The stacking fault energy evaluation of the TWIP and TRIPLEX alloys

E. Mazancová*, K. Mazanec

VŠB – Technical University of Ostrava, Faculty of Metallurgy and Material Engineering, 17. listopadu 15/2172, 708 33 Ostrava, Czech Republic

Received 18 July 2009, received in revised form 28 September 2009, accepted 29 September 2009

Abstract

The contribution deals with the stacking fault energy (SFE) evaluation both of the TWIP high manganese alloys and of the TRIPLEX ones. Chemical composition of the TWIP variant includes varying Mn contents (20, 23, 27, and 30 wt.%) and C levels (0.65, 0.85, 1.0, and 1.2 wt.%). The TRIPLEX variants take into account 12 wt.% of Al content. By use of available thermo-dynamic data and constants the SFE levels of two basic high manganese alloy types are presented. The results are compared mutually and with literary pieces of knowledge. The higher Mn and Al contents significantly increase the SFE. However, the Al influence is stronger. Carbon and the Fe contents show weak effects. The results signify the dominant influence of Mn with decreasing Fe content.

K e y w o r d s: high manganese alloys, TWIP, TRIPLEX, stacking fault energy

1. Introduction

Austenitic steels are characterized by high deformation strengthening level forming conditions for reaching very high strength at favourable plasticity. Austenitic steels have generally low C content and high Ni one securing stable face cube centered lattice (FCC). Nickel can be substituted by cheaper C and Mn as being known in case of Hadfield's steel. This manganese Fe-Mn-C steel type shows favourable properties, however, its weldability is restricted in consequence of high C level (carbide formation). Simultaneously, lower Mn content (of about 12 wt.%) results in martensite phase transformation during plastic deformation. The higher Mn level compensating the lower C content can lead to austenitic structure stabilization and to suppressing of α'-martensite formation [1, 2]. This has been used in case of high manganese materials of new generation being known as the TWIP (twinning induced plasticity) and the TRIPLEX (beside iron three elements).

Within a wide temperature extent, the high manganese TWIP and TRIPLEX alloys show high strength properties, toughness, ductility and high specific energy absorption (E_{spec}) in impact loading, simultaneously. This is the reason why these materials are useful for automotive industry not only in bodywork production, however, for various automotive components as well. These alloys can be also applied as vessels materials for liquid gasses transport. The TRIPLEX variant is also suitable for rotating elements production in consequence of lower matrix density thanks to the increased Al and Mn content [3–5].

The TWIP alloy is characterized by the Fe-Mn--C basic chemical composition with low Al and Si contents, eventually. The second material marked as the TRIPLEX alloy is constituted on the Fe-Mn-C-Al basis. The Al content is higher than 8 % and Si addition is not suitable. Depending on the C contents, Mn usually reaches higher level than 19 wt.% and in this way guarantees the basic austenite microstructure of the FCC type [1–3]. The TWIP alloy microstructure is monolithic, austenitic and the sole deformation process is twinning, whereas the basic FCC TRIPLEX microstructure shows annealing twins, about 10 % of ferrite on the average and practically the same nano-size k-carbides volume fraction. The sole deformation mechanism is shear band induced plasticity (so called SIP-effect) accompanied with dislocation glide. Shear bands have regular arrangement in {111} planes [2].

*Corresponding author: tel.: +420 596 994 409; fax: +420 596 994 401; e-mail address: eva.mazancova@vsb.cz

The chemical compositions of both alloys influence their stacking fault energy (SFE) levels being responsible for high manganese alloys properties. Hence, knowledge of the SFE is very important and enables mechanical properties prediction. The aim of presented work is to deepen knowledge about the SFE levels of the TWIP alloys and especially the TRIPLEX ones, because information is generally not satisfying.

2. Stacking fault energy calculation

The SFE represents an important quantity characterizing the deformation type being realized in given high manganese alloy. The TWIP alloy shows higher SFE than 18 mJ m^{-2}. Given level ensures deformation by mechanical twinning preferentially. Movement is conditioned by slip of partial dislocations of $a/6\ \langle 112\rangle$ leading to the stacking faults in consecutive parallel $\{111\}$ planes. When the SFE is 18 mJ m^{-2} and lower, ε-martensite is formed when the same dislocation glide in every second $\{111\}$ plane type occurs [4]. The deformed area shows very fine lamellar form being of hexagonal structure (HCP). However, that state is not favourable for the TWIP material, because martensite leads to partial matrix embrittlement [1, 3, 7].

