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CALCULATION OF STACKING FAULT ENERGY AND ITS INFLUENCE ON ABRASIVE WEAR RESISTANCE OF HADFIELD CAST STEEL COOLED AT DIFFERENT RATES

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ABSTRACT

The paper presents the relationship between the value of the stacking fault energy of Hadfield steel and the cooling rate of the casting. An scanning electron X-ray spectral electron microanalysis was used to show that the rate of cooling influences the alloying of austenite with manganese, chromium and silicon. This influence is reflected by the non-monotone change of the stacking fault energy with the maximum value at cooling rates of 110–240 °C/min. At these values of the cooling rate, the value of the stacking fault energy exceeds 48 mJ/m^2, resulting in the qualitative change of the deformation mechanism from twinning (twinning-induced plasticity) to dislocation sliding (sliding-induced plasticity). The latter mechanism is characterized by the minimum thickness and abrasive wear resistance of the hardened layer formed on the wearing surface. The alloys cooled at the rates lower than 60 °C/min and higher than 250 °C/min have the value of the stacking fault energy lower than 40 mJ/m^2. In such alloys, the process of deformation twinning is more intensive, and the formed hardened layer has a higher value of abrasive wear resistance. The research group used scanning probe microscopy to investigate the influence of the stacking fault energy on the geometrical parameters of the deformation twins formed on the surface of Hadfield steel in the process of abrasive wear.

1. Introduction

The main advantage of Fe–12Mn–1.2C high-manganese austenite steel (Hadfield steel) is its ability for self-hardening in the process of contact loading, connected with a combination of shock, abrasive and shock-abrasive loads or high specific statistic pressures [1]. Such effects are accompanied by deformation of metal layers on the contact surface and forming the hardened area in these layers [2]. It was displayed that plasticity induced by transformation (TRIP), mechanical twinning (TWIP) and sliding of dislocations (SIP) are the main kinds of deformation mechanisms for austenite steels [3]. Stacking fault energy (SFE) of a solid solution is the decisive factor of possibility of presence of any deformation mechanism [4–6].

The review of technical sources allows to determine the intervals of stacking fault energy for three deformation mechanisms. $\gamma \rightarrow \varepsilon$-martensite transformation is possible in austenite deformation with the values of stacking fault energy less than 16–20 mJ/m^2. Deformation twinning is executed if the value of stacking fault energy in inside the interval 19–48 mJ/m^2. Replacement of a deformation mechanism by dislocation sliding occurs at the values of stacking fault energy above 48 mJ/m^2 [2, 3, 5–32]. The value of stacking fault energy itself depends on several factors, and the alloy chemical composition is the most important among them. It should be mentioned that the elements presented in the composition of austenite steels are classified by two kinds depending on their effect on stacking fault energy: increasing or decreasing its value [7, 28, 30, 33–35]. Many researches were devoted to this problem, and the complete review of them is presented in the work by Arpan Das [36]. It is known also that deformation temperature has direct effect on the value of stacking fault energy, while austenite grain size has inverse effect on this value [37].

There were several theories about the hardening mechanisms of Hadfield steel, and these theories have been changing eventually. At first hardening has been connected with austenite deformation transformation in ε-martensite [7]. However, consequent examination of this steel has shown that deformation in the wide temperature range (–196 –400 °C) doesn't lead to martensite transformation [38]. According to the modern investigations, it can be concluded that deformation twinning (TWIP) and dislocation sliding (SIP) are the main hardening mechanisms of Hadfield steel [7, 39–41]. It leads to forming of a hardened layer consisting of ultrafine-dispersed grains. E.g., Weilin Yan et al. [42] have displayed in their work that grain size in a hardened layer decreases down to 11–17 nm after shot blasting treatment. Consequently, it can be concluded that Hadfield steel with the values of stacking fault energy above 20 mJ/m^2 can be considered as austenite steel in a wide temperature range. This fact has determined its deformation mechanism as twinning and dislocation sliding [8].

However, in spite of the large amount of already undertaken investigations, the data about examination of parameters of deformation twins are practically absent for the case when they should depend on the value of stacking fault energy and should have effect on the properties of a hardened layer. It is actual first of all for different real castings, with their cooling rate before and after crystallization can differ by dozens times. In this case the forming structure will differ as in the size of austenite grains, as well as in its alloying composition, and it will have effect on the value of stacking fault energy.

The goal of this research is calculation of stacking fault energy in cast samples made of Hadfield steel and cooled with different rates. Another goal is determination of geo-

metric parameters of deformation twins and their effect on abrasive wear resistance of the alloys at room temperature.

