A Study on Laser Processing of Tungsten-Rhenium Alloys for Divertor Development

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Tungsten-rhenium alloys are more attractive due to their excellent characteristics, such as high ductility and improved mechanical properties. They can be expected to become some of the candidate materials for the next-generation of nuclear fusion reactors. We have successfully achieved crack-free laser processing in high-doped tungsten-rhenium alloys using a nanosecond Q-switched Nd:YAG laser system. In addition, the connection between the number of cracks and grain size on different rhenium doping concentrations is also characterized.

Keywords: laser processing, crack-free, surface treatment, tungsten-rhenium alloy, divertor, fusion science

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A heat sink material that satisfies the operating environment of a divertor is one of the keys to the operation of a fusion reactor. Tungsten-copper bimetals are promising candidates for plasma-facing materials in nuclear fusion reactors [1, 2]. Numerous studies have shown that tungsten (W)-based alloys have many advantages as plasma-facing materials for the next generation of nuclear fusion reactors. For example, tungsten-rhenium (W-Re) alloys are more attractive due to their excellent mechanical properties, and it has been reported that the strength and recrystallization temperature of pure W can be enhanced by doping Re [3]. Copper (Cu)-based alloys have been recognized as some of the most suitable heat sink materials for supporting armor, due to their high thermal conductivity. However, due to the ductile-to-brittle transition temperature of W and the huge difference between W and Cu, such as the thermal expansion coefficient and elastic modulus etc., W/Cu junctions are prone to stress-induced cracks, which reduce thermal conductivity and structural reliability. Furthermore, since W and Cu do not dissolve each other, intermetallic compounds cannot be formed; only the anchor effect can improve the bonding strength of W/Cu alloy joints [4]. The most common way to achieve the anchor effect is to form micro or nano structures on the surface of the material. Laser processing is a method widely used in micro-nano surface processing and modification of hard and super-hard materials [5, 6]. Moreover, crack-free surface processing has been a research focus due to its excellent mechanical and thermal properties [7, 8]. However, there are few reports on the surface treatment of nanosecond laser processing of W-based alloys.

In this study, W and W-Re alloys were successfully processed using a nanosecond Nd: YAG laser system as the laser processing light source. The dependence of crack numbers and grain size on the Re doping concentration was characterized. Furthermore, smaller grain sizes after laser processing have been demonstrated by increasing the Re doping concentration and we have successfully achieved crack-free laser processing of W-Re alloys.

A Q-switched nanosecond Nd: YAG laser system (SAGA PRO 220-20 SHG, Thales Laser S.A) was employed as the laser processing light source. The laser wavelength used was 532 nm, and the repetition rate and pulse width were 2 Hz and 8 ns, respectively. The number of pulses for laser processing was 100. After focusing with a 200 mm focusing lens, the laser spot size acting on the sample was approximately D_x: 44 µm; D_y: 58 µm. The laser processing fluence per pulse was 100 J/cm^2. We used W-Re (1%, 5%, 25% A.L.M.T. Corp.) alloys with different doping concentrations and ITER-Grade pure W (A.L.M.T. Corp.) as experimental samples. Moreover, all samples were polished by using abrasive paper (P2400, PRESI). After polishing, the specular reflectance at the wavelength of 532 nm was 15%~20% and the surface roughness (Ra) was less than 0.1 µm.

We have successfully achieved laser processing of pure W and W-Re alloys. Typical Field Emission Scanning Electron Microscope (FE-SEM) images of laser-machined craters in pure W and 25% doped W-Re alloy are shown in Fig. 1. The Laser processing depth is 38 µm for pure tungsten and 45 µm for 25% doped W-Re alloy. A certain height of ablation accumulation can be observed around the laser-processed crater, which is one of the characteris-

