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ELECTRON EMISSION FROM INCONEL UNDER ION BOMBARDMENT

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Electron yields from clean and oxydized Inconel 625 surfaces have been measured for H^+, H_2^+, He^+, O^+ and Ar^+ ions at normal incidence in the energy range 1.5–40 keV. These measurements have been made under ultrahigh vacuum and the samples were freed of surface contaminants by bombarding with high doses of either 20 keV H_2^+ or 30 keV Ar^+ ions. Differences in yields of oxydized versus clean surfaces are explained in terms of differences in the probability that electrons internally excited escape upon reaching the surface.

1 INTRODUCTION

The bombardment of solid surfaces by ion beams produces, *inter alia*, electron emission.[1] The study of this phenomenon, called ion-electron emission (IEE) is important for the understanding of inelastic ion-surface collisions and gas discharges, for the accurate measurement of small ion currents and for its role in fusion reactors[2-5] and direct energy converters.[6]

IEE from surfaces can be explained to result from two distinct processes, potential and kinetic emission. Potential emission occurs through the relaxation of the potential energy of the ion-surface system if the ionization potential of the neutral atom of the ion species exceeds twice the work function of the surface. In kinetic emission, the energy required to liberate target electrons is provided by the kinetic energy of the projectile. Kinetic emission predominates over potential emission (when the latter occurs) for ion velocities larger than $0.4\text{–}2 \times 10^7$ cm/s in the case of clean metals[1] and for ion energies larger than 20–60 eV in the case of gas-covered surfaces.[7-9]

In this work we have measured IEE yields γ (defined as the average number of electrons ejected per incident ion) for 1.5–40 keV ions bombarding Inconel targets at normal incidence. The choice of this alloy for our present study was based on the importance which Inconel has being the first-wall material of the JET (Joint European Torus). Our measurements were performed in UHV for two different surface conditions obtained after bombardment with 10^{17} H_2^+ ions/cm^2 at 20 keV or with 5×10^{17} Ar^+ ions/cm^2 at 30 keV.

2 EXPERIMENTAL

2.1 *Apparatus*

The experimental set-up was described in detail previously[10] so only a summary will be given here. The ion beams were produced with a conventional ion accelerator equipped with a radio-frequency ion source. After mass-analysis the beam passes through two stages of differential pumping and into the ultrahigh vacuum chamber. The operating pressure in this chamber with the ion beam on was always kept in the 10^{-10}-Torr range.

Total errors in the measurements of the yields were ±5%. This number includes statistical uncertainties and systematic errors due to the presence of fast charge-transfer neutrals in the beam, and the emission of secondary ions (sputtered and backscattered) from the target. The accuracy of the measurements of ion energy was ±(0.1% + 30 eV).

An evaluation of the surface cleaning methods discussed below were made in a different UHV system using Auger electron spectroscopy (AES) combined with H_2^+ and Ar^+ ion bombardment with a 10 kV ion gun.

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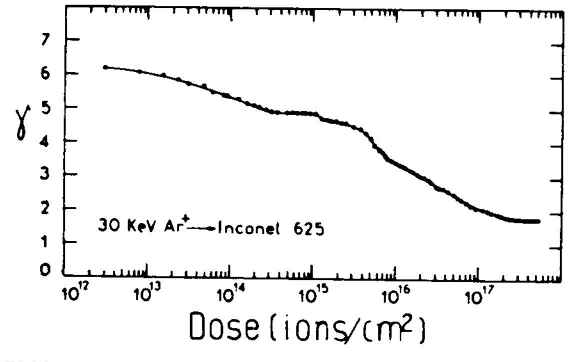

FIGURE 1 Dose dependence of ion-electron yield γ from Inconel 625 bombarded by 30 keV Ar^+ ions.

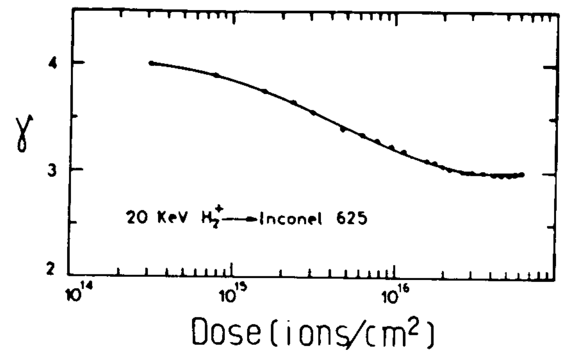

FIGURE 2 Dose dependence of ion-electron yield γ from Inconel 625 bombarded by 20 keV H_2^+ ions.

