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**PERFORMANCE OF A COPPER-LITHIUM ALLOY AS AN
IMPURITY CONTROL SYSTEM SURFACE MATERIAL FOR A FUSION REACTOR**

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ABSTRACT

A copper-lithium alloy was evaluated as a surface material for the impurity control system of the INTOR reactor. Both the medium edge temperature limiter regime and the low edge temperature diverter regime were examined. The analysis used TRIM code data to predict sputtering coefficients for copper-lithium with a 1.5 monolayer coverage of lithium. The REDEP code was used to evaluate the erosion performance for INTOR. Other properties such as fabrication and thermal performance were also briefly assessed. It was found, from the standpoint of erosion, that copper-lithium is a very good candidate material for the medium edge temperature regime, and also works well in the low edge temperature regime. For the medium edge temperature regime, the use of copper-lithium results in an almost negligible erosion rate over the entire limiter surface.

1.0 INTRODUCTION

A promising material for use on fusion impurity control surfaces is a copper-lithium alloy^(1,2) in which thermal and radiation-related segregation processes result in an overlayer consisting entirely of the low-Z lithium component of the alloy. The purpose of the lithium component is to alter the near-surface composition to provide sputtering properties which are not characteristic of the bulk material. In particular, both hydrogen sputtering and self-sputtering are lowered for Cu-Li, compared to bulk copper.

At thermodynamic equilibrium, the region expected to be enriched in the lithium component is only one atomic layer thick. In a radiation environment, however, a broad concentration profile of the lithium is expected, which may extend quite far into the sub-surface region. Copper-lithium has another important and favorable property; that of sputtering nearly all of the low-Z component as a charged particle (Li^+). A sputtered ion quickly returns to the surface via sheath and/or gyroorbit effects. The returning ion has negligible energy. Sputtering of and by the lithium is, therefore, effectively suppressed for Cu-Li.

The purpose of the present study was to begin a more detailed evaluation of the use of this material for an actual design application. The performance analysis was done using the INTOR reactor design.⁽³⁾ Because of the extensive analysis done for INTOR on impurity control issues it is fairly easy to compare present results to other proposed reactor materials.

The analysis focused on the medium edge temperature limiter regime previously identified as being the most likely and at the same time the most difficult regime to work with. The limiter offers a substantial cost savings if it can perform acceptably. The low-temperature divertor regime, which is a key focus of current research, was also examined.

2.0 PROPERTIES OF COPPER-LITHIUM

Copper is frequently the material of choice for high heat flux applications, and may be one of the few materials suitable for heat removal at limiters and divertor plates in spite of problems associated with neutron activation. Because of its high sputtering yield, elemental copper is, however, unsuitable for use as a plasma-side material. Thermal conductivity is a bulk property while sputtering is confined to the uppermost 1-2 atom layers. We therefore seek to alter the near-surface composition to provide sputtering properties which are not characteristic of the bulk material. A copper-lithium alloy has been identified as a way of reducing copper self-sputtering while retaining the desirable bulk properties of copper for limiter and divertor applications.

In order for the self-sustaining overlayer to be of practical use, it must (1) form a reasonably complete low-Z coating which is maintained for times at least comparable to the operating cycle of the fusion device, (2) be

stable at the expected operating temperature of the substrate material, (3) significantly reduce both the light ion and self-sputtering of the high-Z component, (4) have a long lifetime-to-depletion of the bulk inventory of the low-Z component, and (5) must have an erosion rate low enough to prevent significant contamination of the plasma by the overlayer material, although the allowable level for low-Z atoms is relatively high. Additionally, preferential erosion and redeposition properties of the composite material must present an operational advantage over competing materials in a given range of plasma parameters.

