

Investigation of Phase Transformation Mechanism of High Manganese Steel Mn15Cr2 Heat-treated by Subzero Temperature Process

Nguyen Duong Nam, Le Thi Chieu, Nguyen Minh Truc, Pham Mai Khanh*

Abstract— This article presents the results of research on the mechanism of phase transformation of high manganese steel after heat treatment, impact and subzero temperature process. The results of stacking fault energy calculation showed value of stacking fault energy after heat treatment is 28.74 mJ.m^{-2} ; after subzero temperature process at -80°C is 28.55 mJ.m^{-2} . The results of the analysis by SEM, TEM found that no martensite; only twinning and sliding strip. Also in the microstructure has small Cr_7C_3 carbide particles finely dispersed in microstructure. Hardness values of sample after subzero temperature process is smaller than that in untreated sample.

Index Terms— High Manganese Steel (HMnS), TEM, stacking fault energy (SFE), twinning, sliding strip.

1 INTRODUCTION

The Austenitic Manganese Steel is still used extensive with minor modification in composition and heat treatment, primarily in field of mining, earthmoving, oil-well drilling, steel-making manufacturing of cement clay products, rail-roading, dredging... Austenitic manganese steel used chiefly in equipment for handling and processing earthen materials as rock crushers, grinding mills, power-shovel buckets, cane teeth and pumps for handling and in a multitude of classed applications. Another importance use is in railway track work at switches and crossing.

The stacking-fault energy (SFE) is a materials property on a very small scale. It is noted as γ_{SFE} in units of energy per area. Stacking-fault energy is a primary factor in determining the wear resistance of a metal and, primarily, its resistance to galling [1].

A stacking fault is an interruption of the normal stacking sequence of atomic planes in a crystal structure. When the SFE is high the dissociation of a full dislocation into two partials is energetically unfavorable, and the material deforms only by dislocation glide. Lower SFE materials display wider stacking faults and have more difficulties for cross-slip and climb. The

SFE modifies the ability of a dislocation in a crystal to glide onto an intersecting slip plane. When the SFE is low, the mobility of dislocations in a material decreases [2,3].

A subregular solution thermodynamic model was used to calculate the stacking fault energies (SFE) of high-manganese (10 to 35 wt%) steels with carbon contents of 0 to 1.2 wt%. Based on these calculations, composition-dependent diagrams were developed showing the regions of different SFE values for the mentioned composition range [4].

Based on the fact that a single stacking fault can be viewed as two layers of HCP structure, Olson and Cohen proposed that the SFE in face-centered cubic (FCC) steels can be expressed as [1]:

$$SFE = 2\rho\Delta G^{\gamma\rightarrow\epsilon} + 2\sigma^{\gamma/\epsilon} \quad (1)$$

where ρ is the molar surface density along {111} planes, which is related to lattice parameter a . $\Delta G^{\gamma\rightarrow\epsilon}$ is the free energy for the $\gamma\rightarrow\epsilon$ transformation, and $\sigma^{\gamma/\epsilon}$ interfacial energy per unit area of γ and ϵ phases boundary. As for transition metal, the value of $\sigma^{\gamma/\epsilon}$ is usually taken as 9 mJ/m^2 . Based on the regular solution model, $\Delta G^{\gamma\rightarrow\epsilon}$, can be calculated using the following formula:

$$\Delta G^{\gamma\rightarrow\epsilon} = \Delta G_{\text{che}}^{\gamma\rightarrow\epsilon} + \Delta G_{\text{mco}}^{\gamma\rightarrow\epsilon} + \Delta G_{\text{seg}}^{\gamma\rightarrow\epsilon} \quad (2)$$

where $\Delta G_{\text{che}}^{\gamma\rightarrow\epsilon}$, $\Delta G_{\text{mco}}^{\gamma\rightarrow\epsilon}$ and $\Delta G_{\text{seg}}^{\gamma\rightarrow\epsilon}$ are the molar thermochemical free energy difference, magnetic free energy difference and the free energy difference due to Suzuki effect between γ and ϵ , respectively. $\Delta G_{\text{seg}}^{\gamma\rightarrow\epsilon}$ is neglected here since its value is very low.