2. Methods of the research

The samples of cast Hadfield steel with the structure of castings formed at different cooling rates, are the goal of this investigation. Cooling rate has varied from 1.1 to 25 °C/s in the interval of crystallization, and from 14.4 to 327.6 °C/s in the interval of extraction of excessive phase. The chemical composition of the examined steel is presented in the **tab. 1**.

Optical microscope Meiji Techno as well as scanning electron microscope JEPL JSM-6490 LV have been used for revealing of qualitative parameters of microstructure. X-ray spectral electron microanalysis has been conducted using attachment to the scanning microscope INSA Energy. These investigations have been done in the Center of collective usage of the Scientific and research institute of nano-steels at the Magnitogorsk state technical university.

Surface of the samples for scanning probe microscopy has been prepared on the Buechler probe preparing line, using in turn abrasives with grain size 9, 6 and 1 μm respectively. All samples have been prepared with the same conditions: rotation speed 100 min^{-1} and load 12 lbs.

Examination of geometric parameters of deformation twins has been conducted at the scanning probe microscope NanoEducator with resolution 0.3 nm along the axes X and Y, and with resolution 0.03 nm along the axis Z. Such analysis allows to examine the surface topography with high resolution [43].

The formula proposed by Dai Qi-Xun et al., characterizing by good convergence between calculated and experimental results, has been used for calculation of stacking fault energy of solid solution at room temperature (300 K) [44]:

$$\gamma_{SF}^{300} = \gamma_{SF}^{0} = 1.59Ni - 1.34Mn + 0.6Mn^2 - \\ -1.75Cr + 0.01Cr^2 + 15.21Mo - \\ -5.59Si - 60.69(C + 1.2N)^{1/2} + \\ +26.27(C + 1.2N)(Cr + Mn + Mo)^{1/2} + \\ +0.61[Ni(Cr + Mn)]^{1/2}. \quad (1)$$

Where γ_{SF}^{0} — stacking fault energy for pure γ-Fe at room temperature; *[E]* — symbol of a chemical element (content), mass. %.

The testing for abrasive wear resistance has been made by friction on non-rigidly fixed abrasive particles, in accordance with the GOST 23.208-79.

3. Results of the research

Deformation temperature, austenite grain size and chemical composition of the solid solution have the effect of varying of stacking fault energy. The presented research didn't take into account the input in energy measurement of some of these parameters, among them — austenite grain size and testing temperature.

Significant increase of stacking fault energy occurs as a result of decrease of austenite grain size to less than 30 μm [45]. If the average austenite grain size makes 100–200 μm, then energy variation makes appr. 1–2 mJ/m². According to the previously conducted investigations [46], the average grain size varies from 270 to 160 μm, in the case of cooling rate varying in the crystallization interval 1.1–25 °C respectively. Thereby we can neglect by this component in calculation of stacking fault energy. In this connection, we take into account in this research cooling rate of the castings only in the temperature interval of extraction of excessive phase (550–800 °C).

Investigations have been conducted at the room temperature, and its increase in the process of abrasive wear resistance testing was not more than by 15 °C. According to the data [37, 47], such temperature increase is rather small and has not effect on varying of the value of stacking fault energy, thereby it was not taken into account in calculations.

To calculate stacking fault energy, according to (1) formula it was necessary to determine austenite chemical composition as well as stacking fault energy for pure γ-Fe at the room temperature (γ_{SF}^{0}).

The average content of manganese, chromium and silicon in the austenite grain of castings (cooled with different rates in the interval of extraction of excessive phase) has been determined via X-ray spectral electron microanalysis.

Variation of concentration of such elements as nickel, molybdenum and nitrogen was not registered during X-ray spectral electron microanalysis owing to their low content, thereby during calculation their concentration was accepted to be equal for all samples, and the value of content was taken according to the chemical composition (see tab. 1).

It was impossible to determine correctly carbon concentration using X-ray spectral electron microanalysis, so it has been conducted conditionally, based on the data of metallographic investigation [48]. i.e. on the amount of high-carbon excessive phase. That's why it was accepted that practically complete carbon is contained in austenite at high cooling rates (when amount of excessive phase is less than 3%). Thereby carbon concentration is close to 1.1% (when its general content in the alloy makes 1.2%).

