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THE MORPHOLOGY AND DISTRIBUTION OF MnS IN LOW CARBON STEEL

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Non-metallic inclusions are very important (harmful) in steelmaking practice. After oxygen, sulphur is the most important non-metallic element in field of steel metallurgy and sulphides therefore form a second important group of inclusions. Since the morphology of these sulphide inclusions has significant effects on the various properties of steel, numerous studies focusing on morphology and distribution of the MnS inclusions have been conducted over the years. This paper presents the results of the investigation of the MnS inclusion shape and distribution in low carbon steel.

Key words: *steel, non-metallic inclusions, sulphides, shape, distribution*

Morfologija i raspored MnS u niskoougljičnom čeliku. Nemetalni uključci su veoma važni (štetni) u metalurškoj proizvodnji. U području metalurgije čelika sumpor je drugi po važnosti nemetalni element, nakon kisika, te stoga i sulfidi, po važnosti, predstavljaju drugu grupu uključaka u čeliku. Jer je morfologija i raspored ove vrste sulfida je taj bitni faktor koji ima presudan utjecaj na razna svojstva čelika izvedena su mnoga istraživanja na tom polju tijekom zadnjih nekoliko godina. U ovom radu su predstavljeni rezultati istraživanja morfologije i rasporeda MnS uključaka u niskougljičnom čeliku.

Ključne riječi: *čelik, nemetalni uključci, sulfidi, oblik, raspored*

INTRODUCTION

Because non-metallic inclusions play one of the main roles in determination of material properties, considerable efforts have been directed towards the development of alloys and processes to reduce their presence in steel to a minimum. However, the utilisation of inclusions for the control of microstructures is becoming a subject of considerable interest for improving the mechanical properties of steels.

MnS inclusions are found in most steel and their beneficial effects in improving machinabilitiy and retarding grain growth in steels are well known. Since the morphology of these sulphide inclusions has significant effects on the various properties of steel, numerous studies focusing on morphology and distribution of the MnS inclusions have been conducted over the years.

According to the classical work by Sims and Dhale [1] the morphology of MnS can be broadly classified into three types: i.e. randomly dispersed globular sulphides (type 1), grain boundary sulphides (type 2) and angular sulphides (type 3) [1 - 3].

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In view of these facts, the present study has been undertaken with a view to identifying the morphology and distribution of MnS inclusions in low carbon steel.

EXPERIMENTAL PROCEDURE

An experimental investigation was done of low carbon steel (JUS: Č. 1120, DIN C10). The Experiment can be divided into four steps as follows:
a) sample preparation,
b) heat treatment of the samples,
c) metalographical investigation and
d) collecting and the analysis of the data.

Sample preparation

For the purpose of the experiment, a steel bar was cut into six cylindrical samples (∅5×10 mm) which were then prepared for further investigation. The chemical composition of the steel bar is given in Table 1.

Table 1. **Chemical composition of the steel bar**
Tablica 1. **Kemijski sastav čelične šipke**

Element	C	Si	Mn	P	S
% wt	0,11	0,31	0,35	0,011	0,015

Heat treatment of the samples

This step is a basis for the whole experiment. Firstly, the temperature of MnS dissolution was very precisely determined. This temperature was calculated from the MnS stability product equation in low carbon steel [4, 5]:

$$\text{Log}\, K_{\text{MnS}} = \frac{A}{T} + B$$

where:

K_{MnS} = [Mn %] × [S %],
T - temperature / K,
A, B - constants.

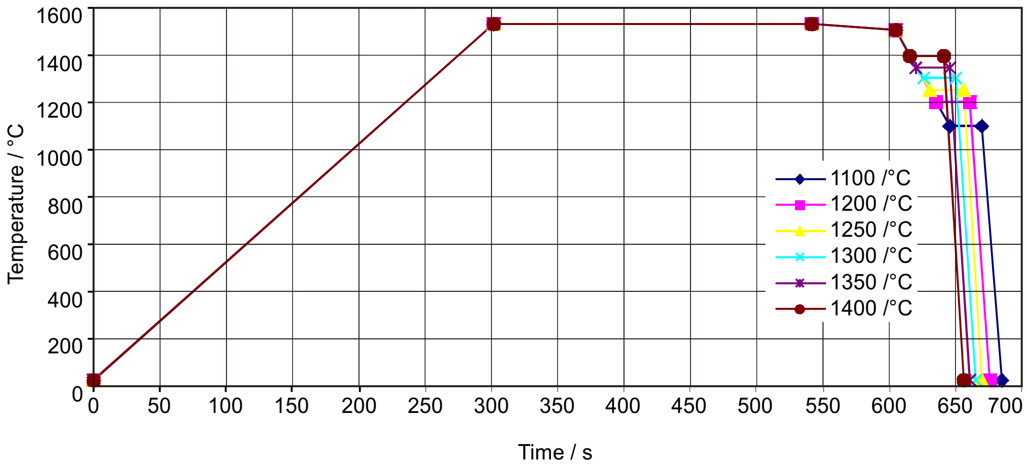

Figure 1. **Applied temperature cycles**
Slika 1. **Primjenjeni temperaturni ciklusi**