2.2 *Target Preparation*

The target used was Inconel 625 made by Huntington Alloys and supplied to us by the Culham Laboratory. It was composed of 61.79% Ni, 21.1% Cr, 9.05% Mo, 3.7% Nb, 3.5% Fe and of smaller quantities of other elements. The samples were only vapour degreased and heated in vacuo to ~200°C during the bakeout of the UHV chamber; their surfaces were found to be oxidized and to have an overlayer of adsorbed impurities (mainly C and F). These layers could be removed efficiently by sputtering with a 30 keV argon beam. This is shown in Figure 1 where γ, which is strongly influenced by the presence of layers of oxide and adsorbed gas, is seen to decrease as the surface is progressively cleaned with increasing bombardment dose. A stable surface, oxidized but free of other contaminants can be seen to be reached at doses between 0.3 and 1×10^{15} ions/cm^2. Under more prolonged bombardment the yield decreases and finally stabilizes to a value which corresponds to that of an oxide-free surface. The first surface condition described can be approximately obtained, and in a more controllable manner, by bombardment with hydrogen ions, which easily remove adsorbed contaminants but sputter the substrate at much smaller rates.[3]

This can be seen in Figure 2 which depicts the variation of γ with the dose of impinging 20 keV H_2^+ ions. The saturation value attained for doses larger than 2.5×10^{16} mol/cm^2 (smaller than at least 10^{17} mol/cm^2) could be well reproduced.

AES measurements revealed that hydrogen bombardment at 7 keV readily cleans the surface from C contamination but is comparatively very inefficient in removing oxygen. Analogous observations on steel have been reported by Bouwman *et al.*[11] but using low energy (800 eV) hydrogen ions. Ion bombardment with 10 keV Ar^+ ions was found to remove C and O to below the detectability level of AES. The difference in ion energy used to get these results and those of Figures 1 and 2, is not expected to be qualitatively important with regards to differential cleaning abilities.

Measurements of γ were made on both clean and oxydized Inconel targets. The ion doses used for these measurements were kept low ($<10^{13}$ ions/cm^2) in order not to alter the surface conditions to any discernable extent. The importance of this precaution, especially for the case of the oxidized surfaces can be readily appreciated from the observation of Figure 1.

3 RESULTS AND DISCUSSION

Figure 3 shows electron yields from Inconel 625 under H^+, H_2^+, He^+, O^+ and Ar^+ for the two surface conditions described above. The data for clean Inconel is very similar to that obtained previously[10,12] for Cr or Cu, which are close in atomic number to Ni, the main constituent of Inconel.

The yields for H^+ were found to be larger than one-half the yields for H_2^+ when compared at the same energy per nucleon, thus showing that H_2^+ is not, in producing electronic excitation, equivalent to two protons of the same velocity. This molecular effect in IEE has been observed in the majority of the work done in the past involving protons and H_2^+ and has been discussed recently by Baragiola *et al.*[13] Figure 3 shows that the molecular effect is more pronounced for the oxide where electrons are in atomic-like orbitals than in the metal where the outer electrons are itinerant.

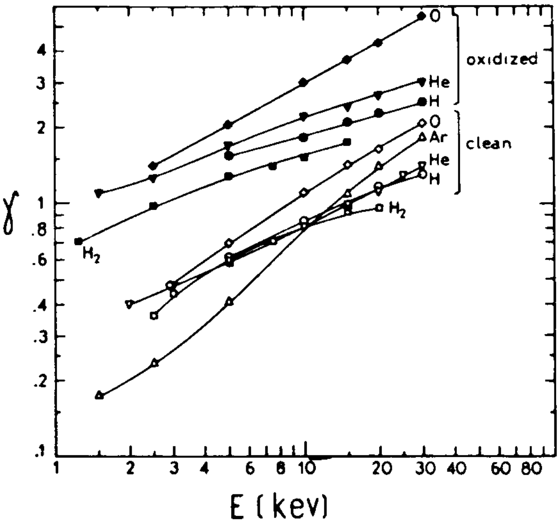

FIGURE 3 Ion-electron yields γ from Inconel 625 with clean and oxidized surfaces. Yields for H_2^+ are shown divided by 2 and at $\frac{1}{2}$ the incident energy.

