Wetting of Solid Iron, Nickel and Platinum by Liquid MnO–SiO₂ and CaO–Al₂O₃–SiO₂

Gavin PARRY and Oleg OSTROVSKI

School of Materials Science and Engineering, University of New South Wales, UNSW Sydney, NSW 2052, Australia.

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Wetting of solid metals—iron, nickel and platinum, by molten MnO–SiO₂ (MS) and CaO–Al₂O₃–SiO₂ (CAS) oxide systems was studied by the sessile drop method at 1 350–1 450°C in reducing atmosphere. Terminal contact angles (after 240 min) for MS system were: for iron substrates—5±2 deg at 1 350°C, 9±2 deg at 1 390°C, 6±2 deg at 1 450°C; platinum—15±2 deg at 1 350°C and 1 390°C, and 12±2 deg at 1 450°C. Contact angle for the Ni–MS system was close to zero—3±2 deg at 1 350°C and 1 390°C. Contact angles with CAS system were: iron—55±2 deg (1 350°C), 60±2 deg (1 390°C), 44±2 deg (1 450°C); nickel—59±2 deg (1 350°C), 60±2 deg (1 390°C); and platinum—15±2 deg (1 350°C, 1 390°C and 1 450°C). Work of adhesion for all substrates with MS system was 910 to 930 mJ/m². Interfacial tension with MS system was 1 480 mN/m for Ni at 1 350 to 1 390°C, and 1 880 to 1 890 mN/m for Pt in the temperature range 1 350 to 1 450°C. For iron, interfacial tension was 1 720 mN/m at 1 350°C; 1 580 mN/m at 1 390°C and 1 450°C. Lower work of adhesion and higher interfacial tension were found for metals with CAS system. Reduction of MnO from MS system was observed, leading to Mn dissolution in metal substrates. Degree of silica reduction from MS system was much smaller in comparison with MnO reduction (negligible for Pt); it was very minor from CAS system. Reduction of oxides and adsorption of oxygen modify the metal–oxide interface, making wetting dynamic and profoundly affecting interfacial properties.

KEY WORDS: interface wetting; interface dynamics; oxides.

1. Introduction

In clean steel, inclusions are formed from residual dissolved oxygen and sulfur, even at such low concentrations as 4 to 10 ppm, due to high oxygen and sulfur segregation during steel solidification. Inclusion morphology and shape (spherical, irregular crystal or film) are affected by metal–oxide interfacial properties. In the temperature range of steel solidification (1 450 to 1 200°C) many oxide/oxy-sulfide segregates remain liquid and spread on inter-den-drite surfaces, depending on the local interfacial conditions. Wetting of solid metals by molten oxides is of interest in strip casting. Strezov et al.1) and Evans and Strezov 2) reported that heat transfer between the molten steel and mould was affected by oxides in the FeO–MnO–SiO₂–MnS system present at the interface. When these oxides were molten, heat transfer between the steel and mould encountered very little resistance. Good wetting of the Cr-coated mould and steel interfaces by the low-melting oxide (similar to the MnO–SiO₂ eutectic) enhances heat transfer, as the molten oxide forms a film across the interface. Recently, Nolli and Cramb3) have also shown that manganese silicate mould coatings can improve heat transfer rates and productivity in strip casting.

In the literature, the majority of work is devoted to molten metal–solid oxide or molten metal–molten oxide interfaces, while data on the contact angles for molten oxide–solid metal system are limited. Molten oxide–solid metal systems are expected to present contrasting “wetting” behavior to the “non-wetting” character of molten metal–solid oxide systems. This can be demonstrated by considering the balance of surface energies given by Young’s equation4):

\[ \gamma_{LV} \cos \theta = \gamma_{SV} - \gamma_{SL} \]

where \( \gamma_{LV} \) is surface tension of a liquid, \( \gamma_{SV} \) is surface tension of a solid, \( \gamma_{SL} \) is the interfacial tension of the actual liquid–solid contact. Given the relatively high surface tensions of metals compared to oxides, the solid metal–liquid oxide configuration is expected to produce good wetting (low contact angle) while liquid metal–solid oxide systems favor a non-wetting state (high contact angle).

