OBJECTIVE

The objective of this project is to create a functionally graded tungsten-steel laminate composite for use in plasma facing components in fusion reactors.

SUMMARY

Tungsten foils in thicknesses 250, 100, and 25 µm and grade 92 steel foils in nominal thicknesses 250, 100, and 76 µm were obtained. The foils were alternately stacked within a stainless steel container and then hot rolled at 1000°C to approximately 80% reduction of the original height to induce bonding. The composite was analyzed with EDS to reveal the elemental composition at the tungsten-steel interfaces. Tungsten foils were electropolished to reveal the grains for EBSD analysis. Samples of the tungsten and steel foils were tensile tested. An initial test was done with select foil samples utilizing digital image correlation to monitor the deformation.

PROGRESS AND STATUS

Introduction

For the plasma-facing components of fusion reactors, tungsten will be the interface between the plasma and the underlying structural component because tungsten has a low sputtering yield, high melting temperature, and relatively high thermal conductivity. However, because tungsten is brittle and has low fracture toughness, it is impractical to fabricate the entire plasma-facing component out of tungsten. Current divertor designs utilize various methods to bond the tungsten surface layer to the underlying structural part of the component that contains the cooling channels, but for future divertors where the operating temperature will be higher, more robust solutions are needed. Advanced steels are being developed for structural components in future fusion reactors. Unfortunately, tungsten and steel have vastly different coefficients of thermal expansion, so a direct joint would be subjected to intense thermal stresses. A tungsten-steel functionally graded material would ideally both improve the fracture toughness as compared to tungsten alone as well as reduce the thermal stresses between the tungsten and steel parts of the plasma-facing component.

Results

Interface analysis

A cross section sample of the rolled composite material was polished for scanning electron microscope (SEM) analysis. The microstructure in the region of the composite that was initially composed of the thinnest tungsten foils and thickest steel foils was examined with the backscatter detector in the SEM (Figure 1a). Four regions are labeled in Figure 1a. Region 1 was the tungsten foil layer and does not contain iron, but does show some Cr from the steel has diffused into the tungsten. Some grains in the tungsten layer are elongated up to 10 µm in the rolling direction. Region 2 is a tungsten rich layer on the order of 1.5 µm thick that contains voids in the range of 0.3-1.6 µm. Comparing Figure 1a and 1b it can be seen that some tungsten has diffused into Region 3, but the boundary between Region 3 and 4 is sharp, where Region 4 is the closest area to the original steel composition.
Figure 1. a) Backscatter electron image of the cross section of the tungsten steel composite. b)-h) x-ray analysis of elemental distribution in the selected region of the composite.

The maps in Figure 1 are qualitative, so to gain more information, quantitative line scans were performed on selected regions. In the SEM image in Figure 2 the tungsten layers have bright contrast and the steel layers have darker contrast.

A region near the left in Figure 2 was analyzed and the results are presented in Figure 3. The line scan goes from the steel phase, through the intermetallic region, into the pure tungsten region, and through to the steel zone on the opposite side. The signal from the trace alloying elements in the steel, Mo, Mn, and V, is multiplied by 100 in all the following profiles for better comparison. It can be seen that the Mo is enriched near the W layer, but all the other alloying elements in the steel are depleted near the W layer. A region composed of thicker tungsten and steel layers, near the right side in Figure 2, is analyzed in Figure 4. The same behavior observed in the thin tungsten region is seen near the thick tungsten region.
Figure 2. A cross-section of the tungsten-steel composite after fabrication.

Figure 3. Quantitative line scan of a thin tungsten layer in the tungsten-steel composite.

As seen in Figure 1a and in both Figure 3 and Figure 4, two separate microstructure layers can be seen between the base tungsten and the base steel zones (Regions 2 and 3 in Figure 1), but their elemental composition cannot be differentiated. A more detailed scan is shown in Figure 5. It reveals that the thin, porous layer near the tungsten is composed of near equal amounts of tungsten and iron. Based on the atomic percentages, it is likely that this layer is a W₆Fe₇ phase. Moving into the more iron rich intermetallic phase, the tungsten percentage quickly drops to 10-20%. In this detailed view it is more clearly seen that Mo enriches closer to the W layer, while Cr, Mn, and V deplete closer to the W layer.
Figure 4. Quantitative line scan of a thick tungsten layer in the tungsten-steel composite.

Figure 5. Detailed line scan to identify the composition of the intermetallic phases between the tungsten and steel layers.

