# STACKING FAULT ENERGY IN HIGH MANGANESE ALLOYS

Eva Mazancová, Karel Mazanec

Received 15th April 2009; accepted in revised form 20th April 2009

#### Abstract

Stacking fault energy of high manganese alloys (marked as TWIP and TRIPLEX) is an important parameter determining deformation mechanism type realized in above mentioned alloys. Stacking fault energy level can be asserted with a) gliding of partial and/or full dislocations, b) gliding mechanism and twinning deformation process in connection with increasing of fracture deformation level (deformation elongation) and with increasing of simultaneously realized work hardening proces., c) gliding mechanism and deformation induced *E*-martensite formation.

In contribution calculated stacking fault energies are presented for various chemical compositions of high manganese alloys. Stacking fault energy dependences on manganese, carbon, iron and alluminium contents are presented. Results are confronted with some accessible papers. The aim of work is to deepen knowledge of presented data. The TWIP and TRIPLEX alloys can be held for promissing new automotive materials.

Keywords: High manganese alloys, stacking fault energy, dislocation glide, twining deformation, shear band induced plasticity.

#### 1. Introduction

High manganese TWIP and TRIPLEX alloys represent new perspective material types, showing not only high strength property, however toughness and ductility in wide temperature interval, too and high specific energy absorption ( $E_{spec.}$ ) in impact, simultaneously. That is reason why those materials are useful for automotive industry and not only for bodywork production however for various automotive components as well. The alloys can be also applied as vessels materials one for liquid gasses transport advantageously. TRIPLEX variant is also suitable for rotating elements production in consequence of lower matrix density thanks of the increased aluminium and manganese content [1-3].

Material TWIP (twining induced plasticity) is characterized by Fe-Mn-C chemical composition with low aluminium content, eventually, even with limited silicon, respectively. Material TRIPLEX (beside iron three elements) is constituted on the basis of Fe-Mn-C-Al with aluminium content higher than 8 wt % and without silicon content. Depending on high manganese type and on carbon content manganese reaches higher level than 19 wt. % usually and in this way guarantees the basic austenite microstructure of the FCC type, consequently [1, 4, 5]. The TWIP alloy microstructure is monolithic, austenitic and the sole deformation process is twinning one, whereas the basic FCC TRIPLEX microstructure shows annealing twins. The microstructure consists of 8-10 ferrite wt. % in average and of the same nano-size k-carbides volume fraction, practically. The sole deformation mechanism is shear induced plasticity, so called SIPeffect accompanied with dislocation glide. Shear bands have regular arrangement in {111} planes. Above mentioned characteristics are depending on stacking fault energy.

The aim of presented work is to deepen knowledge about stacking fault energies being responsible for deformation process type realized in TWIP and TRIPLEX high manganese steels.

#### 2. Stacking fault energy calculation model

Properties of mentioned material types are depended on chemical composition determining stacking fault energy level. Stacking fault energy represents an important quantity characterizing the deformation type being realized in given high manganese alloy. Below mentioned deformation mechanisms can be detected in dependence on the stacking fault energy increase:

E. Mazancová, Prof. Ing. CSc.; K. Mazanec, Prof. Ing. DrSc. – Department of Material Engineering, Faculty of Metallury and Material Engineering, VŠB-Technical University of Ostrava, Tř. 17. listopadu 15, 708 33 Ostrava-Poruba, Czech Republic.

<sup>&</sup>lt;sup>\*</sup>Corresponding author, e-mail address: eva.mazancova@vsb.cz

- a) dislocation gliding and work hardened induced martensite phase transformation;
- b) dislocation gliding and mechanical twinning process;
- c) dislocation gliding [3, 6].