With regard to basic chemical composition, the TRIPLEX variant shows much higher SFE than the TWIP one. The SFE of the TRIPLEX alloy should be within the extent of 80–140 mJ m^{-2} [3, 5]. The SFE can be determined using TEM of thin foils. This method is very complicated and time-consuming. In any case, the SFE defines realized deformation type in matrix, and this is the reason why its mathematical calculation was performed for concrete chemical compositions of high manganese alloys. For ternary system, the SFE comes out from molar surface atoms density ρ in close arranged plane of the $\{111\}$ type, from molar free enthalpy ΔG of the $\gamma \rightarrow \varepsilon$ phase transformation and from interface energy between γ (FCC) and ε (HCP) phases being marked $\sigma^{\gamma/\varepsilon}$ in Eq. (1) [7–9]:

$$\mathrm{SFE} = 2\rho\Delta G^{\gamma\rightarrow\varepsilon} + 2\sigma^{\gamma/\varepsilon}. \qquad (1)$$

For mathematical calculation further necessary parameters were also presented in some works [2, 7–9].

In the case of quaternary system the situation is much more complicated. Consequently, for the TRIPLEX variant the similar SFE calculation was applied as for the TWIP materials, thus for the ternary Mn-C-Fe system, however, Al content (considered 12 wt.%) was subtracted from an iron one. Aluminium significantly contributes to the SFE increase. The SFE values vs. Al contents (maximally 8 wt.%) were already presented in previous works [1, 10–13]. In accordance with those publications an approximation of the mentioned dependence up to 12 wt.% of Al was realized (Fig. 1). The relevant SFE values for Al and those calculated for the Mn-C-Fe systems were added. It was also supposed that Mn, C and Fe did not influence the SFE level of Al importantly [14, 15]. Evaluation of the SFE changes did not comprise an influence of magnetic characteristics connected with $\gamma \rightarrow \varepsilon$ transformation (anti-ferromagnetic $\Leftrightarrow$ paramagnetic process), too. The corresponding parameters are very low [10, 15]. This is the reason why these values were not taken into account.

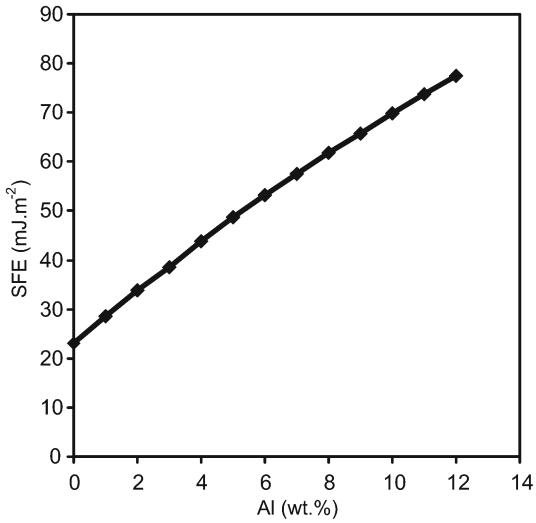

Fig. 1. Effect of aluminium content on the SFE.

Table 1. Chemical composition of the Fe-Mn-C alloys

Mn (wt.%)	0.65 C	0.85 C
	Fe (wt.%)	
10.00	89.35	89.15
14.00	85.35	85.14
19.00	80.35	80.15
21.57	77.78	77.58
23.00	76.35	76.15
26.00	73.35	73.15
30.00	69.35	69.15

3. Chosen experimental material

For high manganese Fe-Mn-C alloy types (the TWIP variant) with the graded Mn content (10–30 wt.%) at constant C level (0.65 and 0.85 wt.%), an evaluation of the SFE was realized using mathematical calculation. Considered chemical compositions are given in Table 1. Further, the same was car-

Table 2. Chemical composition used for the SFE calculation (the TWIP variant)

C (wt.%)	20 Mn	23 Mn	27 Mn	30 Mn
	Fe (wt.%)			
0.65	79.35	76.35	72.35	69.35
0.85	79.15	76.15	72.10	69.15
1.00	79.00	76.00	72.00	69.00
1.20	78.80	75.80	71.80	68.80

Table 3. Chemical composition used for the SFE calculation (the TRIPLEX variant without 12 wt.% of Al)