This work studied wettability and reaction of solid iron, nickel and platinum substrates with liquid MnO–SiO₂ and CaO–Al₂O₃–SiO₂ systems with the aim to contribute to further understanding of solid metal–molten oxide interaction. The choice of silicate systems was made to be representative of typical compositions seen for oxide inclusions in steel. The iron substrate was then expected to exhibit wetting behavior similar to steels, and the nickel was chosen for having similar reactivity to oxygen as iron, while avoiding the \( \gamma–Fe \) phase transformation at the temperatures of interest. Platinum, as an inert metal, exhibits different reactivity with oxygen than the other two metals.
2. Experimental

The study is based upon in-situ observation of high-temperature wettability of a solid metal by molten oxides using the sessile drop method. In these experiments, the change in behavior with time and temperature of a liquid drop of oxide upon a solid metal substrate was recorded. The experiments were conducted in a graphite furnace described elsewhere.6)

A digital video camera with a resolution of 720×576 pixels was used to record image sequences during the wettability experiments. Zoom lenses (one 4×, one 1×) were added to the camera lens to provide the correct focal length. Welding lenses were placed between the camera and the furnace window to reduce glare from the sample at high temperatures.

Iron was obtained in the form of chips (2 mm diameter). Approximately 1 g of iron chips were melted in an alumina crucible under a Varigon (5 vol% hydrogen, 95 vol% argon) atmosphere at 1 600°C. Nickel was obtained as 1 g pellets. The iron or nickel was placed inside an envelope of titanium foil for rolling to a thickness close to 1 mm, giving a diameter of ~15 mm. After rolling, the metal disc was polished down to a roughness of 0.05 μm.

Platinum was supplied in the form of foil of 0.5 mm thickness then polished to the same finish as iron and nickel. Chemical analysis of iron, nickel and platinum by Inductively-Coupled Plasma spectroscopy and LECO analyzers (CS-244 Carbon/Sulfur and TC-436DR Oxygen/Nitrogen) is given in Table 1.

The MnO–SiO₂ (MS) system was prepared from MnO (99.99+% and silica (99.995+%) powders. Silica and alumina (99.8%) powders were used for making the CaO–Al₂O₃–SiO₂ (CAS) system. CaO was produced by calcining CaCO₃ powder (99 wt%) in a muffle furnace. The mixture of pure oxides was melted in a platinum foil crucible in a muffle furnace at 1 500°C, then crushed using a tungsten carbide rod mill to particles of 0.01–0.02 g. Results of X-ray fluorescence (XRF) chemical analysis are given in Table 2. The MnO–SiO₂ system contained 58.5 wt% MnO and 38.5 wt% SiO₂, which is close to the eutectic composition of 61.7 wt% MnO and 38.3 wt% SiO₂. The CaO–Al₂O₃–SiO₂ system was also near the eutectic composition.

Wetting experiments were conducted in atmospheres of Varigon (95% argon, 5% hydrogen) and argon (99.999%). Both inlet gases were passed through copper turnings at 550°C to remove oxygen. A stabilized zirconia oxygen probe sensor manufactured and supplied by MacDhui Engineering Pty, (Melbourne, Australia), measured oxygen partial pressure at the outlet of the furnace (uncertainty in oxygen partial pressure was ±1×10⁻¹⁰ atm).