Binary copper-lithium alloys containing up to 10 at.% lithium have been prepared⁽⁴⁾ by reacting copper and lithium to produce Cu-Li and arc melting the compound with additional copper to produce an alloy with the desired composition. Very little lithium is lost during repeated meltings, indicating that lithium has very low activity in the alloy. The vapor pressure is comparable to that of pure copper and depends on the lithium concentration. Sputtering properties of the alloy have been investigated experimentally. It has been found that at sputter-induced erosion rates on the order of 1 second per monolayer, and temperatures appropriate to the use of copper as a limiter material, an alloy containing as little as 2.6 at.% Li forms an overlayer consisting primarily of lithium.⁽²⁾ The lithium overlayer is stable during extended irradiation at high temperature, and the sample exhibits negligible reduction in bulk lithium concentration after prolonged sputtering at temperatures up to 430 C.⁽⁵⁾ In these experiments, the sheath potential at a limiter surface has been simulated by applying a bias voltage to the sample and monitoring the surface composition during sputtering by means of Auger spectroscopy.⁽⁶⁾ For a temperature range of 140 C to 320 C, spanning the expected operating temperature of a copper limiter in a fusion reactor, a significant fraction (> 90%) of the lithium sputtered from the copper substrate is in the form of secondary ions which for a 20-30 eV or greater sheath potential would be returned to the limiter surface at a point within ~ 100 μm of the point of origin⁽⁷⁾ and make no contribution to the net erosion. Experimentally, a 22 V bias completely suppresses the depletion of the lithium overlayer, as shown in Figs. 1 and 2.

The TRIM computer code has been used to predict the copper and lithium sputtering yields from a matrix characterized by a high degree of surface

Fig. 1. Experimental measurement of Li(KLL)/Cu(MNN) auger signal ratio vs. sputtering dose, with and without 22V sample bias. $T = 140\text{ C}$. $\phi = 3.6 \times 10^{12}\text{ cm}^{-2}\text{ sec}^{-1}$ 3 keV Ar^+ .

Fig. 2. Li(KLL)/Cu(MNN) ratio vs. sputtering dose. $T = 230, 260, 290,$ and 320 C . $\phi = 2.1 \times 10^{14} \text{ cm}^{-2} \text{ sec}^{-1}$ 1.5 keV Ar^+ . Steady state value at 320 C corresponds to 1.5-2 equivalent monolayers of lithium.

segregation, and these values have been used as the input for REDEP. The TRIM results indicate that for a single atomic overlayer of lithium, the copper erosion is reduced by a factor of 4-6 relative to that of pure copper, depending on the mass and energy of the incident particle.⁽⁵⁾ Similar results have been obtained experimentally.⁽²⁾ Analysis of the near-surface lithium concentration by Auger electron spectroscopy indicates the presence of more than one atomic layer of lithium. Physical arguments based on the observed high ion fraction of the sputtered lithium and the stability of the lithium overlayer at temperatures in excess of 400 C⁽⁵⁾ dictate that the effective thickness of the lithium overlayer does not exceed 2 atomic layers. A considerable body of both experimental and calculational evidence now exists to the effect that sputtered atoms originate almost entirely within the first 1-2 atomic layers. Consequently, an overlayer of lithium 1-2 atomic layers thick is expected to provide substantial reduction in erosion of the substrate material. This topic has been reviewed recently by Gruen, Krauss and Pellin.⁽⁸⁾

Calculated yields for the self-sputtering of copper from a pure copper surface and from copper covered with 1 and 1.5 atomic layers of lithium are shown in Fig. 3. For comparison, the self-sputtering yield of tungsten is also shown. For impact energies in excess of 1 keV, the sputtering yield of tungsten exceeds unity, corresponding to the generation of a self-sputtering cascade region. For tungsten, an impact energy of 1 keV corresponds to an edge temperature of ~ 80 eV. (This estimate is based on a sheath potential of 3 T_e and a charge state value of 4 for redeposited tungsten ions.) For copper with a single lithium overlayer, the predicted kinetic energy corresponding to unity self-sputtering yield is 400 eV higher than for tungsten. If the lithium overlayer is as much as 1.5 monolayers thick, a self-sputtering coefficient of unity for Cu-Li is reached at 3400 eV.

