necessary to develop sophisticated chemical composition of high strength steels. Lately a low-Si, Al added Nb-Mo TRIP steels has been developed [9]. The present paper deals with an approach of addition of 1% Al and 1% Si to low carbon auto-body steel. Such composition of the steel allows for ferrite + austenite formation, during continuous annealing at 800°C for hot dip galvanizing process, (Figure 2) [1,7].

Al-Si addition is necessary to achieve rapid ferrite formation during hot rolling finishing temperature at 950°C to 800°C. The remaining austenite supersaturated with carbon is more stable and transforms to bainite- martensite islands, when rapid cooling is applied. During lower cooling rates austenite transforms to ferrite and to bainitic ferrite without carbides. That cause that retained austenite areas can exist within received microstructure [5,6]. Influence of different alloying elements in chemical composition of the investigated steel was considered when calculating the phase transformations diagram which is shown in Figure 2c [3].

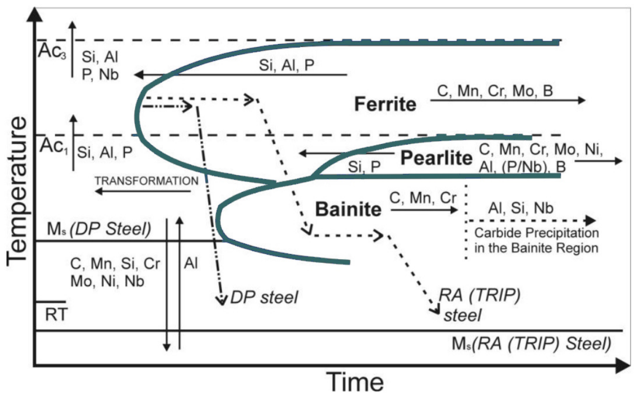

Fig. 1. Influence of alloying elements on TTT behavior [1]

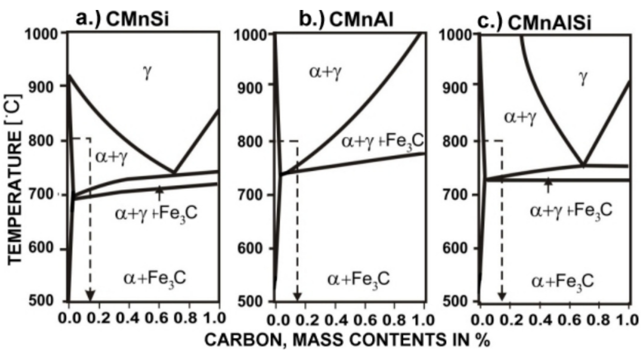

Fig. 2. Phase diagrams of CMnSi, CMnAl [2] and CMnAlSi steels after equilibrium calculations [3]

2. Material and experimental procedure

Chemical composition of the CMnAlSi steel is given in Table 1.

Table 1.
Chemical composition of the investigated steel

Chemical composition [wt %]						
C	Si	Mn	P	S	Al	N
0.150	1.010	1.550	0.013	0.006	1.090	0.003

The steel for the investigations was hot rolled as shown in the Table 2. Then the steel was cold rolled with the reduction 75% to the thickness 1,14. The initial sample had the band ferrite- pearlite microstructure with the amount of ferrite 78%, as shown in Figure 3.

Table 2.
Hot rolling conditions (3 steps, 87% deduction)

Hot rolling conditions	Thickness [mm]	Temperature [°C]	Deformation [%]
Reheating	38.10	1220/1h	0
1st deformation	19,05	1150	50
2nd deformation	9,52	1100	50
3rd deformation	5,08	1000	47
Air cooling to R.T	-	-	-

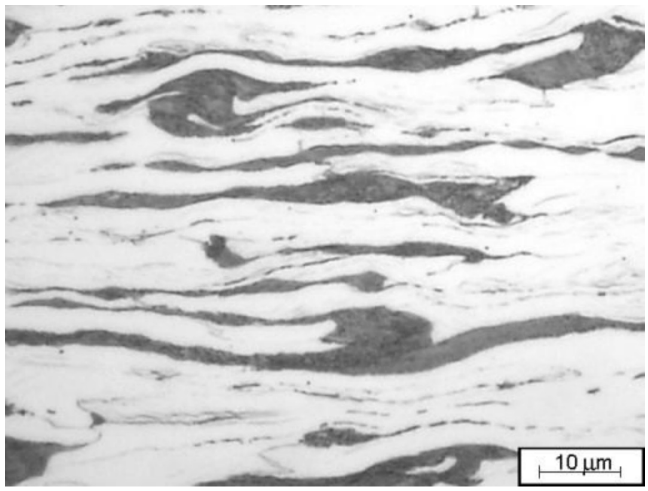

Fig. 3. The strip microstructure after cold rolling of the CMnAlSi steel

The dilatometric investigations from full austenitization temperature range 1200°C/60s were done for the cooling rates 0.5°C/s; 1°C/s; 3°C/s; 10°C/s; 20°C/s; 40°C/s and 80°C/s. Also the experiments from ($\alpha+\gamma$) temperature ranges: 1100°C, 1000°C, 900°C and 800°C with the cooling rate 20°C/s were done.