Table 2. **Applied temperature cycles**
Tablica 2. **Primjenjeni temperaturni ciklusi**

Sample I		Sample II		Sample III	
temp / °C	time / s	temp / °C	time / s	temp / °C	time / s
25	0	25	0	25	0
1535	302	1535	302	1535	302
1535	542	1535	542	1535	542
1510	604,5	1510	604,5	1510	604,5
1100	645,5	1200	635,5	1250	630,5
1100	670,5	1200	660,5	1250	655,5
25	685,5	25	675,5	25	670,5
Sample IV		**Sample V**		**Sample VI**	
temp / °C	time / s	temp / °C	time / s	temp / °C	time / s
25	0	25	0	25	0
1535	302	1535	302	1535	302
1535	542	1535	542	1535	542
1510	604,5	1510	604,5	1510	604,5
1300	625,5	1350	620,5	1400	615,5
1300	650,5	1350	645,5	1400	640,5
25	665,5	25	660,5	25	655,5

The dissolution temperature having been calculated, cycles for heat treatment for each six samples were chosen [3]. The heat treatment for all samples generally consists of five steps:

- heating of the samples to a temperature above their melting point,
- holding at that temperature,
- cooling to the investigated temperature,
- holding at that temperature,
- cooling to the room temperature.

The heat treatment cycles for each sample are presented in Table 2. and Figure 1. Cooling /heating rates in applied treatments are shown in Table 3.

Table 3. **Cooling/heating rates in applied temperature cycles / 1100 °C**
Tablica 3. **Brzina zagrijavanja/hlađenja primjenjenih ciklusa / 1100 °C**

Temperature interval / °C	Cooling/heating rates / $°C \cdot s^{-1}$
25 - 1535	5
1535 - 1510	0,4
1510 - 1100	10*
1100 - 25	cooling at the air*
*The same cooling/heating rates are used for all other investigated temperatures	

Metalographic investigation

After heat treatment, the microstructure of the samples was studied by optical microscopy techniques using “Image analysis” supporting software [1]. There were eight microscopy zones investigated on each sample and from each zone the following data were collected:

- the number of inclusions,
- the area of each inclusion,
- the max. diameter of each inclusion,
- the min. diameter of each inclusion,
- the average diameter of each inclusion,
- the factor of shape of each inclusion[1].

The results having been obtained by measurements, the data were statistically processed [6].

The data collected for all inclusions areas at all temperatures investigated (1100 °C, 1200 °C, 1250 °C, 1300 °C, 1350 °C and 1400 °C) were divided into fifty classes ranging from 0 to 10 μm^2 in area size (the step being 0,2 μm^2). All inclusions with area greater than 10 μm^2 were put into the last class (9,8 - 10,0 μm^2). The same procedure was applied in analysing the data concerning of average inclusion diameter (classes ranging between 0 and 10 μm, step 0,2 μm).

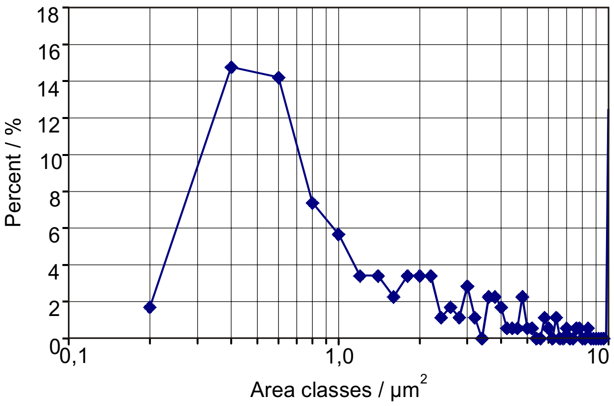

Figure 2. **Percent of the area of the inclusions at classes at 1100 °C**
Slika 2. **Postotak površine uključaka i razreda na temperaturi 1100 °C**

A graphical presentation of dependence of inclusion area and average diameter on temperature is shown in Figures 2. and 3. (the temperature investigated being: 1100 °C).