C (wt.%)	20 Mn	23 Mn	27 Mn	30 Mn
	Fe (wt.%)			
0.65	67.35	64.35	60.35	57.35
0.85	67.15	64.15	60.10	57.15
1.00	67.00	64.00	60.00	57.00
1.20	66.80	63.80	59.80	56.80

ried out for the constant Mn content (20, 23, 27, and 30 wt.%) and varying C content (0.65, 0.85, 1.0, and 1.2 wt.% as Table 2 summarizes). Subsequently, the SFE levels were calculated for the constant Mn content (20, 23, 27, and 30 wt.%), varying C one (0.65–1.2 wt.%) and Fe content corresponding to quaternary Fe-(20–30 wt.%)Mn-(0.65–1.2 wt.%)C-12Al system of the TRIPLEX alloys. Since the value of interaction parameter between the Mn and Al is not available at present, the SFE calculation approach was performed in modified ternary Mn-C-Fe alloy and the Al influence was not taken into account. Namely, some experimentally determined temperatures corresponding to the γ/ε allotropic phase boundary in the Fe-Mn system including Al revealed that contribution of the binary Mn-Al parameter term to the total molar free enthalpy was very small compared to the other terms. Calculated errors corresponded to $\pm 25\,\mathrm{J\,mol^{-1}}$ [16]. However, in final calculation the approximated SFE level of Al (for 12 wt.% of Al) was figured. The chemical compositions of the evaluated TRIPLEX alloys are given in Table 3.

4. Reached results and discussion

Regarding the TWIP alloys, Fig. 2 represents the calculated SFE vs. Mn content. Alloy with Mn range of 10–30 wt.% and the constant C content of 0.65 wt.% shows the SFE difference of $27.60\,\mathrm{mJ\,m^{-2}}$. For the 0.85 wt.% C content, the similar SFE difference represents $24.42\,\mathrm{mJ\,m^{-2}}$. According to Fig. 2, differences between the SFE levels of investigated material containing 0.65 and 0.85 wt.% of C for one Mn level are always negligible. Consequently, C will not cause any important SFE changes under given conditions regarding the TWIP alloy. However, the Mn content will significantly influence the SFE level. The higher Mn volume fraction, the higher SFE can be detected. According to former information [12, 13], lower SFE than $18\,\mathrm{mJ\,m^{-2}}$ leads to $\gamma \rightarrow \varepsilon$ transformation in case of TWIP alloy. Both evaluated TWIP variants show that the threshold level corresponds to 19 % of Mn content. In comparison with Schumann's stability map (after tensile testing) [1, 4] material containing 0.65 wt.% of C is located in possible $\gamma \rightarrow \varepsilon$-martensite trans-

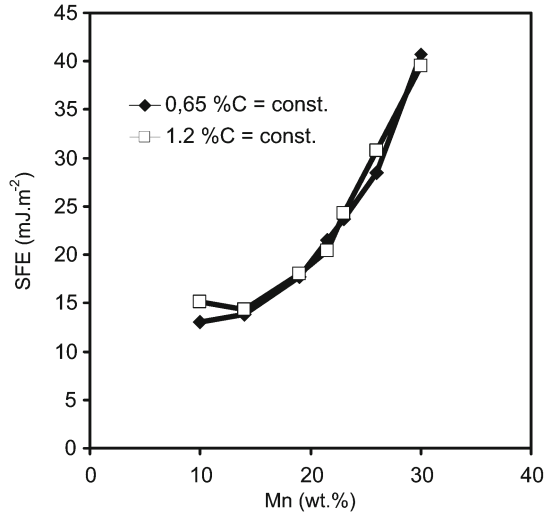

Fig. 2. Calculated SFE values in dependence on the Mn content (the TWIP variant).

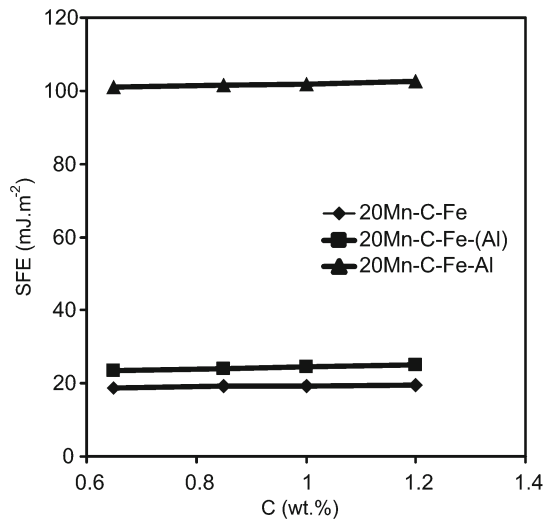

Fig. 3. SFE vs. carbon content for 20 wt.% of Mn.

