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INTERFACIAL TENSION AT THE INTERFACE OF A SYSTEM OF MOLTEN OXIDE AND MOLTEN STEEL

MEDFAZNA NAPETOST NA STIKU STALJEN OKSIDNI SISTEM – STALJENO JEKLO

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This paper is focused on a study of the interfacial tension between selected oxide and metal phases. The experimental research on the interfacial tension was performed in a horizontal resistive graphite Tamman furnace using an original method of measuring. This method consists of fixing both liquid phases in a horizontal position using a mandrel made of tungsten wire in a corundum cover. In this work the influence of the carbon content in the steel on the interfacial tension was studied. For this purpose a steel with 0.411 % of mass fraction of carbon and a steel with 2.64 % of carbon were used. Because of the wide variety of oxide systems used in industry, a characteristic system of casting powder was chosen for this study. This system contains dominant components, i.e., SiO_2, CaO, Al_2O_3 and MgO, as well as a range of attendant mixtures, e.g., Fe_2O_3, TiO_2 and Na_2O. Simultaneously, the influence of SiO_2 on the temperature dependence of the interfacial tension was observed. For this reason a concentration series with gradual additions of SiO_2 was created. It was found that an increasing content of carbon in the steel significantly decreases the interfacial tension between the oxide system and the steel. The interfacial tension was found to decrease slightly with an increase in the content of SiO_2 in the oxide system.

Keywords: steel, casting powder, interfacial tension

Članek predstavlja študijo medfazne napetosti med izbranim oksidom in kovinsko fazo. Določanje medfaznih napetosti je bilo izvršeno z originalno metodo v horizontalni uporovni grafitni Tammanovi peči. Ta metoda sestoji iz zadržanja obeh talin v horizontalnem položaju s trnom iz volframove žice in korundnega pokrova. V tem delu je bil preučevan vpliv ogljika v jeklu na medfazno napetost. Uporabljeno je bilo jeklo z masnim deležem 0,411 mas. % ogljika in jeklo z 2,64 % ogljika. Zaradi velike raznolikosti oksidnih sistemov, ki se uporabljajo v industriji, je bil za študij izbran livni prašek. Ta vsebuje glavne komponente, ki so SiO_2, CaO, Al_2O_3 in MgO, ter vrsto primesi, kot so na primer Fe_2O_3, TiO_2 in Na_2O. Hkrati je bil opažen vpliv SiO_2 na temperaturno odvisnost medfazne napetosti. Zato je bila pripravljena serija z naraščajočo vsebnostjo SiO_2. Ugotovljeno je, da naraščanje vsebnosti ogljika v jeklu občutno zmanjša medfazno napetost med oksidnim sistemom in jeklom. Za medfazno napetost je ugotovljeno, da se nekoliko zmanjša, če se povečuje vsebnost SiO_2 v oksidnem sistemu.

Ključne besede: jeklo, livni prašek, medfazna napetost

1 INTRODUCTION

Interfacial phenomena play an important role in many metallurgical processes in which two immiscible liquid phases co-exist. Numerous steps in primary processing and the refining of materials include a mass transfer through an interface, which significantly affects the rate of individual reactions. Surface and interfacial tensions can accelerate these reactions, or completely dampen them. It is, therefore, necessary to know the properties of the interface, which together with the other physicochemical properties[1] forms the properties of the resulting product. Although various methods[2,3] have been developed for the research of interface phenomena, any experimental investigation remains very difficult. For this reason the literature data for a determination of the interface phenomena, particularly the interface phenomena for slag–metal, are not commonly available.

The aim of this research was to study the interfacial tension in the system involving an oxide phase and a metallic phase. The interfacial tension was calculated using the following equation:

$$\sigma_{(0)-(s)} = \sqrt{\sigma^2_{(0)-(g)} + \sigma^2_{(s)-(g)} - 2\sigma_{(0)-(g)} \cdot \sigma_{(s)-(g)} \cdot \cos\theta} \quad (1)$$

where $\sigma_{(s)\text{-}(g)}$/(mN/m) is the the surface tension of oxide system, $\sigma_{(o)\text{-}(g)}$/(mN/m) is the surface tension of the molten steel, and θ is the wetting angle of the liquid phases.

2 EXPERIMENTAL

2.1 Material

For the investigation of the interfacial tension a casting powder was chosen as a representative of an oxide system. Its composition is given in **Table 1**.

Within this system we investigated the influence of the carbon in the steel on the interfacial tension. For this purpose we choose, as representatives of the metallic phase, the steel (I) containing 0.411 % of carbon, and the steel (II), containing 2.64 % of carbon. The chemical compositions of both steels are given in **Tables 2** and **3**.