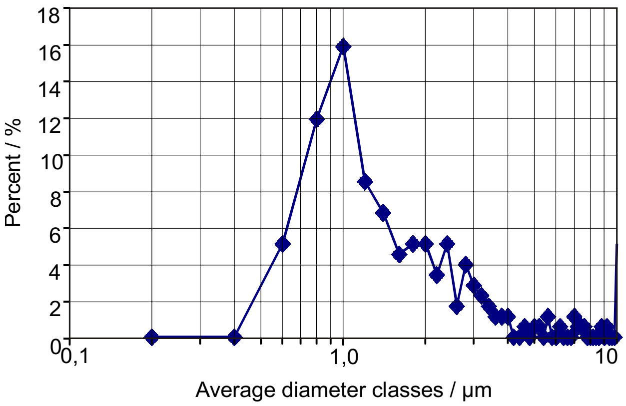

Figure 3. **Percent of the average diameter of inclusions at classes at 1100 °C**
Slika 3. **Postotak srednjih vrijednosti promjera uključaka i razreda na temperaturi 1100 °C**

Due to space limitation, no graphical presentation for each investigated temperature can be presented. Instead, Figures 4. and 5. shown the dependence of inclusion areas

[1] The ratio between grain area and area of the circle drawn around the grain.

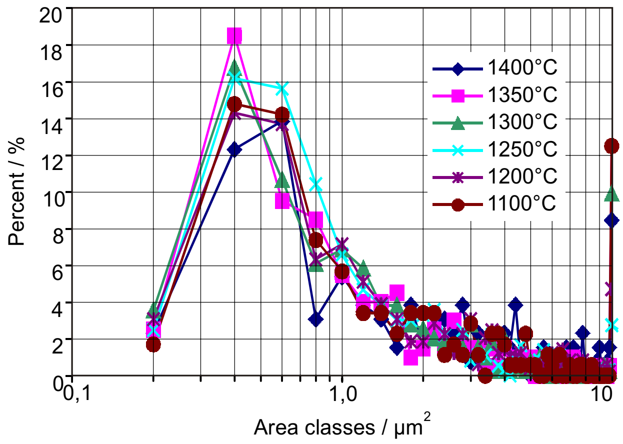

Figure 4. **Percent of area of inclusions at classes for all investigated temperature**
Slika 4. **Postotak površine uključaka i razreda za sve ispitivane temperature**

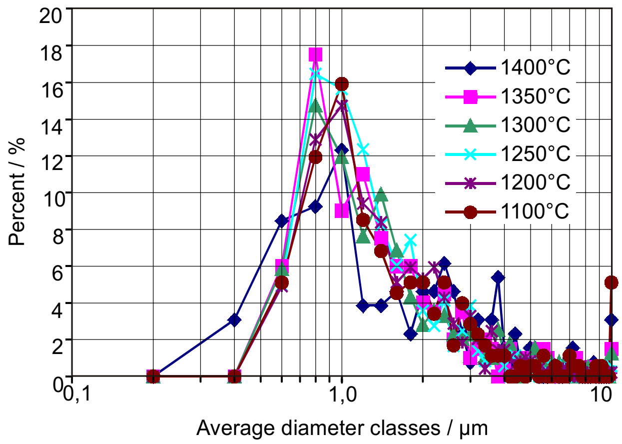

Figure 5. **Percent of the average diameter of the inclusions at classes for all investigated temperature**
Slika 5. **Postotak srednjih vrijednosti promjera uključaka i razreda za sve ispitivane temperature**

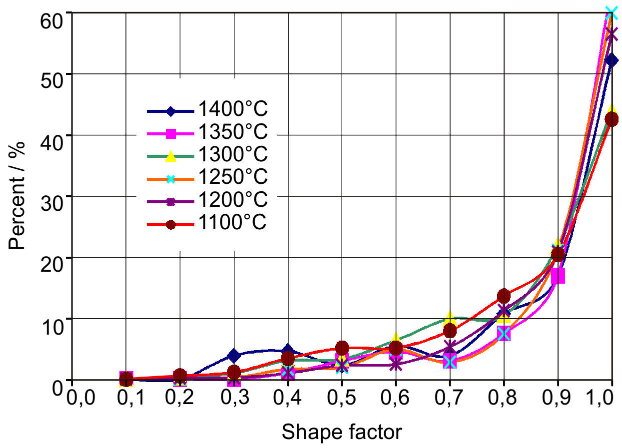

Figure 6. **Shape factor of inclusions for all investigated temperature**
Slika 6. **Faktor oblika uključka za sve ispitivane temperature**