A sample was placed on the sample stage within the furnace, which slides in and out of the hot zone. The base for the stage was aligned using a spirit level on the stage. Before experiments, the furnace was evacuated by a mechanical vacuum pump for 15 min then the furnace was backfilled with Varigon or argon, which passed through the furnace at a flow rate of 30 mL/min. Each experiment began with heating to 1 000°C at rapid heating rates (200–300°C/min), then held for 30 min. Subsequently, experimental temperature was reached at 100 °C/min.

| Table 1. Chemical composition of metal substrates (only elements with concentration >10 ppm). |
|---------------------------------|--------|--------|--------|
| **Element** | **Fe** | **Ni** | **Pt** |
| **Substrate** | **Substrate** | **Substrate** | **Substrate** |
| Au | - | - | 8300 ppm |
| C | 42 ppm | 100 ppm | - |
| Cr | <10 ppm | <0.03 wt.% | 50 ppm |
| Cu | <10 ppm | <0.03 wt.% | 100 ppm |
| Fe | Balance | <0.03 wt.% | 1200 ppm |
| Ni | 14 ppm | Balance | - |
| O | 10 ppm | 78 ppm | - |
| Pd | - | - | 2400 ppm |
| Pt | - | - | Balance |
| S | 27 ppm | 31 ppm | - |

Measurement of surface tensions from low angle curves observed in this work was meaningless; however the contact angle was measured accurately. A public domain graphical analysis program (Grafula3 version 2.10, http://nanodiamond.spb.ru/wesik/grafula3/english.htm) was used to convert the images to pixel co-ordinates. The droplet profile was described by manual selection of 13–25 points along the edge. Each point was accurate to within ±1 pixel (±0.02 mm given the zoom lenses used on the camera). These selected co-ordinates were then subject to simple linear regression to obtain a curve matching the experimental points. The polynomial equation describing this line was used to find the derivative at the limits of the curve and contact angle for the drop. Marking the drop profile showed an error in contact angle calculation of ±2 deg.

After wetting experiments, samples were analyzed visually and chemically by microscopic methods. Initially, the surface appearance of the samples was recorded by the digital video camera and a Nikon 200 optical microscope. Images of the resin-mounted sample cross section were recorded using the optical microscope.

In preparation for analysis by electron microscopy, the resin-mounted samples were carbon coated in a vacuum.
chamber. Samples were then used for scanning electron microscope (SEM) analysis with electron-dispersive spectroscopy (EDS) facility. The SEM machine was a Hitachi S4500 with Oxford Isis EDS.

The Cameca SX50 electron microprobe analyzer (EPMA) was used for quantitative composition analysis of the sample cross-sections. Accelerating voltage was 15 kV; current 20 nA. Standards used were pure Fe, Ni and Pt; rhodonite for Mn, Si and O in the MS system; diopside for Ca, Si and O and sanidine for Al in the CAS system. Profiles across the centre of the oxide–metal interface and parallel to the interface outwards from the drop edge (as near as practical to the surface) were made with a step size of between 5 and 10 μm across and 100 μm parallel to the interface.

ZAF (atomic number, absorption and fluorescence) corrections were used for matrix correction. The error of measurement of manganese and silicon concentration was within 0.2 wt%. The minimum distance between points that gives unambiguous data is ~3 μm.

3. Results

Isothermal wetting of Fe and Pt substrates by MS and CAS systems was studied at temperatures of 1350°C, 1390°C and 1450°C; reactions with Ni substrate were examined at 1350°C and 1390°C; holding time was 30 and 240 min for Fe and Ni substrates and 30 min for the Pt substrate. Change in the contact angle with time as measured for Fe, Ni and Pt substrates at different temperatures is shown in Figs. 1–3.

The contact angles for iron and nickel substrates with MS were much smaller than in reactions with CAS. Very good wetting and dynamic behavior of the contact angle for the MS system were attributed to the interface modification as a result of MnO reduction from the oxide system, dissolution of manganese into the substrate and oxygen adsorption on the metal surface.