Table 1: Chemical composition of oxide system in mass fractions, *w*/%
Tabela 1: Kemijska sestava oksidnega sistema v masnih deležih, *w*/%

casting powder	component	SiO_2	CaO	MgO	Al_2O_3	TiO_2	Fe_2O_3	MnO_2
		37.10	29.00	1.70	12.50	0.50	0.64	0.10
	component	Na_2O	K_2O	P_2O_5	F^-	$C_{tot.}$	CO_2	
		5.10	0.40	0.10	4.10	7.20	4.40	

Table 2: Chemical composition of steel (I), *w*/%
Tabela 2: Kemijska sestava jekla (I), *w*/%

Steel (I)	component	C	Si	Mn	S	P	Cu
		0.41	0.375	0.344	0.011	0.016	0.076
	component	Ni	Cr	Mo	Ti	W	Fe
		0.218	12.392	0.027	0.013	0.084	75.6

Table 3: Chemical composition of steel (II), *w*/%
Tabela 3: Kemijska sestava jekla (II), *w*/%

Steel (II)	component	C	Si	Mn	S	P	Cu
		2.64	2.04	0.57	0.031	0.043	0.020
	component	Ni	Cr	Mo	Ti	W	Fe
		0.022	0.051	0.008	0.034	–	94.5

The influence of SiO_2 on the interfacial tension in an oxide/steel system was also investigated. For this research a concentration series was prepared with gradual additions of (3, 6, 9 and 15) % of SiO_2 to the measured system of casting powder, within the concentration range from 37.1 % to 52.1 %.

2.2 Experimental methods

Differential Thermal Analysis (DTA) was used to obtain the melting temperature of the steel samples.[4] The analysis was performed with the suse of the laboratory system Setaram SETSYS 18_{TM}. The samples with masses of approximately 200 mg were analysed using a controlled rate of heating equal to 15 °C/min. A dynamic atmosphere of Ar (purity > 99.9999 %) was maintained in the furnace during the analysis.

For the calculation of the interfacial tension according to Equation (1) the surface tension and the wetting angle of the liquid phases were determined experimentally. The surface tension of the casting powder, the steel and the concentration series with the addition of SiO_2 was measured using the method of sessile drop. This method is based on a recognition of the geometrical shapes of a drop of melt sessile on a non-wetting pad.[5] A graphite pad was used for the oxide systems and a corundum pad was used for the steel. The experimental measurements were performed in a horizontal resistance furnace under an Ar atmosphere (purity > 99.9999 %).

In order to determine the wetting angles of both liquid systems an original experimental methodology was used. This is schematically represented in **Figure 1a**. The principle of this methodology consists of fixing both liquid phases in a horizontal position.[6]

A sample of steel was put into a corundum pad of the appropriate shape. Afterwards, a tablet of oxide material was put on the steel. For the fixation of both phases in the horizontal position a mandrel formed by a tungsten wire in corundum protection was passed through the centre of the whole sample, as shown in **Figure 1b**. After the melting of both systems the wetting angle was calculated on the basis of the determined contours of the steel and oxide system, as can be seen in **Figure 1c**.

3 RESULTS AND DISCUSSION

The liquidus temperatures of the steels, determined by a DTA analysis, were 1455 °C for steel (I) and 1158 °C for the steel (II).

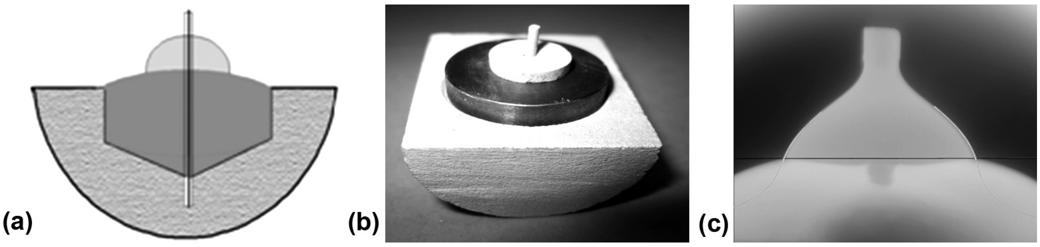

Figure 1: a) Schematic diagram of experimental method, b) a prepared sample before the experiment, c) image of molten phases
Slika 1: a) Shematski prikaz eksperimentalne metode, b) pripravljen vzorec pred preizkusom, c) posnetek staljenih faz

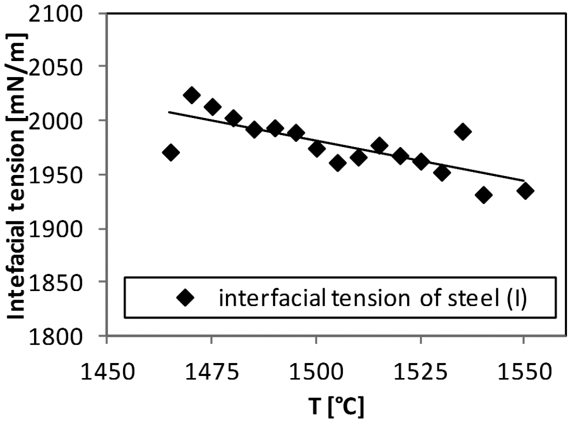

Figure 2: Temperature dependence of interfacial tension of system oxide – steel (I)
Slika 2: Temperaturna odvisnost medfazne napetosti oksidni sistem – jeklo (I)

For the calculation of the interfacial tension according to Equation (1), first of all the surface tensions of the steel and the casting powder were measured. The surface tension of steel (I) was measured within the temperature interval 1465–1550 °C. The surface tension decreased with the temperature in the interval 1770–1680 mN/m. The surface tension of steel (II) was measured within the temperature interval 1185–1550 °C and the values were in the interval 1409–1205 mN/m. From the measured values it is evident that the surface tension of the steel containing 0.411 % of carbon is on average higher by 350 mN/m, compared to the steel containing 2.64 % of carbon. The surface-tension measurements of the oxide system were performed in the temperature interval 1180–1550 °C and the obtained values ranged within the interval 390–370 mN/m.