The two primary methods of deformation in metals are slip and twinning. Slip occurs by dislocation glide of either screw or edge dislocations within a slip plane. Slip is by far the most common mechanism. Twinning is less common but readily occurs under some circumstances. A twin is a very large stacking fault. Twinning occurs when there are not enough slip systems to accommodate deformation and/or when the material has a very low SFE. Twins are abundant in many low SFE metals.

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The high work hardening rate in these austenitic steels was related to dynamic strain aging and the formation of Mn-C dipoles in the face centered cubic (FCC) solid solution or to the deformation twins formed during plastic straining. More recent studies showed that the deformation-induced twin boundaries are as effective in work hardening as the dislocation accumulation. The active deformation mechanism associated with enhanced plasticity and high strength (martensite formation, twinning or glide dislocations) in the high manganese austenitic alloys is controlled by the intrinsic stacking fault (ISF) energy. This stacking fault can be produced by the nucleation and glide of Shockley partials having $a/6\langle 112 \rangle$ Burgers vectors that create a hexagonal close packed region, which is equivalent to the crystal structure of ϵ -martensite. The ISF energy (ISFE) plays a central role in forming ϵ -martensite and deformation twins, and observation of either transformation induced plasticity (TRIP) or twinning induced plasticity (TWIP) depends on ISFE. Deformation induced ϵ -martensite occurs for ISFE below 18 mJ.m^{-2} , whereas deformation twinning may occur between 12 and 35 mJ.m^{-2} . Twinning is delayed to a higher critical shear stress, or a greater strain, as the ISFE is increased and planar slip forming microbands dominates at higher ISFE (mJ.m^{-2}) as evident in fully austenitic steel [1].

2 EXPERIMENT PROCEDURE

Table 1. Chemical composition of sample

Sample	C	Mn	Cr	Si	P	S
(M1)	1.13	15.31	1.91	0.76	0.07	0.02

The experimental alloy was melt in induction furnace and poured to the green sand mould of cylinder ingot with 2.5mm in diameter. The chemical composition of sample was showed in Table 1. After casting, the sample was heat-treated with procedure: modified heat treatment includes 2 steps: the first step is heating sample up to 650°C , soaked at this temperature in 2 hours then cooled in air to room temperature, then the second step is sample was reheated to 1100°C , soaked at this temperature in 3 hours and quenching in water.

If high manganese steel with austenite structure suffers impacted load, plastic deformation occurs on the surface of steel, which results in great increasing of hardness of surface. The experiments were carried out at the load. Sample was applied more than 1000 times by load of 12N/cm^2 .

Then the sample was chilled at -80°C in 14 days.

After heat treatment, the sample was analyzed microstructure on Axiovert 25A and had hardness test ARK600.

The sample was also analyzed by FE-SEM JSM7600F, X-ray D500 and TEM JEM1400 Plus.

3 RESULTS AND DISCUSSION

3.1 Results of SFE

Regarding the High Manganese Steel, the table 2 shows calculated stacking fault energy for this steel. The SFE of this steel is 28.74mJ/m^2 . However, with this stacking fault energy,

this steel can not have $\gamma \rightarrow \epsilon$ transformation. With the result of this calculation, the sample M1 can only happen twinning movement or sliding strip.

Table 2. SFE of sample

M1	SFE (mJ.m^{-2})	
	25°C	-80°C
	28.74	28.55

When carbon steel is greater than 1% of energy in the region disabilities $20\text{-}30\text{mJ.m}^{-2}$ or greater, the hardening of steel will be twinning mechanism or sliding strip. The carbon steel less than 1% of defects are smaller energy 18 mJ.m^{-2} and able to transform to martensite ϵ .

With subzero temperature at -80°C , the SFE's result is almost unchanged.

This is evidenced for the results of microstructure and hardness.