Figure 4 shows the manganese concentration profile in reaction with the MnO–SiO₂ system. The concentration and depth of manganese dissolution in Ni were far more prominent than in Fe and Pt. Platinum showed slightly higher levels of Mn near the interface than does Fe, but the transfer occurred to a similar depth in both; the difference in Mn contents in Fe and Pt was within the experimental error. Dissolution of Mn in Ni decreased the melting temperature of the substrate causing its partial melting and radical change of the interface.

Reduction of silica from the MnO–SiO₂ system and dissolution of silicon into the metal substrate was much

Fig. 1. Contact angle for Fe substrate, 240 min exposure at various temperatures.

Fig. 2. Contact angle for Ni substrate, 240 min exposure at various temperatures.
smaller than observed for MnO and Mn. Relatively low levels of Si dissolved in metal substrates were also observed in reactions with the CAS system. This is seen in Fig. 5 which compares Si concentration profiles in Ni obtained in reactions with CAS and MS systems in 30 min experiments at 1390°C. In the Pt and Fe substrates, no difference in Si dissolution from MS and CAS systems was seen.

The EPMA trace of Mn and Si parallel to the metal surface away from the interface for the MS system is shown in Fig. 6. Mn spread over the surface over a significant distance, while silicon diffused to a lesser degree. Diffusion of silicon in the nickel substrate occurred to a greater level than for iron and platinum across the initial 1 mm away from the interface. Thereafter, no discernable difference was seen for silicon dissolution in all three substrates. Figure 7 presents silicon concentration over the substrate surface for the CAS system. As with the MS system, diffusion of silicon in the nickel substrate was greatest near the interface. Transport of silicon further from the interface was most favored in iron and nickel, with no meaningful evidence of silicon diffusion in the platinum substrate.

Surface appearance of Fe, Ni and Pt substrates with MS and CAS systems is shown in Figs. 8 and 9 respectively. The original color of MS system was black, but appeared brown-orange in most samples of iron and nickel substrates, and purple-orange in platinum samples (Fig. 8(c)). The original CAS system was colorless and transparent, but converted to a black, opaque phase after reaction with iron or nickel. No color change was evident upon reacting CAS with platinum substrates.

4. Discussion

The effect of oxygen in modifying chemistry of the interface and interfacial energies is well recognized in wetting and other surface phenomena. A reactive or non-reactive
regime of wetting depends upon the oxygen partial pressure in the furnace, oxide stability, oxygen adsorption and solubility of oxygen and oxide-forming elements in the substrate.

Solubility of oxygen in solid nickel, iron and platinum is very low. Solubility of oxygen in solid nickel was found in the range of 0.01–0.05 at%\(^7,8)\) and rises to 1.5 at% upon melting.\(^9)\) Iron has similarly low levels of solubility in the solid state—0.0008 at% in \(\gamma\)-Fe, 0.002 at% in \(\delta\)-Fe\(^{10,11})\) while liquid iron near the melting point dissolves 0.06 at%.\(^9)\) According to Zackay et al.,\(^8)\) solubility of oxygen in platinum is negligible.

Intake of oxygen in the wetting experiments depends on the bulk diffusion of oxygen in the metal substrates as well as permeability (product of diffusion coefficient and solubility). At temperatures near those in the present work, iron and nickel have relatively similar levels for oxygen diffusion coefficient and permeability.\(^7,11,12)\) The platinum substrate is expected to have almost no permeability for oxy-

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**Fig. 7.** Composition profile across the substrate surface, 30 min reaction with CAS system at 1 390°C.

**Fig. 8.** Surface appearance of (a) Fe–MS, (b) Ni–MS and (c) Pt–MS systems after 30 min exposure at 1 390°C (from digital camera).