The TWIP variant is connected with higher stacking fault energy than 18 mJ.m<sup>-2</sup> ensuring deformation by mechanical twining preferentially. That movement is conditioned by slip of partial dislocations of a/6<112> leading to the stacking faults in consecutive parallel {111} planes. In case of lower stacking fault energy than is 18mJ.m<sup>-2</sup>  $\varepsilon$ -martensite is formed when the same dislocation glide in every second {111} plane type occurs. Given deformed area shows very fine lamella and/or platelet form being of hexagonal structure (HCP). Under those conditions  $\varepsilon$ -martensite can be originated, being however unsuitable for TWIP material, because its formation leads to a partial ductility reduction [7, 8].

With regard to basic chemical composition the Triplex variant shows much higher stacking fault energy than the TWIP one. The stacking fault energy of the first mentioned variant should lie in interval of  $80-140 \text{mJ.m}^{-2}$  [2, 4]. The stacking fault energy can be determined using TEM of thin foils. This method is very complicated and time-consuming. In essence, stacking fault energy defines realized deformation type in matrix and that is way of its mathematical determination for concrete chemical composition of high manganese alloys. For ternary system the SFE comes out from molar surface atoms density p in close arranged plane of the {111} type, from molar free enthalpy  $\Delta G$  of the  $\gamma \rightarrow \varepsilon$ -martensite phase transformation and from interface energy between  $\gamma$ (FCC) and  $\varepsilon$  (HCP) phases being marked  $\sigma^{\gamma/\varepsilon}$  in eqn. (1) [7, 9]:

$$SFE = 2\rho \Delta G^{\gamma \to \varepsilon} + 2\sigma^{\gamma \varepsilon} \tag{1}$$

Molar surface density ( $\rho$ ) is geometrically stated using the alloy lattice parameter (a) and Avogadro's number in calculation according equation (2) [1]. Ono et al. [10] measured this parameter at normal temperature. On the basis of their results constant value of that parameter being equal 0,361 nm is chosen.

$$\rho = (4/3)^{1/2} \cdot 1/(a^2 \cdot N) \tag{2}$$

In the Fe-Mn-C system molar free enthalpy level  $\Delta G^{\gamma \to \varepsilon}$  can be expressed as follows [6]:

$$\Delta G^{\gamma \to \varepsilon} = X_{Fe} \cdot \Delta G_{Fe}^{\gamma \to \varepsilon} + X_{Mn} \cdot \Delta G_{Mn}^{\gamma \to \varepsilon} + X_C \cdot \Delta G_C^{\gamma \to \varepsilon} + X_{Fe} \cdot X_{Mn} \cdot \Omega_{FeMn}^{\gamma \to \varepsilon} + X_{Fe} \cdot X_C \cdot \Omega_{FeC}^{\gamma \to \varepsilon} + X_{Mn} \cdot X_C \cdot \Omega_{MnC}^{\gamma \to \varepsilon}$$
(3)

In this dependence  $X_{Fe}$ ,  $X_{Mn}$ ,  $X_C$  represent molar fraction of iron, manganese and carbon,  $\Delta G_{Fe}^{\gamma \rightarrow \epsilon}$ ,  $\Delta G_{Mn}^{\gamma \rightarrow \epsilon}$  a  $\Delta G_C^{\gamma \rightarrow \epsilon}$  express changes in molar free enthalpy between  $\gamma$  and  $\epsilon$  phases,  $\Omega_{FeMn}^{\gamma \rightarrow \epsilon}$ ,  $\Omega_{FeC}^{\gamma \rightarrow \epsilon}$ ,  $\Omega_{MnC}^{\gamma \rightarrow \epsilon}$  are differences between interaction parameters of Fe and Mn, of Fe and C, of Mn and C in  $\gamma$  and  $\epsilon$  phases. In presented processing data published in paper [11] for  $\Delta G_{Fe}^{\gamma \rightarrow \epsilon}$  and  $\Delta G_{Mn}^{\gamma \rightarrow \epsilon}$  were used. Further thermo-dynamical data and constants used for the mathematical SFE evaluation are summarized in Tab. 1 [12].

