Fabrication of Cr/Steel Graded-Boundary Material by Laser Beam and Electron Beam

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With the purpose of developing thick metal/metal graded-boundary materials, the fabrication experiment of Cr/Steel graded-boundary materials was carried out using a laser beam and an electron beam. In order to produce a compositionally graded boundary region between the substrate steel and the added Cr metal, a series of surface alloying treatments were performed with both a CO₂ laser beam and an electron beam. A Cr sheet was placed on a commercial low carbon steel, and then a CO₂ laser beam was irradiated on the surface to produce a homogeneous alloyed layer. On this first surface-alloyed layer, another Cr sheet was placed and then the CO₂ laser beam was used again to produce a second surface-alloyed layer. Four sequential repetitions of the laser surface alloying treatment resulted in a compositionally graded region with about a 2 mm thickness from 60%Cr and 40%Fe in the surface region to 0%Cr and 99%Fe in the substrate. Similar procedures were carried out by an electron beam surface alloying treatment to produce Cr/Steel graded-boundary material. Four sequential surface-alloying treatments resulted in a compositionally graded region with a thickness of about 1 mm from 60%Cr and 40%Fe in the surface region to 0%Cr and 99%Fe in the substrate. In both cases, no visible root porosities were found in the graded-boundary region. Since the structures of both the high Cr graded-boundary region and the substrate were both BCC, there was almost no volume change and thus no appreciable cracks were formed in the boundary region between the alloyed layers and the substrate even after rapid cooling.

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1. Introduction

Many structural materials have to frequently support heavy loads and simultaneously endure severe conditions such as high temperature thermal cycles and a corrosive environment. In order to satisfy such conditions, various engineered materials have been developed. Engineered materials are obtained from multi-materials system and they have the various beneficial properties of their individual components. Such materials can be divided into several groups depending upon their properties or services. For example, composite materials with high strength along certain directions, surface-cladded materials which have corrosion resistance or wear resistance on the surface, graded-boundary materials (GBM) having heat resistance and stress relaxation in the boundary region, and various alloys, *etc.* By considering the concentration profiles across boundaries between alloy components for such materials, it is possible to group them into three categories as shown in Figure 1, where the boundary between two components shows an abrupt change, a gradual change and no change. Most engineered materials belong to either the sharp boundary material or no boundary material. Former examples are found in the surface-cladded materials and composite materials, while latter cases are found in most alloys. The graded boundary materials are found in functionally gradient ceramic/metal materials,¹⁾ which were developed in order to relax the high stress concentration in the sharp boundary region of ceramic/metal heat-resistant material systems.

When multi-component materials are heated to a high temperature, thermal and residual stresses are developed in the boundary region between their components due to the different thermal and mechanical properties even under uniform

heating and cooling conditions. If there is a sharp boundary between two components, the high concentration of internal stress is unavoidable in the narrow region along the boundary during the high temperature thermal cycles, and thus some failures such as cracks or distortion very often take place in that region. However, if there is a continuous change in the composition across the boundary, it is possible to avoid the concentration of stress in that region. Such materials are very desirable in the energy industry and in the aeronautical and astronomical industries, where some parts of certain equipment need to endure repeated severe thermal conditions. Therefore, the ceramic/metal functionally gradient materials (FGM) were developed in order to reduce the concentrated thermal stress in the boundary regions.¹⁾ They are usually produced by a powder metallurgical method at high temperature. They are usually used in cases where an external load is not large and a forced cooling is not applied. In such FGMs, the ceramic part provides the heat resistance while the metal part provides the mechanical strength. However, if either the ex-

Fig. 1 Three kinds of composition changes in multimaterial system. (a) sharp boundary, (b) graded boundary, (c) no boundary.