TRIP modification procedure was based on annealing cycles shown in Figure 4 for vertical annealing – hot dip galvanizing line [1].

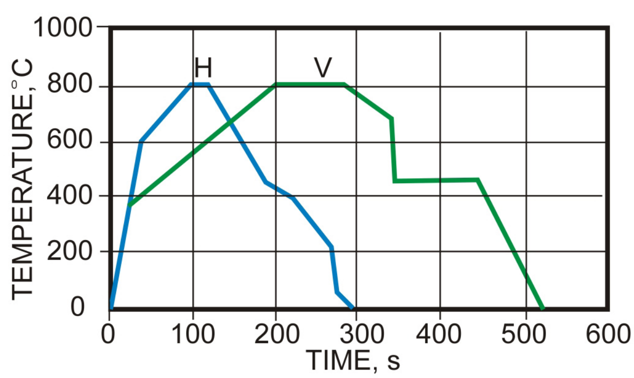

Fig. 4. Annealing cycles for vertical annealing (v)– hot dip galvanizing line and (h)-horizontal HDG line [1]

Microstructure of the DP and TRIP grade steel was observed by optical microscopy and scanning electron microscopy (SEM) JOEL 5400 with additional EDX attachment ISIS 300. The quantitative analysis of the microstructures of the steel were done with the software Image Po Pus 3.0 applied for microstructures observed using light optical microscopy.

Tensile properties were achieved on small flat tensile specimens using MTS 810 machine with digital controller Elextest SE. X-ray diffraction method with Seifert 300 diffractometer was applied for measurement of the residual austenite amount in the structure of the steel. Laboratory experiments of heating and cooling according to the vertical annealing line were set by dilatometer 805DIL. Control rolling experiments were performed using the very same apparatus as well as Gleeble 3500 Test equipment.

3. Discussion of results

Based on the Thermocalc program, the Fe-Al equilibrium phase diagram was calculated for a carbon content of 0.1%. As shown in the presented diagram (Fig. 5) , the maximum solubility of Al in austenite could be shifted to the lower limit and sharp increase in Ac_3 temperature was observed with increasing Al content to 1.09 wt. % Al. Metallographic examination of specimens microstructures revealed that γ loop under influence of chemical composition of the investigated steel was narrowed to the broken line visible in Figure 5 [10] .

The present data shows that Al significantly expands the (α+γ) region, strongly increasing Ac_3 temperature.
For the investigated steel Ac_1 and Ac_3 temperatures equaled respectively 723°C and 1148°C.

3.1. Austenitization at 1200°C/60s

The dilatometric investigations from 1200 °C/60s, allowed for creation of the CCT diagram of the CMnAlSi steel, shown in Figure 6.

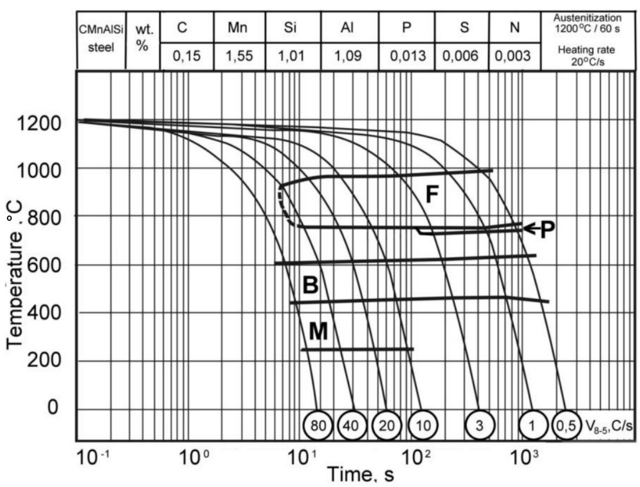

Fig. 6. CTPc diagram of the investigated steel austenitizied at 1200°C/60s

Cooling with cooling rates from 0.5 °C/s to 3 °C/s caused mainly origination of the ferrite - pearlite microstructure with the increasing amount of bainite for higher cooling rates.
The dual phase microstructure (F +B M) can be obtained after cooling with the rates from 10 °C/s to 40 °C/s. The highest cooling rate 80 °C/s causes the origination of hard (M+B) microstructure which is distinguishable in Figure 7. This means that after full austenitization addition of 1.09% Al is not able to decrease austenite stability in terms of the critical rate required for preventing ferrite formation.