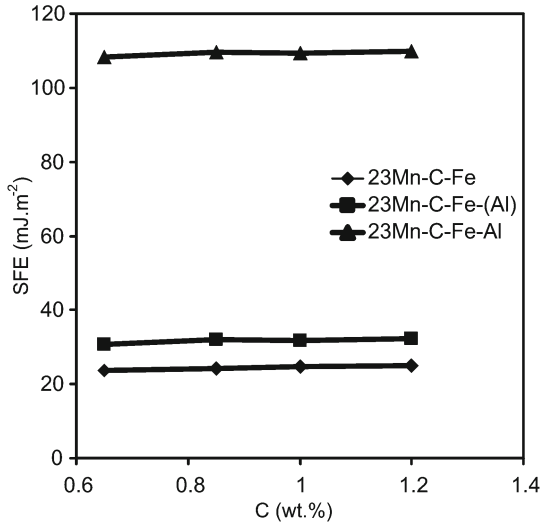

Fig. 4. SFE vs. carbon content for 23 wt.% of Mn.

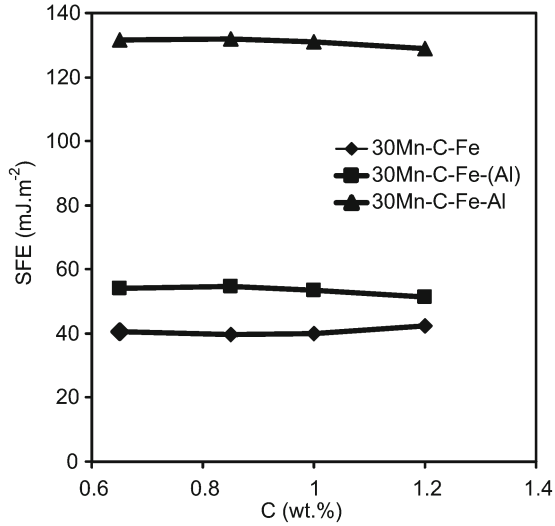

Fig. 6. SFE vs. carbon content for 30 wt.% of Mn.

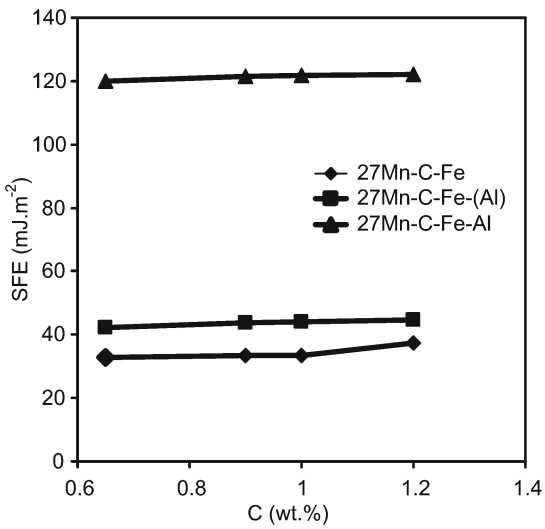

Fig. 5. SFE vs. carbon content for 27 wt.% of Mn.

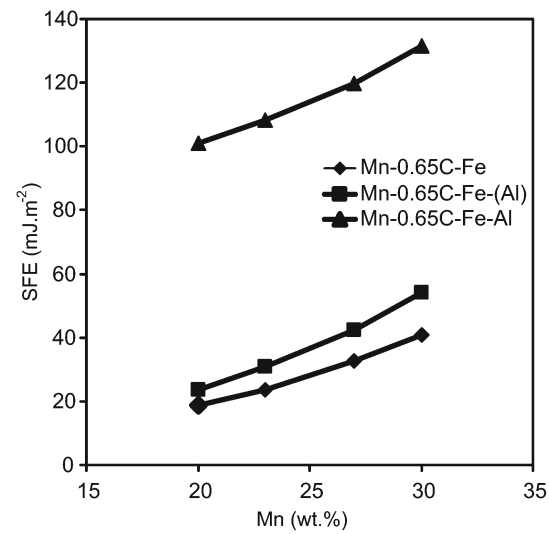

Fig. 7. SFE vs. manganese content for 0.65 wt.% of C.