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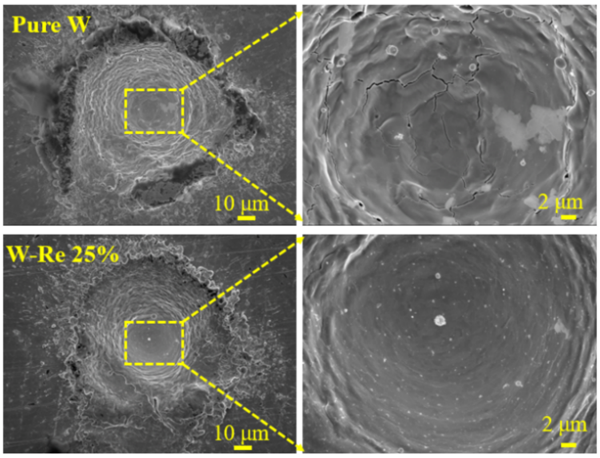

Fig. 1 Typical FE-SEM image of pure W and 25%-doped W-Re alloy.

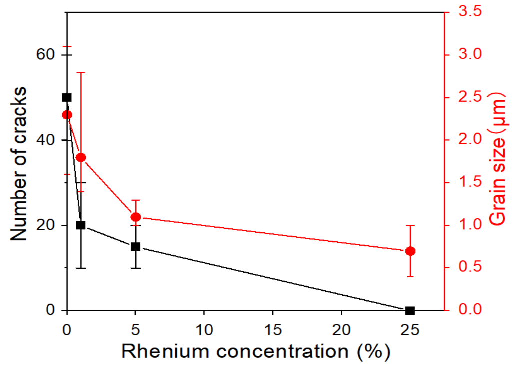

Fig. 2 The number of cracks and grain size after laser irradiation as functions of the Re doping concentration.

tics of nanosecond laser processing and is also conducive to the realization of the anchoring effect. Traces of melting and resolidification can be seen in the high-resolution FE-SEM results, which is the well-known balling phenomenon. This occurrence is mainly due to the non-planar appearance of the bottom after laser processing, as the processing depth increases [9].

Numerous cracks were observed in pure W after laser processing, which can be clearly seen in the high-resolution FE-SEM results (Fig. 1 right). A "crack" can be defined in an area of 10 μm^2, a continuous and uninterrupted break from one point to another, within a length more than1 μm. In contrast, crack-free laser processing of 25% doped W-Re alloy has been successfully achieved, which will significantly improve material properties such as ductility and thermal conductivity. The surface grains after manual polishing cannot be observed with a top-view SEM. However, due to surface tension (by melting), the laser processed areas are smoothed and thus visible even with a top view FE-SEM. The method we use to define the grain size is to take the average of the linear distances from all vertices of a grain to its opposite side, which can be considered as the rough diameter of the grain. Figure 2 shows the dependence of the number of cracks and the grain size within the crater on the Re doping concentration after laser processing. It can be seen that with the increase of the Re doping concentration, the cracks in the material are gradually reduced, and the grain size is also reduced to less than 1 μm. When the material is subjected to sufficient stress and thermal energy, the movement of dislocations can lead to permanent deformation of the grains. However, more grain boundaries can resist the movement of dislocations. Therefore, smaller grains have more grain boundaries and have a larger area-to-volume ratio, which results in a larger ratio of grain boundary dislocations and higher strength [10]. This result suggests the highest concentration of Re doping has better crack suppression ability. In addition, the results of Energy Dispersive X-ray Spectroscopy show that in the 25% doped W-Re alloy, the elemental distribution of W and Re is uniform both in the center of the processed crater and in the accumulation around the crater. This indicates that laser processing has no significant effect on the element distribution uniformity of W-Re alloys.

In summary, we have demonstrated nanosecond 532 nm Nd:YAG laser processing of pure W and W-Re alloys. A relation between grain size and the number of cracks at different Re doping concentrations was found. After laser processing, a smaller grain size was obtained in the 25% doped W-Re alloy. Crack-free laser processing of W-Re alloy has been successfully realized. Crack-free machining of highly doped W-Re alloys has been demonstrated. In future work, we will test the mechanical properties of the crack-free laser-processed W-Re alloy, such as ductility and strength. It can be expected that laser-processed W-Re alloy can become a candidate material for the next generation of nuclear fusion reactors.

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