This is not inconsistent with the fact that at low ion velocities the molecular effect is very pronounced in gas-phase ionization collisions.[14]

The yields for the oxide are in all cases larger than those for the clean surface, a result which is consistent with vast amount of data existing on kinetic IEE[1,15] and on electron-induced electron emission.[16] The explanation usually given for this effect is that in oxides, excited electrons produced on the average deeper in the solid than in the case of metals can escape since electron attenuation lengths in insulators (~200 Å) are larger than in metals (~20 Å).[17] This cannot be however the whole picture since for instance in the case of Aluminum, 10, 20 and 30 Å anodic oxides give the same ion electron yields[18] and since more than 60% of the increase in γ due to oxidation over the values for clean Al is already obtained after the adsorption of about 1.5 monolayers of oxygen.[19]

There are two main other possible reasons for the differences in the behaviour of oxides and metals in IEE. One is an enhanced ionization cross section in the case of oxides and the other a difference in the probability that electrons are emitted into vacuum once they reach the surface. The strong correlation between yields and work function variations during oxygen adsorption,[19,20] suggests that the second reason is dominant.

We will then consider variations in the electron escape probability B. For an isotropic distribution of internally excited electrons[21]

$$B = \left[1 + \frac{I}{E}\right]^{-1}$$

where I is the height of the surface barrier and where E is the electron energy measured from the vacuum level. The barrier height for insulators is the electron affinity which is much smaller than I for metals (for free-electron-like metals I is equal to the Fermi energy plus the work function). This more than compensates for a softer electron energy spectrum for insulators than for metals[22] and causes $\langle B \rangle$, the average value of the escape probability, to be larger for insulators than for metals. This also follows from the work of Alig and Bloom[23] who showed that $\langle B \rangle$ is larger for insulators than for elemental semiconductors which have electron emission characteristics similar to those of metals.[16,17]

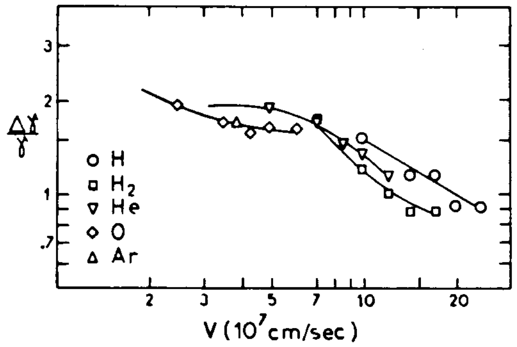

FIGURE 4 Relative increase in the yields for the oxidized versus the clean surfaces of Inconel 625, $\Delta\gamma/\gamma$, as a function of the velocity of the projectiles.

Figure 4 shows the relative increase in the yields for the oxidized versus the clean surfaces, $\Delta\gamma/\gamma$, as a function of the velocity of the projectiles. There is a general trend with $\Delta\gamma/\gamma$ decreasing with increasing ion velocity and roughly independently on the identity of the projectile. This behaviour can be explained if one recalls that $\langle E \rangle$, the average energy of the emitted electrons, is known to increase with increasing ion velocity and not to depend much on the ion type.[24] Equation 1 shows that $\langle B \rangle$ will be larger the larger the value of $\langle E \rangle$, the effect being smaller in the case of oxides than in the case of clean metal surfaces with their larger barrier height. Then the increase of $\Delta\gamma/\gamma$ at low impact velocities reflects the lower transmissivity of metal surfaces for low energy electrons. At velocities smaller than those used in this work, where potential electron emission predominates, the picture will change and $\Delta\gamma/\gamma$ will become negative[25,26] since potential electron yields are smaller for oxides and contaminated surfaces than for metals.

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