Table 1. **Chemical composition of the examined steel**

C	Si	Mn	S	P	Cr	Ni	Al
1.2	0.9	12.3	0.024	0.033	0.8	0.12	0.6

Table 2. **Austenite chemical composition depending on cooling rate in the interval of excessive phase extraction**

Cooling rate of casting, °C/min	Concentration,%						
	Ni	Mn	Cr	Mo	Si	C	N
14.4	0.13	9.3	0.7	0.013	1	0.95	0.02
21	0.13	9.5	0.7	0.013	1	1.00	0.02
24	0.13	9.8	0.8	0.013	1.2	1.04	0.02
60	0.13	10.8	0.9	0.013	0.9	1.05	0.02
108	0.13	10.3	0.8	0.013	0.7	1.08	0.02
196	0.13	10.1	0.8	0.013	0.8	1.085	0.02
255	0.13	9.0	0.7	0.013	0.6	1.09	0.02
327.6	0.13	8.2	0.8	0.013	0.7	1.1	0.02

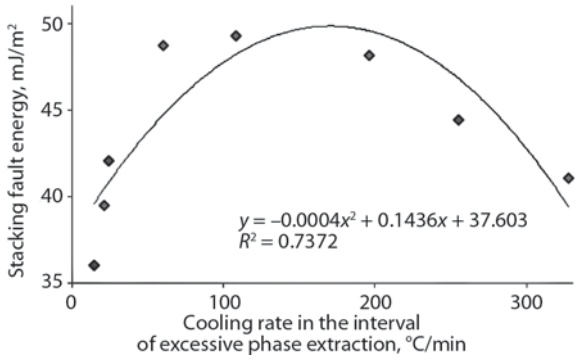

Fig. 1. Relationship between variation of stacking fault energy and cooling rate in the interval of excessive phase extraction

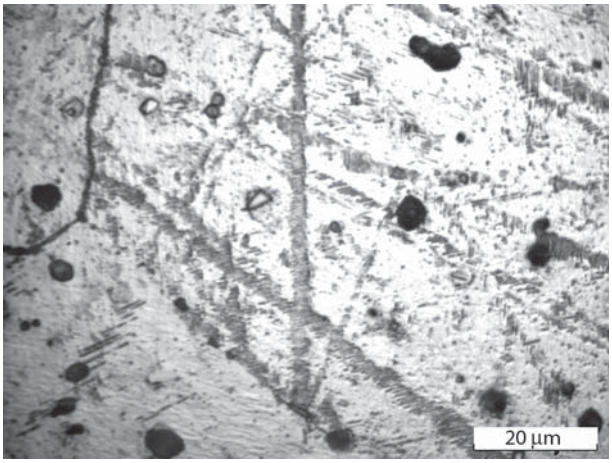

Fig. 2. Microstructure of Hadfield steel, ×1000

At low cooling rates and rather higher amount of extracted secondary phase (more than 14%) we accept carbon concentration about 1%. The features of carbon concentration variation is accepted as a degree one (see **tab. 2**), in accordance to the relationship between amount of excessive phase and cooling rate [48].

Stacking fault energy at the room temperature is accepted as 28 mJ/m², based on the already published data [6, 7, 12, 15, 19, 28–30].

When we have inserted the data from the table 2 and the accepted value in the formula (1), we have received the relationship between variation of stacking fault energy and cooling rate in the interval of excessive phase extraction (**fig. 1**).

The obtained wide interval of the values of stacking fault energy should have essential effect on the parameters of deformation twins.

When the polished samples of high-manganese Hadfield steel have been subjected to pickling, the lines appeared on their surface, and these lines can be identified as scratches by mistake. However, if we enlarge magnification, we can reveal their morphology distinctly: they consist of a collection of parallel lines with width from 2 to 14 μm, and forming of these lines occur at the stage of final abrasive grinding with size of particles from 1 to 9 μm (**fig. 2**).

Based on the review of technical literature, we can suggest that these lines are the boundaries of deformation twins that appear in the process of local surface

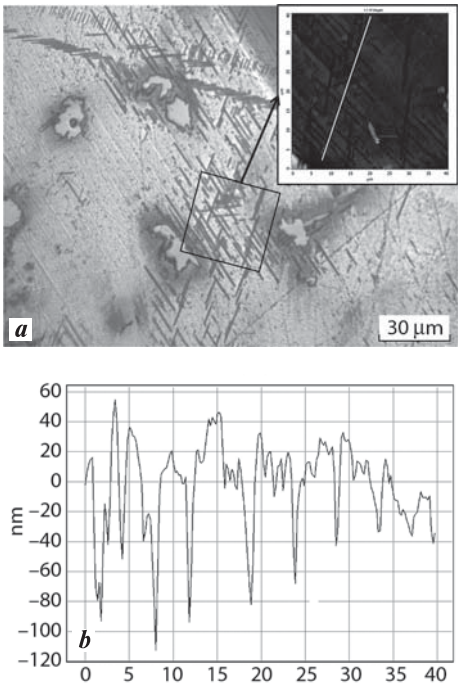

Fig. 3. Surface structure of Hadfield steel, cooled in the interval of excessive phase extraction at the rate 21 °C/min: *a* — microstructure (optical metallography, ×500, a fragment — scanning probe microscopy (40×40 μm); *b* — surface profile along the line marked on the fragment

deformation along the motion route of abrasive particles. It should be mentioned that amount of these lines on the polished surface of a casting depends on cooling rate of the alloy. Minimal amount can be observed for the samples cooled with rate from 110 to 200 °C/min, what is a result of varying the alloy stacking fault energy.