ternal load is large or forced cooling is necessary in order to reduce the temperature of the material, the thermal conductivity and mechanical strength of such FGMs are important. The structures of the FGMs are then preferred to be metal/metal systems, and they can be produced by the powder metallurgical method. When both component metals have similar melting points, a conventional sintering process can be used. If component metals have quite different melting points, they can be produced by a liquid sintering process in which the stepwise stacking of different-sized metal powders is formed, and then sintering of this stacked graded compact and final infiltration with other molten metals are carried out in one step. In this method, the liquid phase heat treatment, through infiltration or liquid sintering, is usually carried out in a reducing atmosphere in order to assure the least oxidation. In this case, although the control of the composition is convenient, it needs to be heated at a high temperature for a long period of time. Such treatment may then change some properties of the materials due to oxidation or infiltration of the reducing species, and thus it is quite possible that some defects are inevitably introduced into the materials.

The formation of an alloy concentration gradient in the boundary region will result in a graded boundary material. During the fabrication of these kinds of graded boundary materials, a heat source with a high energy density is necessary in order to concentrate the large thermal energy only in the surface region and to obtain a series of homogeneous alloyed layers. A high power laser beam is a very efficient tool for a such purpose and the laser surface-alloying treatment can be used to make such graded boundary materials.²⁾ Also, the laser beam is a high energy density beam and easy to control for materials processing. It can be focused to a small spot size by an optical lens. Thus it is possible to deliver a concentrated energy on a local area and cause melting without heating the rest of the substrate area. Therefore, the laser beam is a very useful heat source compared with conventional methods for these kinds of experiments. In this method, the compositions in the boundary region can be controlled by the proper selection of laser power, focusing conditions and scanning speed. Thus, the desired composition and thickness of the graded region can be obtained very quickly in comparison with the powder metallurgical method. For a new method to produce metal/metal graded boundary materials, the application of repeated laser surface-alloying treatments is a

quite promising technique and Inconel 690/Steel GBM^{3,4)} and Ni/Steel GBM⁵⁾ have already been fabricated by this method. In this case some defects such as root porosities and cracks were formed due to the characteristic properties of laser processing and changes in the structures between the surface region and substrate.

As another high energy density beam, the electron beam has advantages when fabricating metal/metal GBMs. While the laser beam is composed of photons, the electron beam is composed of high energy charged electrons. The electron beam can deeply penetrate into metals, and its absorbance on a metal is higher than that of the laser beam. Its spot size can be controlled to produce an increased power density using magnetic lens, and it is also possible to manufacture wide alloyed regions. Also, the absorbance of the electron beam is less susceptible to the temperatures or the structures of the metals than that of the laser beam. For this reason, the electron beam is widely used for certain material processing versus the laser beam, although the electron beam renders some difficulties in the processing of nonconductive materials. In addition, the electron beam processing is carried out under vacuum conditions, so it prevents the formation of root porosities and the oxidation of the alloyed regions. Therefore, both a laser beam and an electron beam were used to fabricate the Ni/Steel GBM⁶⁾ and their results were then compared.

Since both Inconel 690/Steel GBM and Ni/Steel GBM have austenite/ferrite structures, cracks were found in the boundary regions due to differences in the structures and volume changes during the phase transformation between austenite and ferrite. Cr has a BCC structure while the Cr-Fe alloy system⁷⁾ has a ferritic structure regardless of the Cr concentration at room temperature. Therefore, Cr was chosen to fabricate the Cr/Steel GBMs using a laser beam and an electron beam in this study in order to check the differences between the ferrite/ferrite GBM structure and the austenite/ferrite GBM structure.

2. Experimental Procedures

In order to make a Cr/Steel GBM, a pure Cr sheet was used as the added metal and commercial low carbon steel (0.18 mass%C, 0.22 mass%Si, 1.04 mass%Mn) was used as the substrate. The thickness of the Cr sheet was 0.5 mm, while the size of the substrate steel was 80 mm×70 mm with a thick-

Fig. 2 Schematic diagram of laser irradiation on Cr plate in order to produce graded boundary Cr/Steel material.

ness of 15.6 mm.