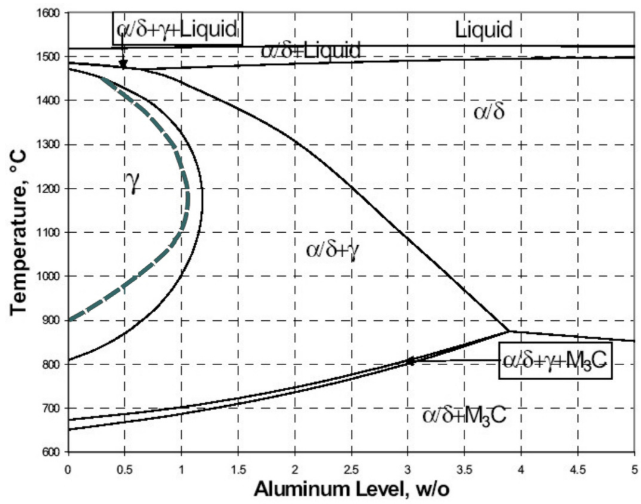

Fig. 5. Fe-0.1C-Al Phase diagram [10]

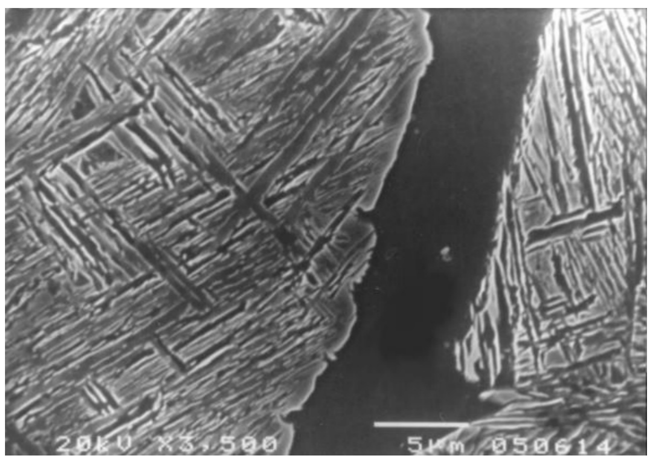

Fig. 7. Sample cooled from 1200°C/60s with the rate 40°C/s, SEM

The exemplary microstructures of the samples cooled from the 1200°C/60 s are shown in the Figures 8-10.

The quantitative analysis of the microstructures allowed for the calculation of the ferrite amount in the samples cooled from 1200°C/60s with the various cooling rates. In Figure 11 volume fraction of ferrite and mean chord of ferrite evaluated from diameters at different angles are presented.