Tab. 1

Thermodynamical data for SFE calculation			
Parameter	Used data	Ref.	
$\Delta G_{Fe}^{\gamma \rightarrow \epsilon}$	-821,85 + 1,685T + 0,00222T <sup>2</sup> [Jmol <sup>-1</sup> ]	[9]	
$\Delta G_{Mn}^{ \gamma \rightarrow \epsilon}$	3 925 – 2,7T + 0,00455T <sup>2</sup> [Jmol <sup>-1</sup> ]	[9]	
$\Delta {G_C}^{\gamma \to \epsilon}$	-24 630 [Jmol <sup>-1</sup> ]	[10]	
$\Omega_{FeMn}^{ \gamma \to \epsilon}$	-9 135,5 + 15 282,1 X <sub>Mn</sub> [Jmol <sup>-1</sup> ]	[9]	
${\Omega_{FeC}}^{\gamma \to \epsilon}$	$\Omega_{\text{FeC}}^{\gamma \to \epsilon}$ 42 500 [Jmol <sup>-1</sup> ]		
$\Omega_{MnC}^{\gamma \to \epsilon}$	26 910 [Jmol <sup>-1</sup> ]	[5]	



Fig. 1. Stacking fault energy (SFE) and aluminium content plotting

For mathematical calculation further necessary parameters were also presented in some works [7, 9]. The above presented data are concerning the ternary system. In case of quaternary one the situation is much more complicated. Consequently, for the TRIPLEX variant similar SFE calculation was applied as for TWIP materials hence for ternary Mn-C-Fe system without aluminium content and its 12 wt. % fraction subtracted from iron one. That alloy is marked as Mn-C- Fe- (Al) below. Aluminium content significantly contributes to stacking fault energy increase. Stacking fault energy values vs aluminium contents were already presented former [13, 14]. In accord with those publications an approximation of mentioned dependence up to 12 wt. % of aluminium was realized and that is presented in Fig. 1. Relevant stacking fault energy values for aluminium and those calculated for the ternary Mn-C-Fe-(Al) system were added (TRIPLEX alloy).

Into evaluation of stacking fault energies changes influence of magnetic characteristics connected with  $\gamma \rightarrow \varepsilon$ -martensite transformation (anti-ferromagnetic  $\Leftrightarrow$ paramagnetic process) is not included. The corresponding parameters are very low (see [6]). It is reason why these values are not taken into account.

Chemical composition (in wt. %) of TWIP alloys

Tab. 2

Chemical composition (in wi. 70) of 1 will alloys				
Mn	C = 0.65	C = 0.85		
	Fe			
30	69.35	69.15		
26	73.35	73.15		
23	76.35	76.15		
20	79.35	79.15		
19	80.35	80.15		
14	85.35	85.15		
10	89.35	89.15		



Fig. 2. Stacking fault energy (SFE) and manganese content (TWIP alloy)

Chemical composition (in wt. %) for stacking fault energy calculation (TWIP)

Mn = 20		Mn = 30		
С	Fe	С	Fe	
0.65	79.35	0.65	69.35	
0.85	79.15	0.85	69.15	
1.00	79.00	1.00	69.00	
1.2	78.80	1.2	68.80	

## 3. Approaching the problem

For high manganese Fe-Mn-C alloy types (TWIP variant) with graded manganese content (10 - 30 wt. % as Tab. 2 demonstrates) at constant carbon level (0.65 and 0.85 wt. %) stacking fault energy evaluation was determined using mathematical calculation. Results are depicted in Fig. 2. Further, the same was carried out for constant manganese content (20 and 30 wt. %) and varying carbon one (0.65 - 1.2 wt. % as Tab. 3 shows). Subsequently, stacking fault energies were evaluated for constant manganese content (of 30 wt. %) with lower iron fraction reduced in 12 wt. % of aluminium content following from Fe-30Mn-(0.6–1.2)C-12A1 TRIPLEX alloy evaluation. Tab. 4 summarizes chemical compositions of evaluated heats.