**Fig. 9.** Surface appearance of (a) Fe–CAS, (b) Ni–CAS and (c) Pt–CAS systems after 30 min exposure at 1 390°C (from digital camera).
gen, with the diffusion coefficient being several orders of magnitude lower at the same temperature.\textsuperscript{13,14} However, adsorption capacity of solid platinum, nickel and iron for oxygen is known to be high. The surface activity of adsorbed oxygen profoundly affects surface tensions.\textsuperscript{15,16,17}

With the use of the 5%H\textsubscript{2}–Ar gas in the graphite furnace, partial pressure of oxygen was measured below 10\textsuperscript{−20} atm (slightly higher during pre-heating at 10\textsuperscript{−19} atm). Therefore, experimental conditions were reducing for MnO and SiO\textsubscript{2} in the MS system and for SiO\textsubscript{2} in the CAS system.\textsuperscript{6} Oxygen released in the reduction reactions may form oxides with metals of substrates, be dissolved in the metal phase, adsorbed on the interface or transfer to the gas phase. Oxygen solubility in solid iron, nickel and particularly platinum is very low; it is adsorbed on the metal surface with high surface coverage but in small quantity. Therefore, oxygen can report to the gas phase.

Low activity coefficients of manganese and silicon stimulate reduction of MnO and SiO\textsubscript{2} oxides with transfer of Mn and Si into the metal substrate. Visual confirmation of reaction was the changing color of oxide phases for most systems (Figs. 8 and 9). Trace levels of reaction product phases (metallic Fe, Ni or Pt) are known to alter color of oxides, even on the ppm level.\textsuperscript{16–22}

Modification of the substrate surface as a result of Mn dissolution was particularly significant for nickel. Dissolution of manganese in nickel decreased the melting temperature of the substrate causing its partial melting, which was observed in some experiments at 1 390°C. Concentration of manganese dissolved in the nickel substrate at 1 350 to 1 390°C reached 10 to 12 wt% (see Fig. 4). The solidus temperature of Ni–Mn alloys having 10 to 12 wt% Mn is in the range 1 330 to 1 380°C,\textsuperscript{23} which is below the experimental temperatures; the liquidus temperature is also close to the experimental temperature. This explains the surface melting of the nickel substrate as a result of its alloying with manganese.

The conversion of the oxide–metal interface from liquid–solid to liquid–(partially) liquid has several effects. The greater mobility in the liquid metal enhances interfacial flux and diffusion within the metal phase. Manganese has a relatively high partial vapor pressure, with known loss of manganese from Ni–Mn liquid alloys to vaporization, adding another interfacial flux.\textsuperscript{24}

No melting of the iron substrate is expected according to the Fe–Mn binary phase diagram.\textsuperscript{23} It follows from the binary Pt–Mn phase diagram\textsuperscript{23} that at 1 350°C and 1 390°C, the Pt–Mn alloy with 10 to 12 wt% Mn is solid. High concentration of manganese dissolved in platinum in the wetting experiments at 1 450°C agrees with literature data.\textsuperscript{25–27}

The occurrence of chemical reaction, such as reduction of MnO and SiO\textsubscript{2}, at the interface is known to provide an additional driving force for wetting, above the balance of surface tensions.\textsuperscript{5,28,29} Reduction of oxides, particularly MnO, in wetting experiments causes change in oxide and substrate chemistry, and makes wetting dynamic.

Immediately after melting, the oxide system spread over a substrate and took a shape that changed only gradually. The change of contact angle in the initial period of a few seconds duration was of a non-reactive character.\textsuperscript{30} Subsequently, the reactive wetting between oxide and substrate with dissociation of MnO or SiO\textsubscript{2} on the interface and adsorption of oxygen on the metal surface and dissolution of Mn and Si into the metal took place. The chemical reaction at the interface progresses towards equilibrium, however the transport of reaction products away from the interface (desorption of oxygen and diffusion of Mn/Si into metal) ensures continued reduction. The reduction reaction and mass transfer of Mn/Si from the interface continuously decreased MnO (SiO\textsubscript{2}) content in the oxide system, altering equilibrium conditions and reaction kinetics. Equilibrium was not achieved under experimental conditions described in the paper.

