Two-body Interaction in Molten Metals and Its External Field Response Analyzed by Atomic Force Microscopy

Yuto Nishiwaki,[1,#] Toru Utsunomiya,[1] Ken-ichi Amano,[2] and Takashi Ichii[1,*]

[1]*Department of Materials Science and Engineering, Kyoto University, Sakyo-ku, Kyoto 606-8501, Japan*
[2]*Department of Applied Biological Chemistry, Meijo University, Tempaku-ku, Nagoya 468-8502, Japan*

Presenting author's e-mail: nishiwaki.yuto.63c@st.kyoto-u.ac.jp

The dispersibility of particles in molten metals plays a crucial role in the production and recycling processes of alloys. Since particle dispersibility is determined by the forces between the particles, experimental measurements and formulation of these forces in molten metals are essential. The force-distance measurement by atomic force microscopy (AFM) provides the interaction force between two solid bodies in a liquid. However, this method is hardly applicable to opaque molten metals because they typically rely on optical beam deflection or interferometry for displacement detection. This limitation prevents the development of experiment-based determination of interparticle forces in molten metals.

Our group has developed an AFM in molten metals using the qPlus sensor, which is applicable to opaque liquids, and demonstrated that strong, long-range attractive forces act between a mica substrate and a W tip in molten Ga by AFM analysis (Figure 1(a)) [1]. Since GaO_x covers the surfaces of nonmetals and base metals such as mica and W in molten Ga, the detected tip-sample forces are interpreted as the interaction forces between the GaO_x surfaces.

In a vacuum, the van der Waals force causes such long-range attraction between dielectrics. However, it is not evident whether the van der Waals force is also the origin of long-range forces in conductive molten metals. Therefore, this study employed a noble metal tip and substrate to determine the origin of these forces. Noble metals such as Au form an intermetallic phase (*e.g.,* $AuGa_2$) with Ga, which is exposed at the interface instead of GaO_x. However, the formation of an intermetallic phase also changes the shape of the noble metal tip during the measurement. Therefore, AFM measurement in molten metals using a noble metal tip is challenging and requires a lower alloying rate than that of Au. We found that Pt exhibits a significantly lower alloying rate than Au and exposes $PtGa_x$ (PtGa, $PtGa_2$, *etc.*) on the interface by *in-situ* AFM analysis. We have also developed a reproducible electropolishing method for Pt-20% Ir alloy tips [2]. We performed force-distance curve measurements with tips and substrates of GaO_x (mica, W) or $PtGa_x$ (Pt, Pt-Ir). Both pairs of $PtGa_x$ tip-GaO_x substrate and GaO_x tip-$PtGa_x$ substrate showed weaker attractive force than the GaO_x tip-GaO_x substrate pair (Figure 1(b,c)). These results correspond to the dielectric constant dependence of the van der Waals force derived from Lifshitz theory. In contrast, the $PtGa_x$ tip-$PtGa_x$ substrate pair showed a long-range repulsive force with a decay length of about the Thomas-Fermi length instead of the attractive force derived from Lifshitz theory (Figure 1(d)). This was explained by the shielded Coulomb interaction between the surfaces charged by the large work function of Pt. In the presentation, the origin of these forces will be discussed in more detail, together with measurements of their dependence on temperature and external electric field.

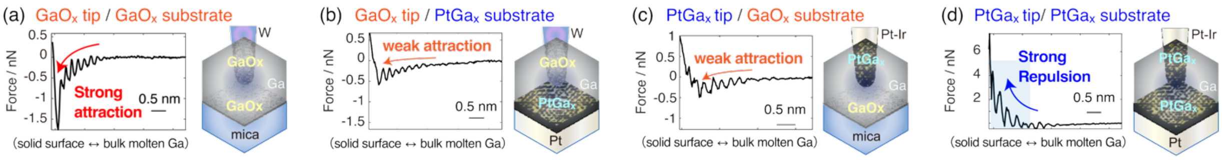

Figure 1. Force-distance curves between (a) GaO_x tip-GaO_x substrate, (b) GaO_x tip-$PtGa_x$ substrate, (c) $PtGa_x$ tip-GaO_x substrate, and (d) $PtGa_x$ tip-$PtGa_x$ substrate obtained in Ga.

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