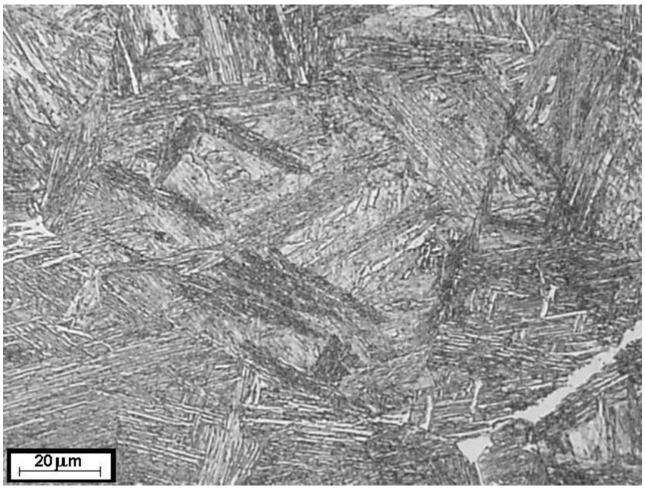

Fig. 8. Sample cooled from 1200 °C/60s with the rate 40 °C/s

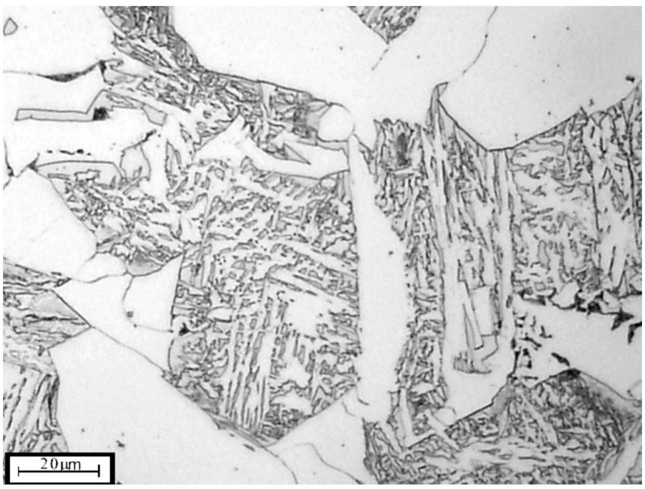

Fig. 9. Sample cooled from 1200 °C/60s with the rate 3 °C/s

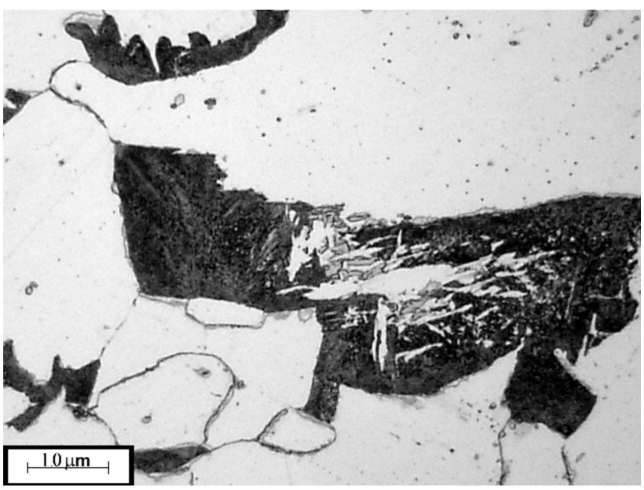

Fig. 10. Sample cooled from 1200 °C/60s with the rate 0.5 °C/s

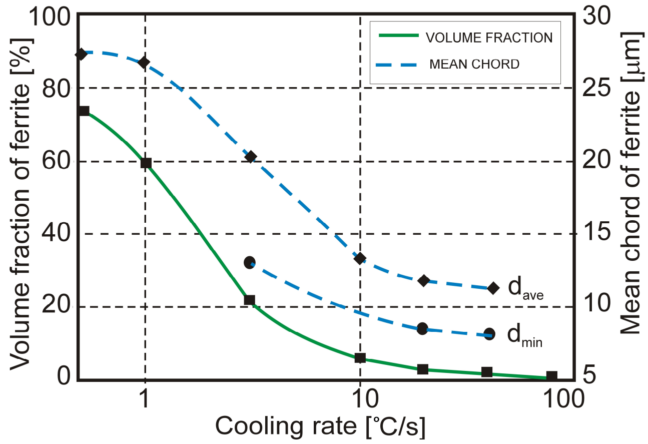

Fig. 11. Quantitative analysis of the amount of ferrite in the samples cooled with the various cooling rates

The ferrite amount was decreasing with the increasing of the cooling rate. For 0.5°C/s the amount of ferrite equaled 74%, for 1 °C/s – 60%, for 3 °C/s – 23% ,for 20 °C/s – 3%, and for 40 °C/s about 1%. In the sample cooled with the higher cooling rate (80°C/s) there was no ferrite. The mean chord of the ferrite grain for the slowest cooling (0.5 °C/s) equaled 27.5µm , and for the highest 40 °C/s equaled 12.7µm. Width of elongated ferrite grains at the grain boundaries of former austenite is shown with line describing d_{min} in Figure 11.

3.2. Austenitization from (α+γ) temperature range

The dilatometric and microstructural investigations from (α+γ) temperature ranges: 1100 °C, 1000 °C, 900 °C and 800 °C with the cooling rate 20 °C/s were done. Sample cooled from 1100 °C had the martensite-bainite microstructure with the small amount of ferrite on the grain boundaries (Figure 12). After cooling from 1000°C the dual phase F+(BM) microstructure was obtained (Figure 13). Cooling from 900 °C to 800 °C caused the origination of the very fine TRIP type microstructure consisted of ferrite matrix with the retained austenite and bainitic ferrite on the grain boundaries (Figure 14).

The quantitative analysis of the microstructures shows that the volume fraction of ferrite increases with lowering temperature of partial austenitization, and the mean chord of the ferrite grain was decreasing. What is important is that ferrite chord size is very small for austenitization below 900°C. The results are shown in Figure 15.

3.3. Hot dip galvanizing processes

New steel chemistry design was established for the formation of suitable mixtures of multiphase microstructures in terms of mechanical properties and type of transformation behavior dependence on processing route.