In order to determine the effect of the value of stacking fault energy on geometric parameters of deformation twins, the surfaces of several samples have been examined via scanning probe microscope. The surface topography has been captured at preset place via optical microscope (**fig. 3**, *a*), and then the surface profile along the determined line has been received (**fig. 3**, *b*).

After determination of geometric parameters of deformation twins, the relationship between their ledge height and cooling rate of castings (**fig. 4,** *a*) and stacking fault energy (**fig. 4,** *b*) has been built. At the same time, relation between cooling rate and thickness of twins was not found, while this thickness is inside the interval 0.9–1.4 μm.

After obtaining the relationship between parameters of deformation twins and the value of stacking fault energy, it is necessary to determine their effect on hardening of samples made of Hadfield steel. To determine the hardening level, they have examined abrasive wear resistance of the samples that were subjects for X-ray spectral electron microanalysis and scanning probe microscopy. The relationship between the ratio of abrasive wear resistance for cast Hadfield steel and cooling rate of castings in the temperature interval of excessive phase extraction (fig. 5, *a*) and the value of stacking fault energy (fig. 2, *b*) has been built on the base of obtained data.

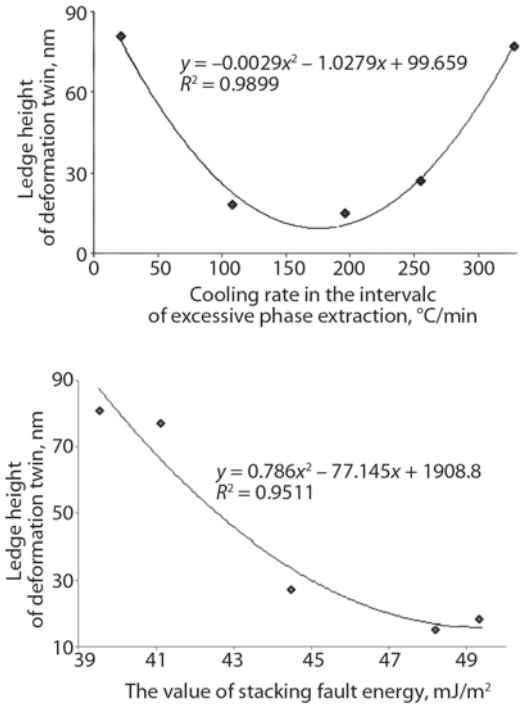

Fig. 4. Relationship between ledge height of deformation twin and cooling rate (*a*); stacking fault energy (*b*)

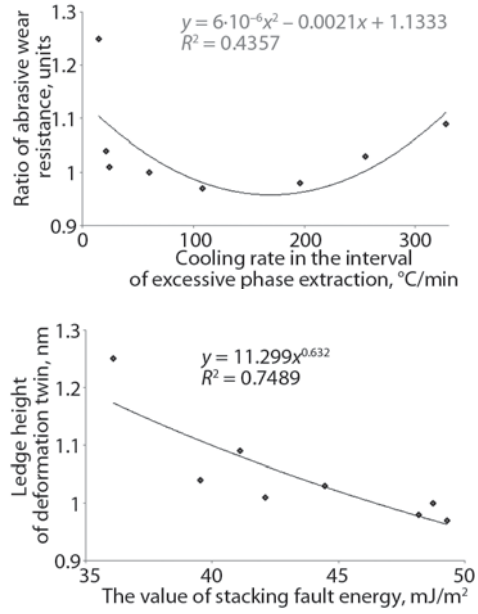

Fig. 5. Relationship between the ratio of abrasive wear resistance of cast Hadfield steel and cooling rate in the interval of excessive phase extraction (*a*); stacking fault energy (*b*)

4. Discussion about the results

According to the results obtained in this research it can be concluded that the alloy cooling rate after crystallization plays the main role in forming of the alloy properties.