Preliminary calculations of the lithium concentration profile for 2.6 at.% Li in Cu undergoing 3 keV Ar^+ bombardment⁽⁹⁾ have been made. The model used is not quantitatively correct but suffices to show that the profile depends rather sensitively on a number of parameters, including the projectile mass, kinetic energy, angle of incidence, the displacement profile and the charge state of the sputtered atoms. The latter point is illustrated in Fig. 4 for 500 eV D^+ bombardment. Additionally, it is expected that redeposition processes will further alter the composition profile and hence the partial

Fig. 3. TRIM results for the calculated self sputter yields of $\text{Cu}^+ \rightarrow \text{Cu}$, $\text{W}^+ \rightarrow \text{W}$, $\text{Cu}^+ \rightarrow \text{Cu}$ with 1 atomic layer of Li, $\text{Cu}^+ \rightarrow \text{Cu}$ with 1.5 atomic layers of Li. Yields are for normal incidence.

Fig. 4. Calculated lithium concentration depth profiles for 2.6 at % Li in Cu, assuming Li^+ secondary ion fractions of 0 (●), 50% (▲), 90% (■), and 98% (▼).

sputtering yields. This effect has not yet been treated in a self-consistent manner. However, it is likely that subsurface Cu-Li compound formation will have an even greater impact on the solute concentration profile. For the purpose of the TRIM and REDEP calculations it has been assumed that the lithium is concentrated entirely at the surface in a layer of 1.5 atomic layers thick, approximately representing the range consistent with experimental results.

The sputtering yield of deuterium on copper-lithium was also computed by the TRIM code and the results are shown in Fig. 5. These values, and values scaled for tritium and helium sputtering, were used in the performance calculations. As shown, sputtering yields for Cu-Li are substantially lower than for copper.

3.0 EROSION/REDEPOSITION ANALYSIS

Using the sputtering and reflection coefficients found from the TRIM code, the REDEP computer code⁽¹⁰⁾ was used to compute the erosion of the INTOR limiter and divertor coated with Cu-Li. Table 1 summarizes some of the input data used for the calculations. As discussed above, the use of a 1.5 monolayer Li coverage, and a 100% Li charged-sputtered fraction, in the calculations, are believed to be plausible based on experimental data. The data for the angle of incidence of ions are based on calculations⁽¹¹⁾ using a particle-following kinetic code applied to the sheath region with a shallow angle magnetic field geometry. An important result, in the present context, is that a heavy atom such as copper impacts at approximately normal incidence when accelerated through the sheath potential. Compared to hydrogen,⁽¹²⁾ there is less conversion of the sheath-acquired energy into gyromotion for a copper ion. For D-T neutrals, the angle of incidence, and the overall charge exchange sputtering were scaled from DEGAS code results for beryllium.⁽¹³⁾ For the divertor analysis, no charge exchange sputtering was assumed. In general, angle of incidence data needs to be examined experimentally for this and other materials.

An important assumption for the present REDEP calculations is that the redeposited material has the same sputtering properties as the original material, i.e., Cu-Li with a 1.5 monolayer Li coverage. This seems a reasonable

Fig. 5. TRIM results for the calculated sputter yields of $D^+ - \text{Cu}$, $D^+ - \text{Cu}$ with 1.5 atomic layers of Li. Yields are for 60 deg. (from normal) incidence.

Table 1. REDEP Analysis Input Data Summary

Parameter	Value
1. Limiter type	bottom, 2-sided, curved, pumped limiter - INTOR design.
2. Divertor type	outer collector plate of INTOR single null divertor.
3. Coating material	Cu-Li, 1.5 monolayer Li coverage.
4. Plasma edge temperature - limiter	100 eV (at start of scrapeoff).
5. Plasma edge temperature - divertor	30 eV (at separatrix - near plate).
6. Angle of incidence of D-T, He ions	60 deg (from normal)
7. Angle of incidence of DT charge exchange neutrals	45 deg
8. Angle of incidence of redeposited copper ions	0 deg
9. Charge fraction of sputtered lithium, $\text{Li}^+ / (\text{Li}^+ + \text{Li}^0)$	100%
10. Surface binding energy of Cu-Li	3.4 eV

assumption based on the above mentioned phenomena of surface segregation processes. As with other candidate surface materials, the properties of redeposited surface layers needs further investigation.