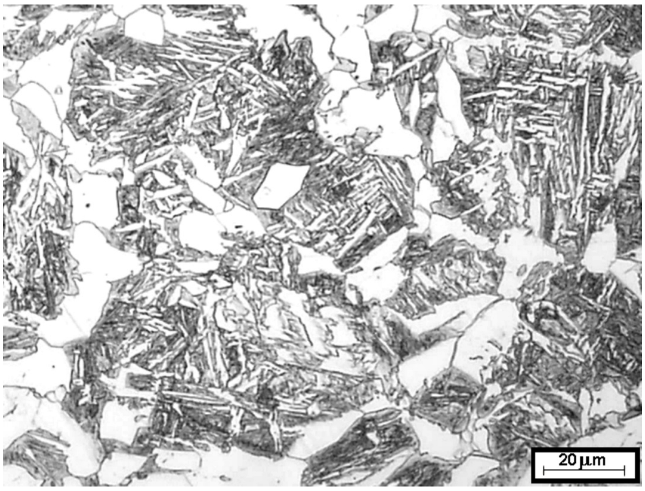

Fig. 12. Sample cooled from 1100 ^{o}C/60s with the rate 20 ^{o}C/s

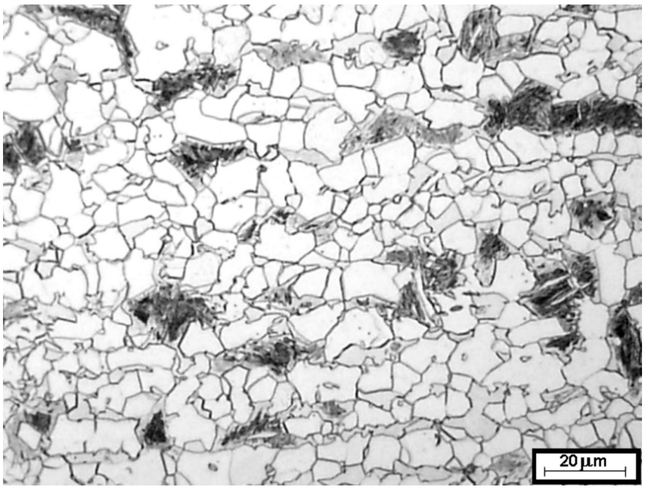

Fig. 13. Sample cooled from 1000 ^{o}C/60s with the rate 20 ^{o}C/s

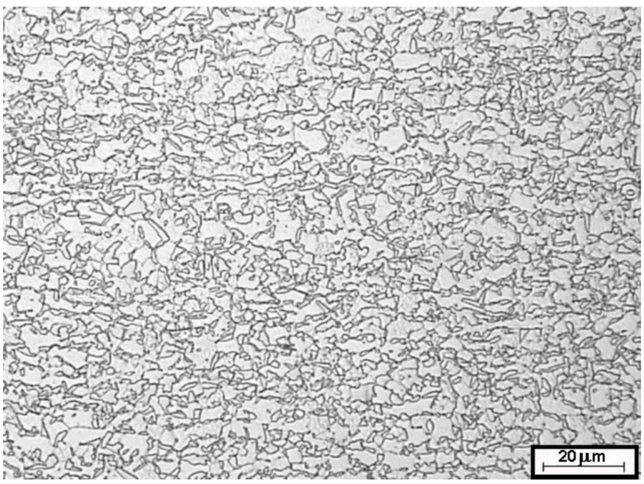

Fig. 14. Sample cooled from 900 ^{o}C/60s with the rate 20 ^{o}C/s

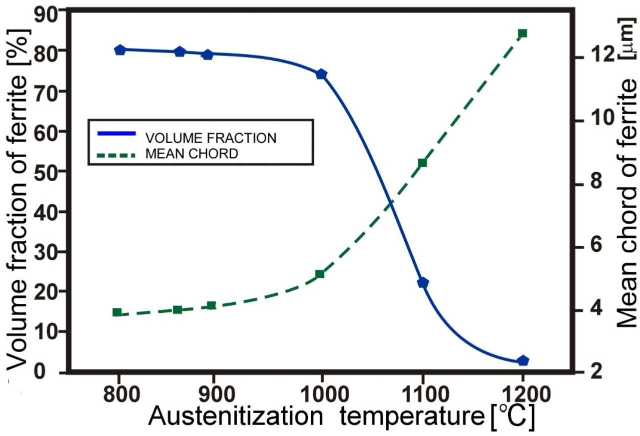

Fig. 15. Quantitative analysis of the volume fraction and mean chord of ferrite in the samples annealed at the various temperatures

Aluminum and silicon elements are essential to encourage proeutectoid ferrite formation, in order to produce Dual Phase microstructure during control rolling of the investigated steel. Usually the steel was hot-rolled after soaking at 1220^{o}C, in three passes at temperatures 1200 ^{o}C, 1100 ^{o}C and 1000^{o}C and cooled in the air. The received microstructure was mainly ferrite and pearlite. The strip microstructure after cold rolling is shown in Figure 3.

As it is established from the results in Figure 15 it is possible to lower finishing rolling temperature down to 900^{o}C and 800^{o}C to achieve further grain refinement of ferrite. At low finishing rolling temperature the reduction in the pass should be more than 30%, to enhance nucleation of ferrite. Thus received microstructure at finishing rolling temperature (FRT) will consist more than 75% of ferrite, the rest being austenite. Then fast cooling was applied. At cooling rate 80^{o}C/s mainly martensite was formed from austenite and some areas were represented by retained austenite. At lower cooling rates 40^{o}C/s and 20 ^{o}C/s small amounts of bainitic ferrite were formed [3-6].

The addition of silicon allows for suppressing the carbide precipitation during bainitic transformation. That fact appears to be crucial for retained austenite TRIP steel production.

The applied technology consisted of annealing cycle of cold rolled strip, which was modeled for vertical continuous galvanizing line. Annealing temperature was 800 ^{o}C during 100 seconds than first cooling step at rate 2 ^{o}C/s, and then second rapid cooling 30 ^{o}C/s to temperature of bainite formation 450 ^{o}C was applied. Specimen was hold 100 seconds and cooled at 6÷20^{o}C/s rate to room temperature. The amount of retained austenite measured by X-ray diffraction method was 10-17%. Carbon concentration within austenite islands was established at the level 0.4 to 0,8 and sometime to 1,05% C. The received microstructure consisted of matrix of the polygonal ferrite and expitaxial ferrite formed during cooling to temperature 450 ^{o}C and small islands of bainitic ferrite and retained austenite and occasionally found martensite areas were observed [3-6].