formation area unlike alloy with 0.85 wt.% of C being situated on the threshold level as it follows from calculation. This deviation only represents 3.75 mJ m^{-2} and can be taken as insignificant. On the basis of electron microscopy results some authors shift the $\gamma \rightarrow \varepsilon$-martensite transformation to 20–25 mJ m^{-2} [2, 4].

Further, for the constant Mn content (20, 23, 27 and 30 wt.%) and varying C level (1 and 1.2 wt.%) the SFE was calculated as well. In Figs. 3–6 (SFE vs. C content) and in Figs. 7–10 (SFE vs. Mn content), down curves summarize results. In all figures down curve representing the TWIP alloy is described as Mn-C-Fe. The increasing C content leads to very low SFE changes generally. The TWIP alloys with 20, 23 and 30 wt.% of Mn and 0.65–1.2 wt.% of C content show 0.59, 1.41 and 1.59 mJ m^{-2} differences in SFE. The determined changes represent 3.1, 6.0 and 3.9 % increase in SFE with 0.55 wt.% C growth, as can be seen in Figs. 3, 4 and 6. It is partially surprising that chemical composition of the TWIP variant with 27 wt.% of Mn and considered C interval (0.65–1.2 wt.%) shows 4.76 mJ m^{-2} of the SFE difference. Mentioned level represents 14.6 wt.% and the Fig. 5 (down curve again) demonstrates the SFE dependence on the C content with constant Mn one (27 wt.%). Within the 20–30 wt.% of Mn and constant C content the SFE levels increase between 20.2–22.8 mJ m^{-2}. On average it corresponds to 21.3 mJ m^{-2} representing 110.7 %. The highest SFE change shows the TWIP variant with 30 wt.% of

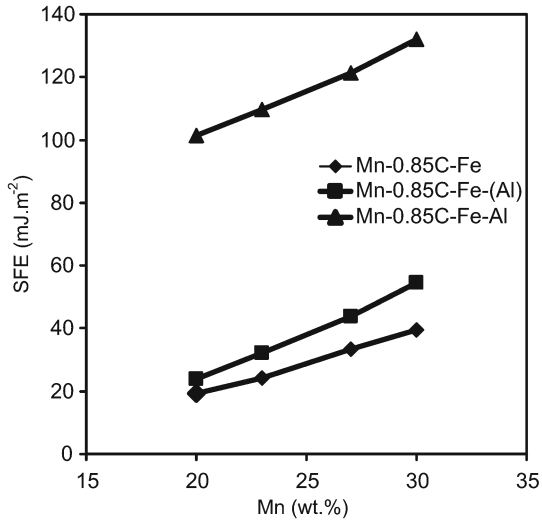

Fig. 8. SFE vs. manganese content for 0.85 wt.% of C.

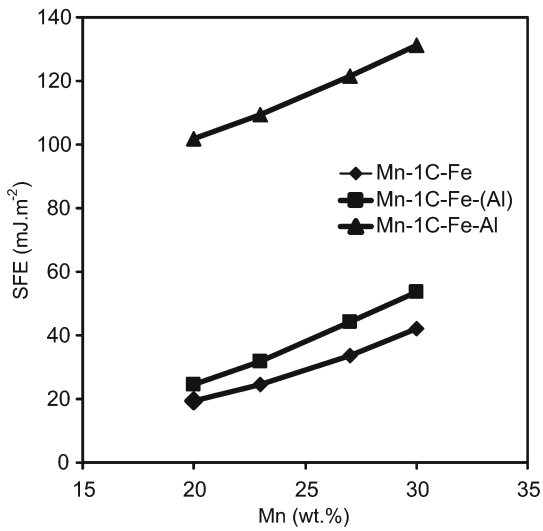

Fig. 9. SFE vs. manganese content for 1.0 wt.% of C.

Mn. The above-described results are given in Figs. 3–6.