Under experimental conditions in this work, metal–oxide equilibrium was not achieved; however the rate of the oxide–metal reaction in isothermal experiments was low. Considering that a response of interfacial forces to the changing chemistry of the interface was much faster than the change itself, we can operate with a quasi-equilibrium state and estimate interfacial tension and work of adhesion defined as $W_{\text{ad}} = \gamma_{\text{Me}} + \gamma_{\text{oxide}} - \gamma_{\text{H}} = \gamma_{\text{oxide}} (1 + \cos \theta)$. The surface tensions of metals and oxides used in the calculations are given in Table 3.

Calculated interfacial tension and work of adhesion using contact angle measurements after 240 min exposure for Fe and Ni and 30 min for Pt substrate are summarized in Tables 4 and 5. Work of adhesion for the MS system changes in a very narrow range 910–930 mJ/m\textsuperscript{2}. This is a reflection of good wettability of all three metal substrates by the MS system; the contact angle between the MS and different substrates is in a range of 2–15 deg. The trend in interfacial tensions of the MS system with different metals ($\gamma_{\text{H}} = \gamma_{\text{Me}} - \gamma_{\text{oxide}} \cos \theta$) follows the trend in the surface tensions of these metals.

For iron and nickel substrates with the CAS system, work of adhesion is lower and interfacial tension is higher than with MS, reflecting the difference in wetting. Contact

### Table 3. Surface tension of metals and oxides.

| Phase | Surface tension (mN/m) | Temperature (°C) | Reference |
|-------|-----------------------|------------------|-----------|
| γ-Fe  | 2170                  | 1360 – 1400      | 135       |
| δ-Fe  | 2040                  | 1440             | 135       |
| Ni    | 1940                  | 1357 – 1437      | 135       |
| Pt    | 2340                  | 1310             | 135       |
| MnO-SiO\textsubscript{2} | 465 | 1350 – 1450 | 135       |
| CaO-Al\textsubscript{2}O\textsubscript{3}-SiO\textsubscript{2} | 425 | 1350 – 1450 | 135       |

### Table 4. Interfacial tensions for MS and CAS systems with Fe, Ni and Pt (mN/m).

| Substrate | MS system | CAS system |
|-----------|-----------|------------|
|           | Temperature | Temperature |
| 1350°C   | 1390°C    | 1450°C    | 1350°C   | 1390°C    | 1450°C    |
| Fe       | 1720 (γ-Fe) | 1590 (δ-Fe) | 1580 (δ-Fe) | 1980 (γ-Fe) | 1780 (δ-Fe) | 1700 (δ-Fe) |
| Ni       | 1480       | 1480       | -           | 1770       | 1750       | -           |
| Pt       | 1890       | 1890       | 1880        | 1930       | 1930       | 1930        |
angle between platinum and CAS is 15 deg, about the same as between platinum and MS. Difference in the work of adhesion and interfacial tension between the Pt–CAS and Pt–MS systems is due to the 40 mN/m difference in the surface tensions of CAS and MS systems.

High work of adhesion is expected in reactive systems with strong chemical bonds. Values of work of adhesion found for the Pt–MnO–SiO₂ system correspond well with data of Towers. Interfacial tension for the Pt–MnO–SiO₂ system measured by Towers was 1 300 to 1 400 mN/m, based upon assumed platinum surface tension 1 800 mN/m. Recalculated for γ₀=2 340 mN/m, their interfacial tension would be 1 840 to 1 940 mN/m—comparable to present findings. Values for other solid metal–liquid oxide systems were not found in literature; however, it was reported for the solid oxide–liquid metal systems. Work of adhesion for these systems is strongly dependent on the level of oxygen dissolved into the metal. Ogino et al. reported an increase in work of adhesion from 500 to 1 000 mJ/m² upon dissolution of 0.12 wt% [O].