Tab. 4

Tab. 3

Chemical composition (in wt. %) for stacking fault energy calculation (TRIPLEX with 12 wt. % of aluminium)

Mn = 20		Mn = 30		
С	Fe	С	Fe	
0.65	67.35	0.65	57.35	
0.85	67.15	0.85	57.15	
1.00	67.00	1.00	57.00	
1.2	66.80	1.2	56.80	

## 4. Results and discussion

Regarding the TWIP alloy (Tab. 2 shows chemical composition), in Fig. 2 calculated stacking fault energies vs manganese content are ploted. Alloy with manganese range of 10-30 wt. % and constant carbon content of 0.65 wt. % shows stacking fault energies difference corresponding to 27.60mJ.m<sup>-2</sup>. For the 0.85 wt % carbon content the similar stacking fault energies difference represents 24.42 mJ.m<sup>-2</sup>. According Fig. 2 differences between stacking fault

energies of investigated material containing 0.65 and 0.85 wt. % of carbon for one manganese level are always negligible. Consequently, carbon will not caused any important stacking fault energy changes under given conditions regarding the TWIP alloy. However, stacking fault energy will be influenced by manganese content. The higher manganese volume fraction the higher stacking fault energy can be detected.

According former information [4] lower stacking fault energy than 18 mJ.m<sup>-2</sup> leads to  $\gamma \rightarrow \varepsilon$ transformation in case of TWIP alloy. Evaluated both TWIP variants show, the threshold level corresponds to 19 % of manganese content. In comparison with Schumann's stability map (after tensile testing) [4] material containing 0.65 wt. % of carbon is located in possible  $\gamma \rightarrow \varepsilon$ -martensite transformation area unlike alloy with 0.85 wt. % of carbon being situated on the threshold level as it follows from calculation. This deviation represents 3.75mJ.m<sup>-2</sup> only and could be taken for an insignificant. On the basis of electron microscopy results some authors shift the  $\gamma \rightarrow \varepsilon$ martensite transformation to 20-25mJ.m<sup>-2</sup> [2, 4, 15].

Stacking fault energy plotting versus carbon content with constant manganese levels for TWIP alloy and Mn-C-Fe-(Al) one Fig. 3 (20 manganese wt. %) and Fig. 4 (30 manganese wt. %) demonstrate. Increasing carbon content leads to very low stacking fault energy changes generally. TWIP aloy with 20 wt. % of manganese and 0.65-1.2 wt. % of carbon content shows 0.59mJ.m<sup>-2</sup> difference in stacking fault energy only, whereas TWIP alloy with 30 wt. % of manganese content 1.59 mJ.m<sup>-2</sup> in above mentioned carbon interval. Both changes present 3.1 % and 3.9 % increase in stacking fault energy with 0.55 % carbon growth as in Fig. 3 and Fig. 4 can be seen. Regarding differencies in stacking fault energy of alloys (with 20 wt % and 30 wt. % manganese content in carbon interval 0.65 -0.85 wt. % ) having lower iron fraction reduced in 12 wt. % of aluminium content (TRIPLEX alloy), those correspond 1.47mJ.m<sup>-2</sup> (for 20 wt. % of Mn) and 3.32mJ.m<sup>-2</sup>, thus 3.3% and 6.5%. Both differencies are of comparable level how Fig. 3 and Fig. 4 represent. Between TWIP alloy and Mn-C-Fe-(Al) one stacking fault energy differences are not higher than twice (twice for 20 wt. % of manganese and 1.7 times for 30 wt. % of manganese). It could be stated, detected differences are not important, as well.