Figure 6 shows the REDEP results for the limiter calculation. Since the two sides of the limiter have approximately the same behavior, results are shown for the right side only. As shown, the total gross erosion rate varies from ~ 22 cm/yr at the limiter center to ~ 4 cm/yr at the leading edge. This rate refers to the erosion of copper from the surface, on the basis of steady state operation. The total gross rate is the sum of the hydrogen, helium, and self-sputtering contributions. At the fairly low plasma temperatures encountered near the leading edge, self-sputtering is negligible. The net growth rate, which is the difference between the redeposited and sputtered rates, is almost zero over the entire surface with only a very small growth rate occurring in the leading edge vicinity.

The net growth behavior for Cu-Li is considerably better than for low-Z coatings, specifically Be and C (see Ref. 3) and better than other compounds such as TiC.⁽¹⁴⁾ There are two basic reasons for the better performance of Cu-Li: (1) the sputtering coefficients are lower for Cu-Li than Be or C, and (2) sputtered Cu atoms have shorter mean free paths for ionization, this due mostly to their heavier mass. Because of the latter reason, Cu is more likely to be ionized in the scrapeoff zone and return to the point of origin than the lighter materials.

It should be noted that these results depend on models of the plasma parameters in the scrapeoff zone, i.e., density, temperature fall offs, etc., and are therefore subject to change with changes in the plasma model. However, we would expect that the advantage of Cu-Li over other materials examined would be maintained.

Another important result from the REDEP limiter calculation is the amount of copper entering the plasma. This amount is expressed as the effective sputtering coefficient S_{eff} , defined as the ratio of the copper current entering the plasma to the DT current incident on the limiter. The value found for the limiter is $S_{eff} = 1.0 \times 10^{-4}$. S_{eff} can also be thought of as a "plasma contamination fraction" in the sense that the average impurity copper concentration in the plasma, in steady state is given by $N_Z/N_{DT} = S_{eff} \frac{\tau_Z}{\tau_{DT}}$ where the τ 's refer to the respective particle confinement times. One dimensional

Fig. 6. REDEP calculation for INTOR limiter, $T_0 \approx 100$ eV coated with copper-lithium alloy.

transport code studies have shown that $\tau_z/\tau_{DT} \approx .2$ for materials like vanadium.⁽¹⁵⁾ For copper this ratio would be expected to be similar; this would imply an average copper concentration in the plasma of $\sim 2 \times 10^{-5}$. This value is acceptably small.⁽¹⁵⁾

For the low edge temperature divertor case the results for Cu-Li are as follows. The gross erosion rate is ~ 20 cm/yr at the separatrix; this value lies between the rates found for W and Mo.⁽¹⁶⁾ There is essentially zero net erosion over the plate due to very high redeposition fractions. Thus, Cu-Li functions well for a divertor plate application in this regime.

4.0 PERFORMANCE COMPARISON

Table 2 compares the performance of Cu-Li to three leading candidate surface materials for a variety of key issues. The issues related to sputtering of Cu-Li were assessed based on the calculations described here. Other issues for Cu-Li were assessed based on the previous analysis for other Cu alloys.

Although sputtering behavior is a very important consideration, there are other factors which affect the choice of a plasma side material. Besides sputtering erosion, the factors involved in materials selection are response to disruptions, heat transfer and thermal stress, fabrication, radiation damage, activation, and tritium permeation. The Cu-Li alloys are limited in operation to plasma edge temperatures ≤ 200 eV due to self-sputtering considerations. Only low-Z elements like Be and C, whose self-sputtering coefficients never exceed unity, can be used at higher edge temperatures.*

The Cu-Li alloys appear to have favorable characteristics with respect to thermal stress considerations and tritium permeation. The high thermal conductivity of low alloy content copper alloys results in reduced thermal stresses and the capability to accommodate high heat fluxes. Thermal stresses associated with property mismatches at the interface of the plasma side material and heat sink material should be reduced or eliminated since Cu-Li would either be bonded to another copper alloy with similar properties or it may be possible to use Cu-Li as both the plasma side and structural material. The

* There is some indication (see ref. 11) that high reflection coefficients at glancing angles of incidence may be a problem even for Be and C, but this needs further assessment.