The alloy cooling rate in the interval of excessive phase extraction has the effect on correlation of alloying elements between austenite and secondary phase and, respectively, on the value of stacking fault energy of the solid solution. Concentration of such carbide-forming elements as manganese and chromium at first rises with increase of cooling rate, then achieves its maximal value at the rate values 110–200 °C/min, and afterwards decreases. Silicon content enlarges steadily owing to less extraction of excessive phase: dissolution of the same silicon amount in a large volume of austenite leads to lowering of its average concentration (see table 2).

Additionally, alloy cooling in the interval of excessive phase extraction with cooling rate 110–240 °C/min leads to rise of the values of stacking fault energy of the solid solution above 48 mJ/m² (see fig. 1), what reflects in replacement of the twinning deformation mechanism by dislocation sliding (TWIP → SIP). The samples cooled at this rate are characterized by minimal amount of deformation twins. The twins themselves have in this case the minimal height (see fig. 4, *a*). It testifies that the twinning process, when excessing the energy threshold 48 mJ/m², is suppressed both as quantitatively (via decrease of general amount of twins in the structure), as well as qualitatively (minimal height of ledges). The less value of stacking fault power at high and low cooling rates provides assistance in passing of the twinning process. In this case large amount of deformation twins with increased height of ledges (see fig. 4, *b*) is observed in the structure; it corresponds to the results obtained in the work [34].

The revealed relationships between stacking fault power and twins geometry correlate well with the relationship between the ratio of abrasive wear resistance and the alloy cooling rate. It is shown that the alloys cooled in the interval of excessive phase extraction at the rates less than 60 °C/min and more than 250 °C/min (see **fig. 5,** *a*) are characterized by the most high wear resistance. It proves practically that deformation twinning in the area subjected to loads is the main hardening mechanism for austenite steels (including Hadfield steel).

The alloys cooled at the rates inside the interval 110–240 °C/min display the lowest abrasive wear resistance. It is caused by qualitative replacement of deformation mechanism (TWIP → SIP) when the value of stacking fault power exceeds 48 mJ/m² (see **fig. 5,** *b*). Forming of more fine and less hardened layer is the feature of the SIP mechanism, and in general it leads to lowering of abrasive wear resistance for a high-manganese steel.

5. Conclusions

Cooling rate of the austenite steel has the effect on the value of stacking fault energy via alloying properties of the solid solution. Stacking fault energy, in its turn, determines deformation mechanism and hardening level in the area of friction contact or static load.

The relationship between stacking fault energy and alloy cooling rate is calculated for Hadfield steel in the temperature interval of excessive phase extraction. It is shown that the value of stacking fault energy exceeds 48 mJ/m² at cooling rates 110–240 °C/min, and it leads to replacement of TWIP deformation mechanism by SIP.

Castings made of Hadfield steel with the values of stacking fault energy less than 40 mJ/m^2 are characterized by the highest abrasive wear resistance. In this case maximal amount of deformation twins with more expressed geometry is forming in the sreucture.

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FEATURES OF THE DISTRIBUTION NON-METALLIC INCLUSIONS IN THE STRUCTURAL ZONES OF A 24.2 TON INGOT OF 38ХН3МФА STEEL

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ABSTRACT

The paper reports findings on the distribution of non-metallic inclusions in the structural zones as well as throughout the mass of a 24.2 ton ingot of 38ХН3МФА steel. It is shown that the distribution of non-metallic inclusions in steel varies throughout the height and cross-section of the ingot. The amount of sulfide and oxysulfide inclusions exceeds that of oxides. It is discovered that the inclusions are presented by compound oxides of manganese, silicon, vanadium, chromium and aluminum; besides, there are sulfide and oxysulfide inclusions as well.

The findings prove that there exists a correlation between the contamination index of sulfides and oxysulfides on the one hand, and the ingot height, on the other hand. In the upper part of the ingot, below its hot top, the distribution of the inclusions and their numbers almost fully coincide due to extended heat exposure. In the middle and bottom parts of the ingot in the zone of columnar and large randomly oriented crystals there is a pronounced inverse relation between the distribution of sulfides and oxysulfides.

The investigation of inclusions reveals the major role of oxysulfides in the formation of sulfides which are generally located at grain boundaries and reduce metal ductility. This is particularly important for vacuum cast steel since oxygen shortage reduces the amount of oxysulfides and leads to the escape of sulfides and an undesired form.

1. Introduction

The production of large forgings with a homogenous chemical composition to manufacture power engineering components is a challenging task because it is required to ensure uniform properties evenly distributed throughout the mass of large-size parts of high capacity units.

The formation of non-metallic impurities is closely related to melt solidification, and these relations affect the formation of grain size and its structure. As a result, a plastic and elastic deformation field is formed, and this field determines the properties and machinability of the part to be manufactured.