3.2 Microstructure

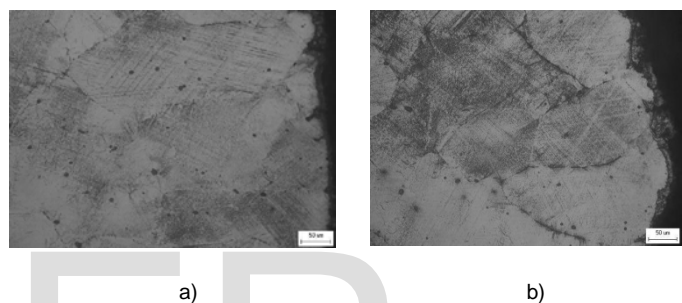


Fig 1. Microstructure of sample after heat treatment (a), impact and cooling process (b)

Figure 1 is the microstructure of sample after heat treatment and after impacted load and cooling process at -80°C in 14 days.

The microstructure show that there is no martensite existing, just twin appearance on the surface.

On the bearing surface, the density of twins is higher, certainly harder. Because of austenite flexible organization and small grain size after heat treatment process, forces are easier to transmit. Therefore the more impacted load of sample, the more twinning appearance after cooling. Due to the transformation, surface of high manganese steel will be stiffer and it is available for hash-working conditions.

The microstructure of sample after impacting also show no cracks on the surface. This can prove that the austenite structure is homogeneous, the carbide particles are very small and fine, so that reduce the residual stresses associated.

Carbide

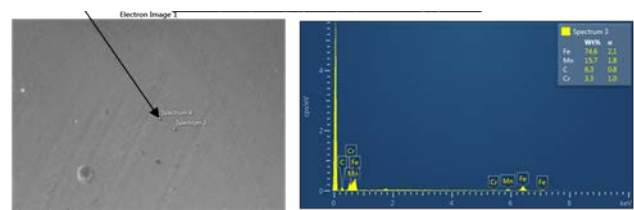


Fig 2. EDS of sample after heat treatment

Figure 2 presents the results of EDS analysis sample after heat treatment. In Figure 2 can be seen carbide particles dispersed in the austenite. This carbide particles act as reinforcing

the key, slip resistance, abrasion resistance increases for steel. Such means when the sample was added Cr, more of sliding tackle, but also create more refined, increased hardness. In addition, as discussed above, the chromium content increases, more carbides, austenite grain size is smaller, less shock effect, but tend to multi-dimensional crystal, the sliding resistance increases, so the possibility of hardening increases.

Carbide black component was determined by EDS point analysis method. The results showed that the composition of the black particles distributed in austenite grain sufficient alloy elements: Mn, Cr and carbon, the element manganese (15.7); Cr (3.3%) and C (6.3%), we can see that when I baked at 1100°C, most carbide dissolved in austenite most, only a very small amount, equivalent to the form component complex carbides, M_7C_3 types exist.

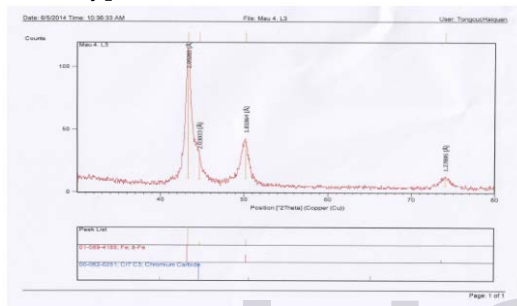


Fig 3. Xray of sample after heat treatment

When XRD diffraction analysis of sample after heat treatment at 1100°C austenite found next to platform while Cr carbide particles are present as Cr_7C_3 dispersed austenite inside the base (Figure 3). It can be concluded that the microstructure of sample with 2% Cr, after heat treatment at 1100°C includes background austenite and a small amount of M_7C_3 dispersed.

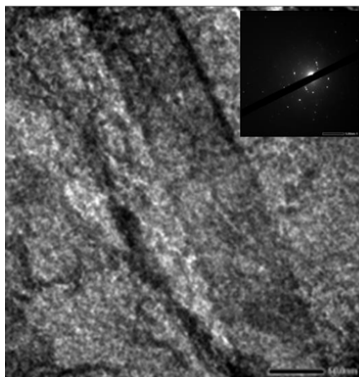


Fig 4. TEM of sample after impact process

The TEM image shows no martensite existing, just twin appearance on the surface of sample.