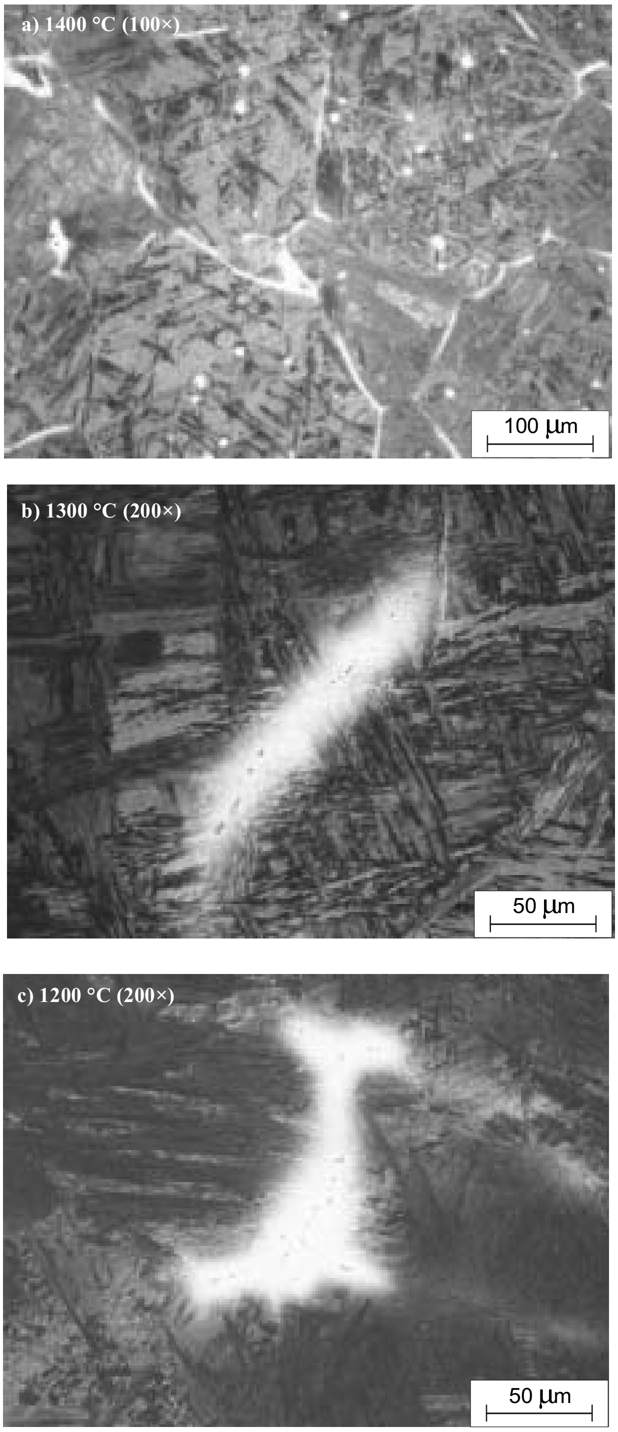

Figure 7. **Distribution of the MnS inclusions at different investigated temperatures (etching: KLEMM $Na_2S_2O_3$-K_2SO_4)**

Slika 7. **Raspored izlučenih MnS uključaka na različitim ispitivanim temperaturama (nagrizanje: KLEMM $Na_2S_2O_3$-K_2SO_4)**

and average diameters on temperature for all temperature cycles applied.

The data concerning inclusion shape factors were divided into ten classes ranging between 0 and 1,0, step being 0,1. A schematic showing the dependence of inclusion shape factor on temperature for all temperature cycles applied is presented in Figure 6.

All the above-mentioned data give no information about the precipitation place of MnS inclusions. This information was obtained on performing metallographic etching the etching results for three investigated temperatures are presented in Figure 7.

CONCLUSIONS

The following conclusions were based on the theoretical background and the results obtained during the investigation:

1. The inclusions are nearly spherical in shape.

2. The behaviour of the inclusion areas is almost the same for each applied temperature cycle.

3. The behaviour of the inclusion diameters is almost the same for each applied temperature cycle.

4. The behaviour of the inclusion shape factors is almost the same for each applied temperature cycle.

5. The inclusions within the grain can be classified as type 1 of MnS inclusions.

6. The inclusions on the grain borders can be classified as type 2 of MnS inclusions.

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