Figure 3 and Fig. 4 demonstrate significant stacking fault energy susceptibility further to manganese content again. Two TWIP alloys containing 20 and 30 wt % of manganese show the stacking fault



Fig. 3 Stacking fault energy (SFE) dependence on carbon content, with constant manganese content (20 wt. %)



Fig. 4 Stacking fault energy (SFE) dependence on carbon content, with constant manganese content (30 wt. %)

energy discrepancy of 20.67-22,83mJ.m<sup>-2</sup>, representing 21.8mJ.m<sup>-2</sup> in average. In case of Mn-C-Fe-(Al) alloy those differences correspond 27.86-29.71mJ.m<sup>-2</sup> thus 28.8mJ.m<sup>-2</sup> in average. Detected changes in stacking fault energies of the TWIP and Mn-C-Fe-(Al) alloys are significant already. In comparison with the TWIP alloy, the Mn-C-Fe-(Al) one shows higher stacking fault energy level always. The higher manganese contents are analysed in alloys, the more important differences are observed in calculations. This begs the question whether in Mn-C-Fe-(Al) alloy the lower iron content does not contribute to higher manganese predomination effecting the stacking fault energy intensively. Namely, the same iron change of 0.55 wt. % causes differences of  $0.53 \text{ mJ.m}^{-2}$  (average value) in stacking fault energy of TWIP and of Mn-C-Fe-(Al) alloys where 20 wt. % of manganese is constant unlike the 2.75 mJ.m<sup>-2</sup> (TWIP alloy) and 4.35 mJm<sup>-2</sup> (Mn-C-Fe-(Al) alloy) corresponding to 30 wt. % of manganese being constant. That is true, the differencies are very low, however indicate that iron content is negligible and confirm the manganese weight in high manganese alloys.

Tab. 5 Calculated stacking fault energy levels (in mJ.m<sup>-2</sup>) for 20 a 30 wt % of manganese (in wt. %) and varying carbon content (in wt. %)

N Ave	SFE	С			
IVIN		0.65	0.85	1.0	1.2
	none Al	23.50	24.03	24.43	24.97
20	with Al	101.00	101.53	101.93	102.47
	none Al	54.05	54.68	53.62	51.36
30	with Al	131.55	132.18	131.12	128.86

As from Fig. 1 follows the stacking fault energy of 12 aluminium wt. % is corresponding to 77.5mJ.m<sup>-2</sup>. After adding that level to values depicted in Fig. 3 and Fig. 4 (curves for 20 and 30 manganese volume fraction of Mn-C-Fe-(Al) alloy) total stacking fault energies of Mn-C-Fe-(Al) alloy containing 20 and/or 30 wt. % of manganese can be obtained. These data are summarized in Tab. 5 varying with different canbon content slightly being in agreement with carbon influence on stacking fault energy level. The average determined stacking fault energies equel  $101.73 \text{mJ.m}^{-2}$  (for 20 manganese wt. %) and 130.93mJ.m<sup>-2</sup> (for 30 manganese wt. %). Calculated stacking fault energies values of TRIPLEX alloys compared with those being presented in work [13] are in good coincidence.

## 5. Conclusions

In work stacking fault energies of high manganese alloys (TWIP and TRIPLEX) were calculated and compared with available results.

Carbon and iron content does not influence stacking fault energy significantly unlike manganese and aluminium content. TWIP alloys with different carbon content (0.65 and 0.85 wt. %) show none differencies practicaly. Those are observed with varying manganese level (from 10 wt. % to 30 wt. %) corresponding  $26 \text{mJ.m}^{-2}$  in average. In case of considered carbon contents the stacking fault energies correspond to  $19 \text{mJ.m}^{-2}$  (for 20 wt. % of manganese) and  $40 \text{mJ.m}^{-2}$  (for 30 wt. % of manganese) approximately.

According calculations and using approximation of aluminium stacking fault energy the total stacking fault energies of TRIPLEX alloys with two different manganese levels (20 and 30 wt %) and 12 wt. % of aluminium corresponded 102mJ.m<sup>-2</sup> (20 wt. % of manganese content) and 131mJ.m<sup>-2</sup> (30 wt. % of manganese content) in average. Those results are in good coincidence with already presented conclusions.

#### Acknowledgements

Authors acknowledge the Ministry of Education, Youth and Sports of Czech Republic for financial support of project MSM6198910015.

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