Regarding differences in the SFE of the modified TRIPLEX alloys (with 20, 23, 27, and 30 wt.% Mn content in carbon interval 0.65–1.2 wt.%) having lower Fe volume fraction (decreased in 12 wt.% of Al content), those correspond to 1.47 mJ m^{-2} (for 20 wt.% of Mn), to 1.53 mJ m^{-2} (for 23 wt.% of Mn), to 2.38 mJ m^{-2} (for 27 wt.% of Mn), and to 3.32 mJ m^{-2} (for 30 wt.% of Mn), thus to 6.3, 5.0, 5.6 and 6.5 % (in sequence). It can be also noted, the detected SFE differences are not important with varying C content. All observed changes are of comparable level, as the second (middle) curve of each plot (of the Figs. 3–6) demonstrates. These curves are described as the Mn--C-Fe-(Al).

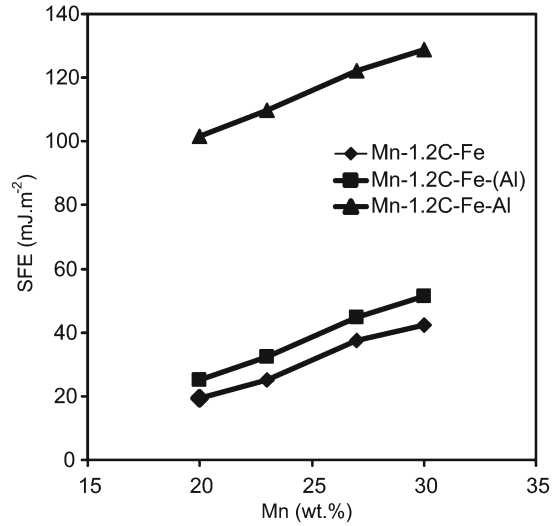

Fig. 10. SFE vs. manganese content for 1.2 wt.% of C.

Between the TWIP alloy and the modified TRIPLEX one the SFE differences are not higher than 1.4 times (maximal level for 30 wt.% of Mn) and 1.3 times on average. The curves for the Mn-C-Fe-(Al) modified TRIPLEX variants (total chemical composition only equals 88 wt.%) demonstrate higher SFE level unlike the TWIP alloys, even when both materials have comparable Mn and C contents. The Fe level is only by 12 wt.% higher in the TWIP alloy (total chemical composition equals 100 wt.%). This bags the question. Does not the Mn content show a more dominant effect (on the SFE level) with decreasing Fe volume fraction? The reached results indicate it.

Diagrams of SFE vs. varying Mn content and the constant C level (0.65, 0.85, 1.0 and 1.2 wt.%) show Figs. 7–10. The down curves represent the TWIP variant again. The SFE increases of the TWIP alloys (between 20 and 30 wt.% of Mn and constant 0.65, 0.85, 1.0 and/or 1.2 wt.% of C) correspond to 21.3, 20.2, 20.5 and 22.8 mJ m^{-2} (21.2 mJ m^{-2} on average) representing 115.6, 104.7, 105.9 and 117.3 %, respectively, or 110.9 % on average. In case of the modified TRIPLEX variant (the middle curve of the Figs. 7–10) the SFE increases equal 26.4–30.6 mJ m^{-2} (29.2 % on average) representing 105.7–130 % (120.7 % on average). The highest difference was found out for the lowest C content and the lowest SFE difference was mathematically detected when the C content was lying on the level of 1.2 wt.%. Anyway, results indicate a stronger Mn effect in matrix with lower C content.

As follows from Fig. 1, the SFE of 12 Al wt.% is corresponding to 77.5 mJ m^{-2} [15]. After adding this value to each calculated SFE level for the modified TRIPLEX variant, the total SFE of the Mn-C--Fe-Al alloy containing four different Mn levels (20–30 wt.%) can be obtained. These data are summar-

ized in Figs. 3–6 for one Mn level (being constant) and varying C content and/or in Figs. 7–10 for one C content and varying Mn level. The final SFE of the TRIPLEX alloy is always demonstrated by the upper curve (being denominated as the Mn-C-Fe-Al) in each diagram. The SFE is lying on the level of 101–132 mJ m^{-2}. The average determined SFE levels equal 101.73 mJ m^{-2} (for 20 Mn wt.%) and 130.93 mJ m^{-2} (for 30 Mn wt.%). The calculated SFE values of the TRIPLEX alloys were compared with these being presented in [11, 14] and after their approximation up to 12 wt.% of Al. The SFE levels (for 20, 23, 27, and 30 wt.% of Mn) correspond to 110.4, 115.4, 123.9, and 129.6 mJ m^{-2}, respectively. The average value equals 119 mJ m^{-2}. In work [14] carbon content was only lying between 0.053–0.08 wt.% and Si, P and S contents were also analysed in chemical composition. Especially the Si content moderately supported the SFE increase. In presented contribution the heats were clean. Using ultrasound during solidification a high Al homogeneity was supported.