Typical microstructure of RA-TRIP steel is shown in Figure 16 at 1000 x magnification. Residual austenite areas are mainly rounded in shape, some of them formed individual lathes at the former grain boundaries. The mean ferrite diameter was 4.5 µm while dimensions of retained austenite and bainitic ferrite could be estimated from SEM micrographs taken at 5000x magnification. Figure 17 shows details of microstructure of RA-TRIP steel.

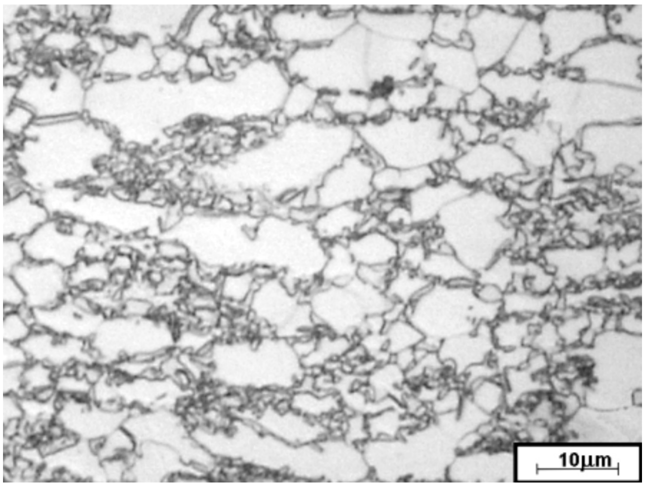

Fig. 16 . Typical TRIP microstructure of the investigated CMnAlSi steel

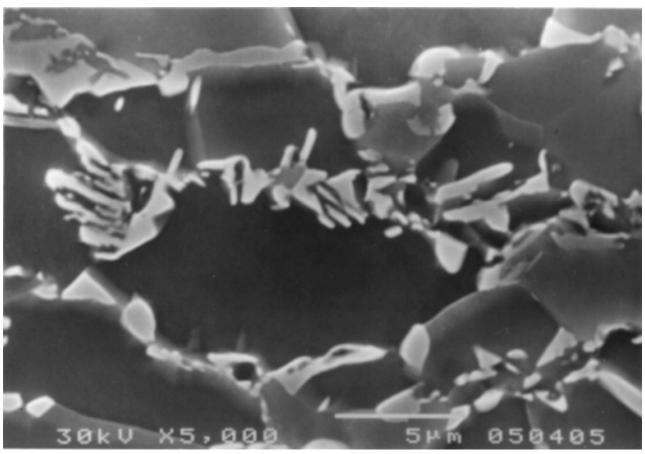

Fig. 17. SEM micrograph of the investigated steel

Al-alloying with small Si addition (Si $\leq$ 0,5%) is assumed to be more useful for hot dip galvanizing process because of the steel better wetting behavior. Steels with higher Al addition show a gradually better formability in terms of elongation and work hardening characteristics. It was previously discussed in literature that addition of Al and Si will favor the bainite transformation [2]. We have observed small or very small amount of bainite formed. The action of Al and Si elements was rather towards formation of austenite alloyed with carbon at 800 ^{o}C and epitaxial ferrite during cooling to 450 ^{o}C making the retained austenite more supersaturated with carbon up to 1.05%. Such areas maintained as residual austenite islands at room temperature. It was even possible to distinguished areas of the residual parts of the retained austenite with EDX which is shown in Figure 18.

The x-ray diffraction analysis of the samples cooled according to the scheme from Figure 4 showed the occurrence of the three reflexes of ferrite (0,202nm; 0,143nm; 0,117nm) and one of the austenite (0,207nm). Only ferrite reflexes were observed in the cold rolled sample. The exemplary X-ray diffraction of the sample heat treated according to the hot dip galvanizing line scheme (v) is shown in the Figure 19.