Table 2. Performance Comparison of Cu-Li With Several Leading Candidate Surface Materials

Key Issue	Desirable Behavior	Cu-Li	Be	W	C
Self-sputtering threshold energy	no limit	3.4 keV	no limit	1 keV	no limit
Plasma edge temperature limit	no limit	200 eV	no limit	50 eV	no limit
Net erosion behavior for medium edge temperature limiter regime	0	<0.3 cm/yr	>5 cm/yr	not useable due to self-sputtering	>5 cm/yr (physical sputtering only)
Net erosion behavior for low edge temperature divertor regime	0	0	10 cm/yr	0	10 cm/yr
Plasma contamination behavior	acceptable	acceptable	acceptable	acceptable	acceptable
Disruptions	no vaporization or melting, low electromagnetic forces	possibly large melt layer thickness & large magnetic forces	possibly large melt layer thickness	high threshold for melting, possibly NO melting or vaporization	very good-low vaporization, no melting
Heat transfer & thermal stresses	high thermal conductivity, low elastic modulus close match in properties between plasma side and heat sink materials	has potential for very low thermal stresses when bonded to copper heat sink or when used as a monolithic structure	possible high thermal stresses because of property mismatch with heat sink	possible high thermal stresses because of property mismatch with heat sink	low thermal stresses but possible problems because of property mismatch with heat sink
Fabrication	low cost, fabricable in thicknesses $\approx$ 1 cm, weldable or brazable, machinable	unknown in large sizes	can be formed by powder metallurgy, brazable, expensive	available in sizes to 2 cm thick, not weldable but brazable, difficult to machine, expensive	readily available but potential problems with bonding
Radiation damage	little or no effect of neutron damage on bulk properties to $\sim$ 50 dpa low swelling & creep	unknown	potentially poor due to high helium generation rates	potentially poor due to radiation hardening & embrittlement	poor radiation response—cannot be used $>2\text{MW}\cdot\text{yr}/\text{m}^2$
Activation	low afterheat, no long term decay products	poor	good	high activation—short term, good—long term	good
Tritium permeation	should provide effective barrier for permeation to coolant, should have low inventory in material	good	good	good	potentially high tritium inventories

very low solubility of hydrogen in copper results in low tritium permeation rates.

The concerns of Cu-Li alloys involve disruption response and activation. If large amounts of energy are deposited on the surface during disruptions, the melt layer that forms could be thick, and eddy current forces that occur during disruptions could result in the loss of the melt layer. The actual amount of erosion is uncertain, however, since the disruption conditions cannot be accurately specified at this time. Copper is known to become highly activated during irradiation, and in fact, is the poorest of the candidate materials with respect to activation.

The fabrication and irradiation properties of Cu-Li alloys are largely unknown, and experimental work is needed in these areas.

5.0 CONCLUSION

Based on the present performance analysis, a copper lithium alloy appears to have good potential as an impurity control material for fusion applications. As shown, the sputtering properties of a self-sustaining layer of lithium on copper of only 1.5 atomic layers thick would allow the material to be used as a tokamak limiter or divertor with plasma edge temperatures in the range of 0 - 200 eV, a range unmatched by any other material. The self-sustaining overlayer is maintained by favorable thermodynamic driving forces and radiation-enhanced diffusion kinetics. Since the lithium component tends to be sputtered as a charged ion, which quickly returns to the surface, there is apparently little lithium lost in any event. While there are some drawbacks to the use of copper-lithium and several areas of uncertainties this is also true of the other candidate materials. Indeed, since there are few viable candidate materials for impurity control the addition of even one to the list is of major significance, in our opinion. Other alloys exhibiting similar sputtering properties as Cu-Li but with different bulk properties may also be possible, and these are currently being explored.

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