After a Cr sheet was tightly gripped on a substrate steel plate by a vise-type jig on both sides, a 4 kW CO₂ laser beam irradiated the specimen. The scanning speed was 15 mm/s and Ar gas was used as the shielding gas. In order to make a deep and wide surface-alloyed layer, the aspect ratio (melted depth/melted width) was set to about 1 and the laser beam overlapped by about 50%, the previously treated area on the surface during each scanning pass. After the first Cr surface-alloying treatment, another Cr sheet was placed on the previously laser irradiated surface in order to produce a second alloyed layer, and then the same procedures were consecutively repeated 4 times. Figure 2 shows the schematic diagrams of the laser irradiation for the fabrication of a Cr/Steel GBM. The same materials and procedures were used to fabricate the Cr/Steel GBM by an electron beam. In this case, the accelerating voltage was 50 kV, the beam current was 30 mA, the scanning speed was 8.3 mm/s and the vacuum condition was 1.3×10^{-3} Pa.

In order to determine the microstructure, the phase and composition of each alloyed layer, optical microscopy, X-ray diffraction method (XRD) and energy dispersive spectroscopy (EDS) were used. Also, the microhardness of the alloyed layers were measured using a 200 g load.

3. Results and Discussion

Figure 3 shows the cross-sections of the Cr/steel GBMs produced by the laser beam and the electron beam. The figures show 4 sheets of unmelted Cr on the right side in the laser beam-treated specimen and on the left side of the electron beam-treated specimen. No appreciable porosities or large cracks were observed.

Figure 4 shows the graded concentration profiles of Cr and Fe from the surface into the substrate for the laser beam treated specimen and the electron beam-treated specimen. As shown in Fig. 4(a), the concentration of Cr changed from about 60 mass% in the 4th layer to 0 mass% in the substrate and that of Fe changed from about 40 to 99 mass% in the graded region of the laser-beam treated specimen. Meanwhile, concentration gradients were obtained from about 60 to 0 mass% for Cr and about 40 to 99 mass% for Fe in the graded region of the electron beam treated specimen as shown in Fig. 4(b). As shown in this figure, the electron beam treatment resulted in a homogeneous composition in the 4th layer and a fair concentration gradient in the graded region as compared to the laser beam treatment. Since the laser beam cannot penetrate deep into the metal and the processing is performed very quickly, the absorbed laser energy is accumulated only in the surface region and the thermal energy cannot as quickly transferred far into substrate. Thus, the formation of the deep and fair graded region did not occur. Meanwhile, the absorbance of the electron beam on the metal is large, and it can penetrate deep into a metal substrate in comparison to the laser beam. Therefore, the electron beam resulted in a more homogeneous alloy composition and deeper 4th layer. According to EDS point analysis in each alloyed layer, the alloying elements were fairly well mixed in spite of the very short melting period for both cases. If a thicker graded re-

Fig. 3 Cross-section of graded boundary Cr/Steel material. (a) laser beam irradiation, (b) electron beam irradiation.

Fig. 4 Concentration profiles of Cr and Fe in graded boundary Cr/Steel material. (a) laser beam irradiation, (b) electron beam irradiation.

gion is required, it is possible by increasing of the number of stacked sheets and surface-alloying treatments. If a more linear concentration gradient is required, it is possible by de-

Fig. 5 XRD analysis of graded boundary region. (a) Cr, (b) laser beam irradiation, (c) electron beam irradiation.

creasing the thickness of the added metals.