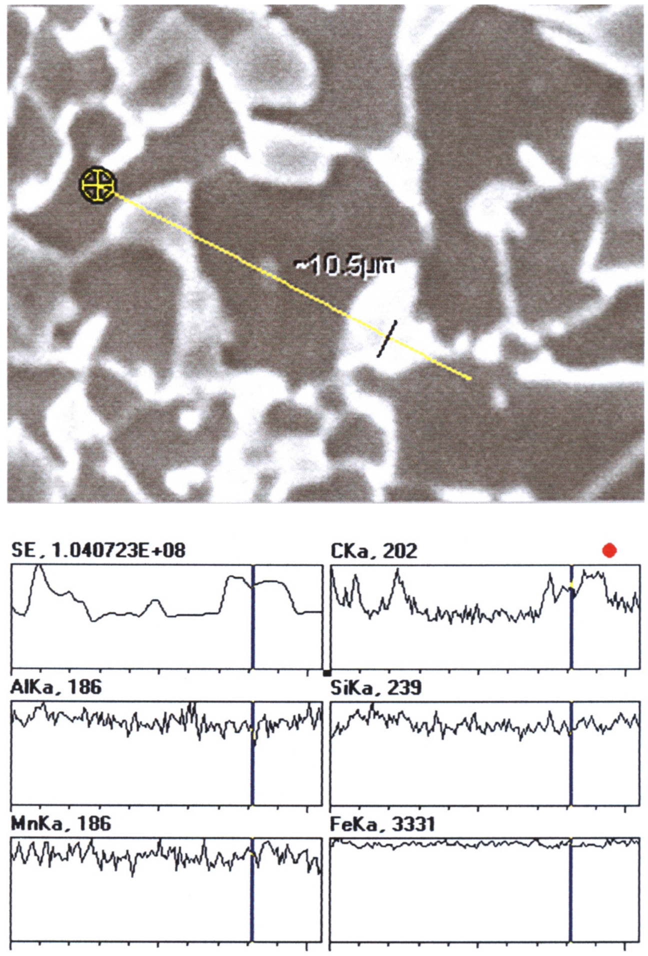

Fig. 18. Line chemical composition analysis of RA-TRIP steel

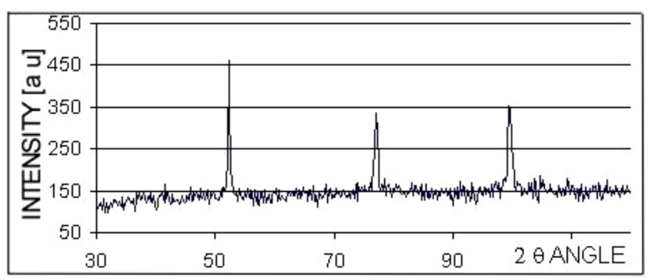

Fig. 19. X-ray diffraction of the sample in the initial state

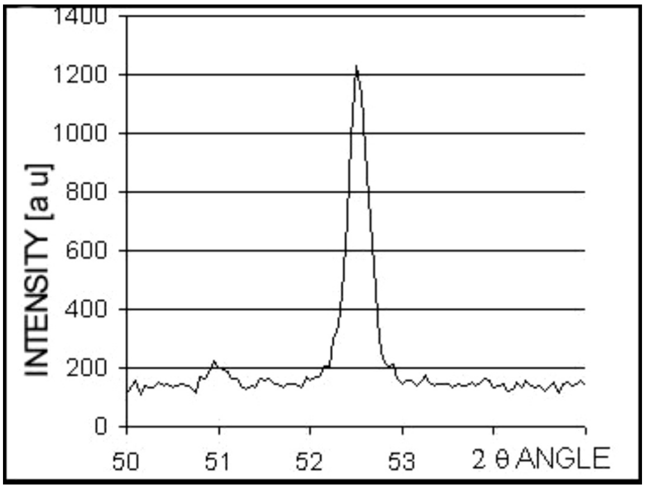

Fig. 20. X-ray diffraction of the sample heat treated according to the hot dip galvanizing line scheme (v)

Table 3.
Results of the X-ray diffraction of the samples from the investigated CMnAlSi steel

Phase type	2θ angle	d_{hkl} [nm]	hkl	Samples
Fe_{α}	52,4 77,2 99,6	0,202 0,143 0,117	011 002 112	Cold rolled microstructure
Fe_{α}	52,4 77,2 99,6	0,202 0,143 0,117	011 002 112	HDG microstructures
Fe_{γ}	51,1	0,207	111	

3.4. Mechanical properties

Mechanical properties of the strip after annealing for RA-TRIP microstructure were as follows:
$YS_{0,2}$ =472MPa, TS=716MPa, Uniform elongation UE=23%, Total elongation TE=29%. Hardening exponent n=0,23.

The Vickers hardness HV of the samples were calculated from the Maynier's empirical formula [11] :

$$H_v = X_m Hv_m + X_b Hv_b + (X_f + X_p) Hv_{f+p} \tag{1}$$

for:

$$Hv_m = 127 + 949\%C + 27\%Si + 11\%Mn + 21\log V_r \tag{2}$$

$$Hv_b = -323 + 185\%C + 330\%Si + 153\%Mn + (89 + 53\%C - 55\%Si - 22\%Mn)\log V_r \tag{3}$$

$$Hv_{f+b} = 42 + 223\%C + 53\%Si + 30\%Mn + (10 - 19\%Si)\log V_r \tag{4}$$

where:
V_r – cooling rate at the temperature 700°C [°C / h],
H_v- total hardness HV,
Xv_m, Xv_b, Xx_{p+f} – the amount of martensite, bainite, pearlite with ferrite.