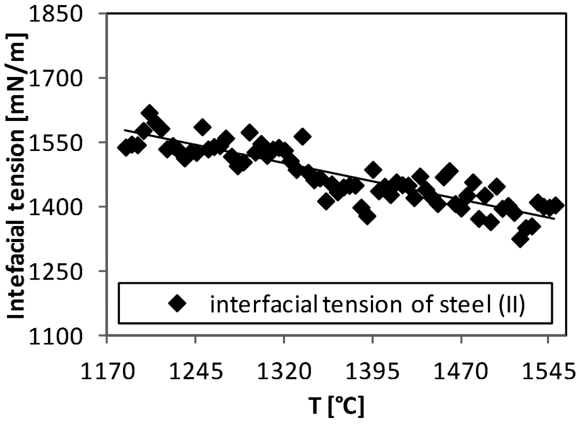

Figure 3: Temperature dependence of interfacial tension of system oxide – steel (II)
Slika 3: Temperaturna odvisnost medfazne napetosti oksidni sistem – jeklo (II)

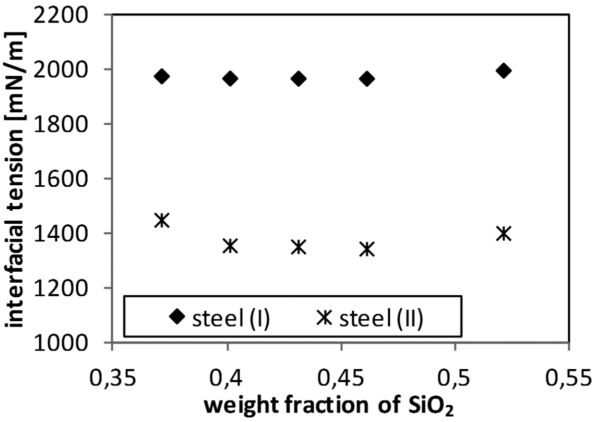

Figure 4: Dependence of interfacial tension on mass fraction of SiO_2 at a temperature of 1500 °C
Slika 4: Odvisnost medfazne napetosti od masnega deleža SiO_2 pri temperaturi 1500 °C

During the next stage of the experimental research the wetting angles were measured in the interface systems oxide/steel (I) and oxide/steel (II). The values of the wetting angles for steel (I) increased slightly with the temperature in the range of 2–2.4 rad; in contrast to that in steel (II) the values decreased slightly in the interval 2–1.75 rad.

From the experimental data the interfacial tension was calculated according to Equation (1). **Figures 2** and **3** show the temperature dependences of the interfacial tension of steel (I) and steel (II).

From **Figures 2** and **3** it is evident that the interfacial tension in both systems decreases with the temperature. The values of the interfacial tension of steel (I) varied from 2020 mN/m to 1930 mN/m. The values of the interfacial tension of steel (II) were in the interval 1540–1330 mN/m. From these temperature dependences it follows that the values of the interfacial tension are, in steel (II), on average lower by 25.5 % (505 mN/m) in comparison with the values of the interfacial tension of steel (I).

Moreover, the influence of SiO_2 on the interfacial tension in both steels was determined experimentally. **Figure 4** shows the dependence of the interfacial tension of the system oxide/steel (I) or oxide/steel (II) on the content of SiO_2 at a temperature of 1500 °C. It is generally true that in the case when the melt contains the ions Si^{4+}, they will have a decisive influence on its structure, since silicon is the most electronegative of all the elements of the system, and with oxygen it creates stable complexes with a strong covalent bond.

The ions Al^{3+} also play an important role in formation of polyanion networks. It is evident from **Figure 4** that the trend of influence of the SiO_2 content on the interfacial tension is the same in both steels. The interfacial tension in the systems with additions of (0, 3, 6 and 9) % of SiO_2 decreases slightly. This confirmed the theory about SiO_2 functioning as a networks former. In the case of the system with the addition of 15 % of SiO_2 the values of the interfacial tension increase slightly. This phenomenon may be caused by the formation of phases with shorter chains and a change of the coordination of the Al^{3+} cations.

4 CONCLUSIONS

We can summarise the obtained results as follows:

- The interfacial tension between the molten steel and the molten casting powder with dominant components of SiO_2, CaO, Al_2O_3 and MgO decreases with temperature.
- A higher content of carbon in steel decreases the values of the interfacial tension at the interface system involving molten oxide and molten steel.
- The interfacial tension of the system involving molten casting powder and molten steel decreases with an increasing content of SiO_2 in the concentration interval 37.1–46.1 %.

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