Figure 5(a) shows the XRD peaks of Cr, and Figs. 5(b) and (c) show the XRD results of the alloyed layers produced by the laser beam and the electron beam, respectively. The Fe–Cr phase diagram⁷⁾ shows that the Fe–Cr alloy has a BCC structure at room temperature regardless of the concentrations of Cr and Fe. As expected, the XRD results showed that all the alloyed layers consisted of a ferritic structure for both the laser beam-treated specimen and the electron beam-treated specimen. Since Cr and Fe are BCC at room temperature, it is quite reasonable that all the alloyed layers showed α -peaks regardless of the alloy concentrations for both cases. Although the Inconel 690/steel⁴⁾ and Ni/steel⁵⁾ GBMs resulted in a volume change and oblique cracks did appear near the alloyed region, no appreciable cracks were formed in the Cr/steel alloyed region. Since the Ni alloy was FCC and the Fe substrate

Fig. 6 Microhardness of graded boundary Cr/Steel material. (a) laser beam irradiation, (b) electron beam irradiation.

was BCC, the volume change due to a martensitic transformation during the rapid cooling caused the formation of oblique cracks. However, the absence of any structural change between the alloyed layers in the Cr/Steel material may result in less distortion and less stress concentration. Thus, it is believed that there was no appreciable volume change between the alloyed layers for both cases, since all the structures were single phase from the surface to the interior of the substrate at room temperature. However, since the cooling rates were very rapid for both cases, minute solidification shrinkage cracks were found in the alloyed region, especially for the laser beam treated specimen.

Figure 6 show the microhardness of the graded regions for both the laser beam-treated specimen and the electron beam-treated specimen. Each point was the average of 4 measured points for the laser beam-treated specimen and the average of 3 measured points for the electron beam-treated specimen. Each point was marked by a 5% error bar. As shown in the figures, the hardness gradually increased as the Cr concentration increased for both cases. The hardness of the heat-affected zone (HAZ) was higher than that of the substrate region in the laser beam-treated specimen as shown in Fig. 6(a), while it did not increase in the electron beam-treated specimen. Since the heat-affected region was transformed into martensite, the hardness should be much higher than the value in the figure. According to a reference book, the microhardness is about 450Hv if 0.18 mass% C steel is transformed into the regular martensitic phase. However, the repeated laser beam treatments supplied much thermal energy to the HAZ and caused

a tempering effect in this martensitic phase, and thus the hardness was reduced to about 230HV for the laser beam treated specimen. For the electron beam-treated specimen, the heat input was much larger than the laser beam treated specimen. Although the powers were 267 Ws/cm and 181 Ws/cm for the laser beam and the electron beam, respectively, their absorbances on the surface are quite different. The laser beam cannot pass through metal and most of it is reflected on the metal surface. The absorbance of the laser beam on a metal surface depends upon the conductivity of the metal, and thus this means that the absorbance depends on the temperature of the metal. Usually, the absorbance of a CO₂ laser beam on a metal surface is less than 10% at room temperature. When the metal is melted, the structure takes on an amorphous phase and the absorbance increases to about 40%.⁸⁾ For the electron beam, the absorbance is more than 80% on a metal surface since the metal is a good electron conductor. Therefore, even though the laser beam energy was greater than the electron beam energy, the energy absorbed in the metal was much greater in the electron beam-treated specimen compared with the laser beam-treated specimen. This fact can be represented by a comparison of the 4th alloyed layers in Figs. 4(a) and (b). Therefore, it is believed that the martensite, which was formed in the HAZ by the first electron beam treatment, was transformed into ferrite and thus the microhardness of the HAZ returned to almost the value of the substrate.

4. Conclusions

The Cr/steel graded boundary materials were fabricated using a laser beam and an electron beam. Four sequential repetitions of the laser beam treatment resulted in a graded boundary region with a thickness of about 2 mm from 60% massCr and 40 mass%Fe in the surface region to 0 mass%Cr and 99 mass%Fe in the substrate. Four sequential repetitions of the electron beam treatment resulted in about a 1 mm graded region with similar alloy concentration profiles. Since Cr and Fe have a BCC structure, the entire graded region resulted in a ferritic phase and thus defects due to phase changes such as oblique cracks were not formed in both cases. If the thickness of each alloyed layer is reduced and the number of alloyed layers is increased, the concentration profiles of the alloying elements will become more linear in the graded region and the thickness of the graded region will become greater in the GBM.

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