5. Conclusions

For varying Mn content (10–30 wt.%) and two C levels (0.65 and 0.85 wt.%) the stacking fault energies (SFE) of the TWIP alloys were calculated. The results confirmed an important increase of the SFE level with a higher Mn content. For varying Mn contents (20–30 wt.%) and broader C range (0.65–1.2 wt.%), the SFE results showed the same tendency as in an above-mentioned case and a weak C impact on the SFE increase.

For four Mn levels (20, 23, 27, and 30 wt.%), four C contents (0.65, 0.85, 1, and 1.2 wt.%) and one Al level (12 wt.%), the SFE of the TRIPLEX alloys were calculated. In comparison with the TWIP alloys the results of the SFE calculations of the TRIPLEX alloys (lower Fe content by presented 12 wt.% of Al) indicated more predominant Mn effect. The C content (0.65–1.2 wt.%) showed the same tendency to the SFE level like in case of the TWIP alloys. The total SFE of the TRIPLEX alloy was calculated as a sum of the SFE of the modified TRIPLEX alloy (without Al content) and the aluminium SFE found after the approximation of known data (the SFE vs. Al content). The results are relatively in good agreement with former presented data.

Acknowledgements

This work was financially supported by the Ministry of Education of the Czech Republic under the project MSM6198910015. This support it gratefully acknowledged.

References

[1] SCHUMANN, V. H.: Neue Hütte, *17*, 1972, p. 605.
[2] GRÄSSER, O.—FROMMEYER, G.: Mat. Sci. Technol., *14*, 1998, p. 1213.
[3] MAZANCOVÁ, E.: New material types for automotive industry – physical engineering properties of high strength materials alloyed with manganese and of metal hydrides alloys for hydrogen storage (in Czech). Ostrava, VŠB – TU Ostrava 2007.
[4] SCOTT, S.—ALLAIN, M.—FARAL, M.—GUELTON, N.: Revue de Métallurgie, 2006, *103*, p. 294.
[5] FROMMEYER, G.—BRÜX, U.: Steel Research Int., *77*, 2006, p. 627.
[6] BRACKE, L.—MERTENS, J.—PENNING, J.—DE COOMAN, B. C.—LIEBEHERR, M.—AKDUT, N.: Met. Mat. Trans., *37A*, 2006, p. 307.
[7] OLSON, G. B.—COHEN, M.: Met. Mat. Trans., *7A*, 1976, p. 1897.
[8] LEE, Y. K.—CHOI, C. S.: Met. Mat. Trans., *31A*, 2000, p. 355.
[9] ONO, Y.—TSUCHIYAMA, T.—TAKAKI, S.: Tetsu-to-Hagané, *84*, 1999, p. 309.
[10] ALLAIN, S.—CHATEAU, J. P.—BOUAZIZ, O.—MIGOT, S.—GUELTON, N.: Mat. Sci. Eng. A, *387–389*, 2004, p. 158.
[11] DUMAY, A.—CHATEAU, J.-P.—ALLAIN, S.—MIGOT, S.—BOUAZIZ, O: Mat. Sci. Eng. A, *483–484*, 2008, p. 184.
[12] MAZANCOVÁ, E.—KURSA, M.—MAZANEC, K.: Metallurgical Journal, *61*, 2008, p. 71.
[13] BLECH, W.—PHIU-ON, K.—HEEVING, CH.—HIRT, G.: Steel Research Int., *78*, 2007, p. 536.
[14] SATO, K.—ICHINOSE, M.—HIROTSU, Y.—INOUE, Y.: ISIJ Int., *29*, 1989, p. 868.
[15] MAZANCOVÁ, E.—MAZANEC, K.: Materials Engineering, *16*, 2009, p. 22.
[16] ISHIDA, K.—NISHIZAWA, T.: Trans. Jpn. Inst. Met., *15*, 1974, p. 225.