**Tensile tests**

To tensile test the foils, specialized grips were designed and fabricated. Standard tensile grips for SSJ-3 style samples rely on pressure exerted on the shoulder of the sample to keep it in place during the tensile test. For foil samples, the standard method does not work because the sample shoulder can bend or deform, allowing the sample to slip out of the grips. The grips for foil samples were designed with an extra piece that can be screwed in place to provide pressure to the tabs rather than the shoulder of the samples (Figure 6). Initial tests with the new grips confirmed that the grips are able to hold the sample in place during the tensile test. The grips were fabricated from Inconel 718 with titanium screws to allow future high temperature tensile tests.
Figure 6. Tensile grips for foil samples with inserts to apply pressure to tab sections of samples.

Tensile samples were cut using EDM from all three tungsten thicknesses and the thicker two steel materials. The tensile samples were cut with the tensile direction (a) parallel, (b) perpendicular, and (c) at 45 degrees to the rolling direction. The data for the 25 µm tungsten foil samples has the most spread and may not be truly representative of the material properties because several of the samples fractured in two places (Figure 7). For the 100 and 250 µm tungsten samples, the expected trend is clear. The samples cut parallel to the rolling direction have the highest strength, the samples cut perpendicular to the rolling direction have the least ductility, and the samples cut at 45 degrees show some ductility but lower ultimate strength than the parallel samples (Figure 7). Because no strain gauge could be placed on the foil samples without impacting the test results, the tensile frame motion was recorded to estimate the elongation of the samples. Therefore the x-axis values plotted in Figure 7 and Figure 8 include the sample deformation as well as the machine compliance and are calculated as

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\text{(crosshead displacement)/(original gauge length)} \times 100\%
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Figure 7. Tungsten foils tensile test results at room temperature. Sample labels including “a” were cut with the tensile direction parallel to the rolling direction, “b” perpendicular, and “c” at 45 degrees. Values on the x-axis are calculated from the crosshead displacement.

For the 100 µm thickness steel foils, the samples cut perpendicular to the rolling direction exhibited less ductility than the other direction samples (Figure 8). However, the ultimate strengths of all of the samples are similar. The trend of tensile behavior with comparison to rolling direction is unclear for the 250 µm steel foil samples (Figure 8).
Figure 8. Steel foils tensile test results at room temperature. Sample labels including “a” were cut with the tensile direction parallel to the rolling direction, “b” perpendicular, and “c” at 45 degrees. Values on the x-axis are calculated from the crosshead displacement.

Digital image correlation
Because strain gauges cannot be attached to the foil samples, digital image correlation (DIC) was investigated to potentially give more information about the sample deformation during the tensile test. Two steel samples 250 µm thick, two tungsten samples 250 µm thick, and one tungsten sample 25 µm thick were used in an initial test of the DIC system. When tested with the special grips, too much of the gauge section was blocked by the grips, so no useful DIC information was collected. Additionally, for the tungsten samples, little to no deformation was observed before fracture. The steel samples were thick enough to be tested without the additional inserts in the grips, which allowed the entire gauge section to be viewed. The data from the steel tests is being analyzed. To utilize the DIC method for the thinner foils will require modifying the grips to allow the camera to view more of the gauge section.

Metallography
Previous efforts to mechanically polish the foil samples have been unsuccessful, so as an alternative, electropolishing was performed on tungsten samples 250 and 100 µm thick. The electropolishing used a 2 wt. % solution of KOH. The samples were dipped in the solution for 20 seconds at each of three voltages: 20, 25, 30 V. The electropolishing was more successful at revealing the grains than previous mechanical polishing attempts (Figure 9). The electropolish was not uniform over the whole sample surface, so some areas can be found where the grains are not as clearly revealed. Also, the electropolishing leaves behind an artifact of small raised areas on the tungsten surface. The rolling direction is approximately vertical on the page in Figure 9, the direction along which the grains are elongated.
Figure 9. Tungsten foils imaged in SEM after electropolishing. a) W foil 100 µm thick b) W foil 250 µm thick

After electropolishing, the tungsten foils were imaged with Electron Backscatter Diffraction (EBSD) to reveal the grain orientations. For both samples the EBSD data was taken with a 0.2 µm step size and no clean-up operations were performed on the data. For the tungsten foil 100 µm thick (Figure 10) the texture along the (001) to (111) edge of the inverse pole figure is clearly visible. For the tungsten foil 250 µm thick (Figure 11) the texture is not as distinct as for the 100 µm thick foil but has some concentration of grains with orientations between (001) and (101). For both samples, strain can be observed in the EBSD images by the spectrum of colors present in each grain.
Figure 10. Tungsten foil 100 µm thick after electropolishing. a) grain map b) inverse pole figure showing the texture c) SEM image of analyzed zone d) pole figure of grain orientations.

Figure 11. Tungsten foil 250 µm thick after electropolishing. a) grain map b) inverse pole figure c) SEM image of analyzed zone d) pole figure of grain orientations.