Literature values for interfacial tension of liquid Fe and Ni on solid oxides indicate a range of 1 450 to 2 300 mN/m. The main determinant was oxygen adsorption; Ogino et al. reported decrease of the interfacial tension to about zero with visible emulsification when dissolved oxygen in Fe reached 600 ppm.

Reports of work of adhesion for liquid Fe on solid Al₂O₃ substrates are in the range 500 to 685 mJ/m². This encompasses the values observed for Fe and Ni substrates at most temperatures, indicating a similar balance of interfacial energies.

Oxygen is a surface-active element in both liquid and solid metals, and although solubility of oxygen in liquid metal is by orders of magnitude higher than in solid, the oxygen concentration on a metal surface is close to saturation in solid as in liquid metal. The increased oxygen adsorption with MnO and SiO₂ reduction will lower interfacial tension, and enhance wetting behavior.

### Table 5. Work of adhesion for MS and CAS systems with Fe, Ni and Pt (mJ/m²).

| Substrate | MS system | CAS system |
|-----------|-----------|------------|
|           | Temperature | Temperature |
|           | 1350°C | 1390°C | 1450°C | 1350°C | 1390°C | 1450°C |
| Fe    | 930 | 930 | 930 | 670 | 640 | 730 |
| Ni    | 930 | 930 | - | 640 | 640 | - |
| Pt    | 910 | 910 | 920 | 840 | 840 | 840 |

5. Conclusions

In contrast to poor wetting of oxides by molten transition metals, solid metals—iron, nickel and platinum—are wetted by molten oxides very well. Measured terminal contact angles (after 240 min) for the MnO–SiO₂ system under reducing conditions were: for iron substrates—5 ± 2° (1 350°C), 9 ± 2° (1 390°C), 6 ± 2° (1 450°C), and platinum—15 ± 2° (1 350 and 1 390°C), and 12 ± 2° (1 450°C). Contact angle for the Ni–(MnO–SiO₂) system was close to zero—3 ± 2° at 1 350 and 1 390°C. “Terminal” contact angles after 240 min reacting CaO–SiO₂–Al₂O₃ system with metal substrates were: iron—55 ± 2° (1 350°C), 60 ± 2° (1 390°C), 44 ± 2° (1 450°C); nickel—59 ± 2° (1 350 °C), 60 ± 2° (1 390°C); and platinum—15 ± 2° (1 350, 1 390 and 1 450°C).

Substrates reacted with molten oxide systems with reduction of oxides and interface modification. Reaction at the interface aided wetting in metal–oxide systems, above the balance of surface tensions, leading to dynamic wetting behavior. Significant MnO reduction and manganese dissolution into substrate was observed in reactions with all three substrates. Silica also was reduced in reaction with Fe and Ni, although the extent of reduction was much smaller in comparison with MnO, and was not observed in reaction with Pt. No silicon was detected in the platinum substrate.

Oxygen solubility in the substrate metals was below the detectable level, with a greater tendency to adsorb at the metal–oxide interface since the reducing conditions made oxide formation on the substrates unfeasible. Adsorbed oxygen is known to be strongly surface active, lowering the surface tension of the metal substrates and favoring wetting conditions.

Interfacial tension of the substrates with the MS system was relatively high: iron—1 580 to 1 720 mN/m; nickel—1 480 mN/m; and platinum—1 880 to 1 980 mN/m. Values with CAS system broadly reflected the less wetting configuration: iron—1 700 to 1 980 mN/m; nickel—1 750 to 1 770 mN/m; and platinum—1 930 mN/m. These values compared reasonably with literature values determined for comparable molten oxide-solid metal systems, and also similar molten metal–solid oxide systems.

Work of adhesion was determined for all substrates with the MS system as 910 to 930 mJ/m². Values varied more widely between substrates with CAS system: iron—640 to 730 mJ/m²; nickel—640 mJ/m²; and platinum—840 mJ/m². Greater work of adhesion reflected better bonding at the interface when strong wetting (low contact angle) took place.

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