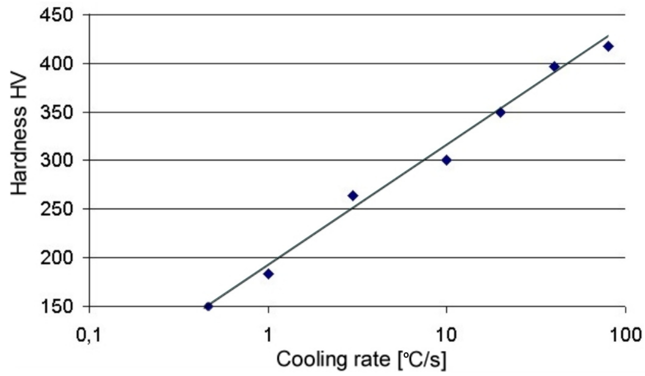

Fig. 21. Vickers hardness HV of the samples austenitizied at 1200°C/60s, cooled with the various cooling rates, estimated from the Maynier's formula

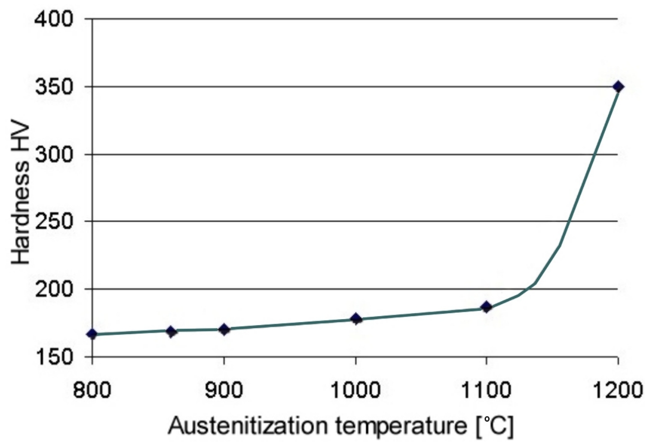

Fig. 22. Vickers hardness HV of the samples austenitizied at various temperatures, cooled with the cooling rate 20°C/s, estimated from the Maynier's formula

4. Conclusions

1. Full austenitization of CMnAlSi steel is possible when heating over 1150°C will be applied.
2. CCT diagram of CMnAlSi steel was established for cooling in the range 80°C/s till 0.5°C/s from temperature 1200 °C.
3. Bainite transformation bay is very pronounced on CCT diagram from temperature 1200 °C but is diminished when continuous cooling is applied from intercritical range (α+γ) for temperatures 860 °C and 800 °C.

4. There is possibility to produce “dual-phase” CMnAlSi steel grade with controlled rolling at finishing temperature below 900 °C to 800 °C and fast cooling.
5. Steel CMnAlSi is well suited for production of TRIP grade via heating cycle which correspond to vertical hot dip galvanizing process.
6. Retained austenite (RA) was detected in multiphase structure of TRIP steel using X-ray diffraction method and bigger volumes of RA were analyzed with EDS system attached to scanning electron microscope.

Acknowledgements

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References

[1] B. Ehrhardt, T. Gerber, H. Hofmann, T.W. Schaumann. Steel Grips 2 No. 4 (2004) 247-255.
[2] D. Mahieu, L. van Dooren, B.C. Barbe, B.C. De Cooman. Steel Research 73 No. 6+7 (2002) 267-273.
[3] A. K. Lis; B. Gajda. Inżynieria Materiałowa nr 5 (147) XXVI (2005) 597-600.
[4] A.K. Lis, W. Gliński, J. Lis. Proceedings 12th International Scientific Conference “Achievements In Mechanical & Matreials Engineering, Gliwice-Zakopane, AMME’2003, (2003) 609-612.
[5] J. Adamczyk, A. Grajcar. 11th International Scientific Conference on Contemporary Achievements in Mechanics, Manufacturing and Materials Science, Zakopane (2005) 1-6
[6] J.Lis, B.Gajda, A.K. Lis. Proceedings 12th International Scientific Conference “Achievements In Mechanical & Matreials Engineering, Gliwice-Zakopane, AMME’2003, (2003) 605-608.
[7] A.K. Lis, B.Gajda. 11th International Scientific Conference on Contemporary Achievements in Mechanics, Manufacturing and Materials Science, Zakopane (2005) 585-591.
[8] E. Girault, A. Martens, P. Jacques, Y. Houbaert, B. Verlinden, J. van Humbeeck. Scripta Materialia 44 (2001) 885-892.
[9] O.A. Girina, N.M. Fonstein: Developments in Sheet Products for Automotive Applications. Materials Science & Technology (2005) 65-76.
[10] P. Maynier, J. Dollet, P. Bastien, D.V. Doane, J.S. Kirkaldy, [eds.:] AIME, New York, NY (1978) 518.
[11] O. Muransky, P. Hornak, P. Lukas, J. Zrnik, P. Sittner. 11th International Scientific Conference on Contemporary Achievements in Mechanics, Manufacturing and Materials Science, Zakopane (2005) 694-697.