The bright field image in figure 4 can be found in the form of twinning strip after the crystals are impacted. The width of the twinning of the nano-sized. The diffraction pattern (figure 4) shows the crystal structure of high manganese austenitic steel after impacting is the FCC network system with crystal faces oriented parallel, more clearly confirmed the arrival of twinning organizations from austenite phase in austenitic manganese steel.

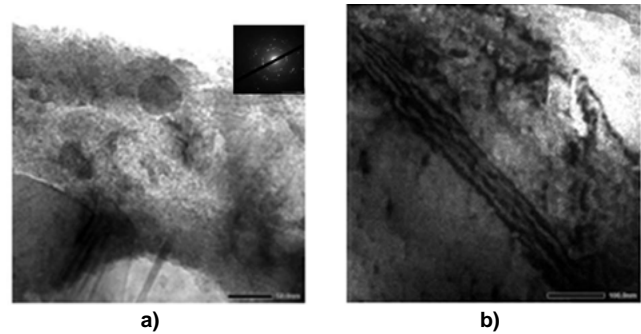


Fig 5. TEM of sample after impact and cooling process

After cooling at -80°C in 14 days, there is still no martensite existing of sample. This is also consistent with the results of some authors who have studied about high manganese steel. The shape of carbide can be seen on the TEM images. Chromium carbide is like a circle (5a). The black lines (5b) can be the signal of dislocation with impact load and the interactive points between dislocation and carbide phases (small and fine).

3.3 Hardness

Table 3. Result hardness of heat treatment

Sample	M1
Hardness (HB)	182

Can be explained that the results of the measurements in Figure 2, 3, 4 when the sample added Cr, chromium carbide appeared in microstructure thereby increasing the hardness of the sample. In addition to increasing the amount of Cr, not only increase the amount of hard phase, but also causes more is dissolved in austenite increases chromium as hardening for this phase. Small austenite grain size in the presence of Cr also contributes to increased stiffness, strength to steel.

High hardness, a small fine carbide distribution are the factors that increase the resistance to abrasion, an important requirement for the more wear-resistant high manganese steel.

The hardness values were changed because of the effect of the impact force decreases from surface to core of sample.

Table 4. Microhardness of sample

The depth	Microhardness (HV) from surface to core								
	100	150	200	250	300	400	500	600	Core
M1	301	284	277	272	268	265	261	261	241
M1 (-80°C)	266	258	247	245	243	245	241	241	241

Table 4 shows the hardness values of sample after heat treatment and after impacted load then cooling from surface to core of sample.

The hardness values of sample after heat treatment is higher than after cooling process. At the surface, the value of sample after heat treatment is 310HV, after cooling (-80°C) is 266HV. On the other hand, the influence of the depth of transformation's layer is also decrease. This can be seem as the signal of phase transformation when cooling.

Based on this results received from the microstructure of the sample, which may explain the hardness measurement results as follows:

When conducting bumps, the hardness of sample is increased. With impact resistant, the hardness was increased due to the appearance twinned with a lot of different directions. The increasing of hardness will increase abrasion resistance, extending the life of the details manufactured from this steel.

Such as small particles as small as the chromium content increases, the ability to turn hard to increase, grain boundaries brake bias effect for two reasons:

- Particle size, the number of grain boundaries is much more where grain boundaries are not orderly structure.
- Two adjacent particles in polycrystalline different orientation, so the difference is very difficult to change "dramatically", the grain boundary sliding passing. As a result, differences can only move freely within the county; the smaller of the particle size and shorter of free movement distances, the higher the hardening effect.

4 CONCLUSION

1. Calculated stacking fault energy of the High Manganese Steel Mn15Cr2 at room temperature is 28.74mJ.m^{-2} and at sub-zero temperature (-80°C) is 28.55mJ.m^{-2} . This confirms that there is no martensite in the microstructure of HMnS.
2. Analytical results held after impact are only twinning or sliding strip and carbide dispersion.
3. Hardness values of sample after subzero temperature is reduced significantly negative compare with samples after heat-treatment.

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