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# Friction Stir Welding of Monel 400: Microstructure, Substructure, and Mechanical Properties

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## 1. Introduction

Conventional fusion welding processes for joining the Monel alloys cause the formation of dendritic structures, macro and micro segregations, porosities, shrinkages, residual stresses, large distortions, and etc., which reduce the final mechanical properties. Friction stir welding (FSW), as a solid state process, has been proven to be a promising joining method which may eliminate the issues of fusion welding. Until now, many researches have shown that FSW can be used to weld different metals and alloys. However, an investigation into the FSW of Monel alloys is lacking. For the first step of the Monel FSW, it is very necessary to have an understanding of the microstructural evolution during the process. It is expected that the outcomes of the current study would open a new window for joining Monel alloys.

## 2. Experimental Procedure

Monel 400 plates (100 mm × 50 mm × 2 mm) were friction stir welded at a tool rotational and traverse speeds of 400 rpm / 100 mm $min^{-1}$. A WC-Co tool consisted of a ø12 mm shoulder and a pin of ø3×1.75 mm was employed. For microstructure study, the samples were cut from the transverse cross section of the joints perpendicular to the welding line. The samples were then prepared and characterized using orientation imaging microscopy (OIM) with a step size of 100 nm at different microstructural zones. For studying the mechanical properties, microhardness test was conducted.

## 3. Results and discussion

The OIM data including inverse pole figure (IPF) maps and grain boundaries characterization distribution (GBCD) plots for base metal (BM) and stir zone of the joint (SZ) are illustrated in Figure 1. The TEM images of the BM and SZ are shown in Figure 2. In addition the Taylor factor maps of the BM and SZ are depicted in Figure 3. The hardness results showed that the hardness values for the BM and SZ were 162-175 Hv, and 207-218 Hv, respectively.

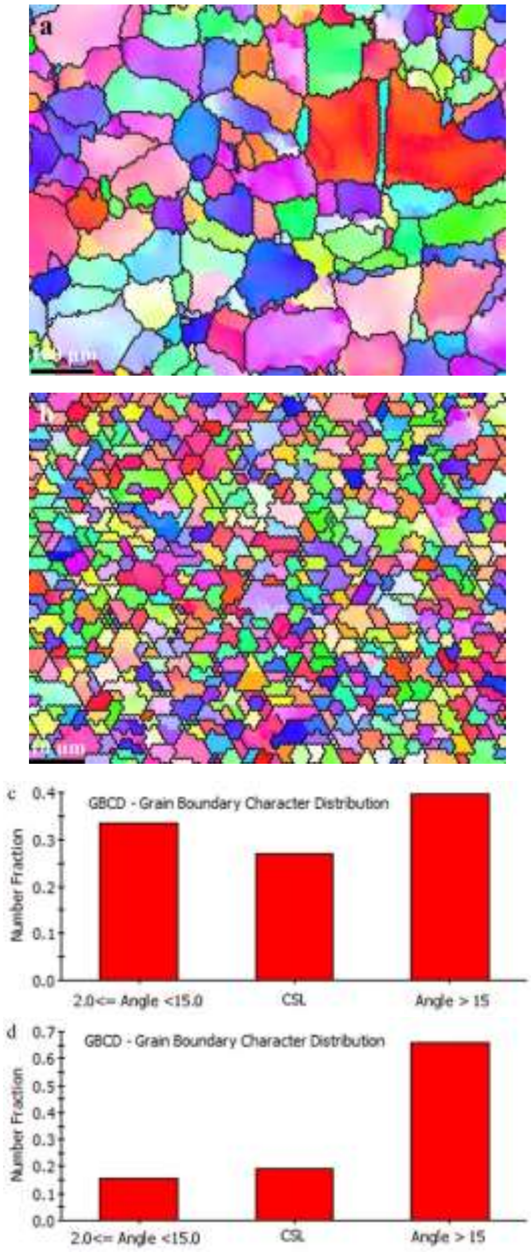


Figure 1. IPF and GBCD for the (a and c) BM, and (b and d) SZ

The different strengthening mechanisms can be responsible for the higher hardness of the SZ, which is strongly influenced by microstructural evolution during FSW. It is well documented that the $\sigma_y$ can be formulated by the following equation:

$$\sigma_y = \Delta\sigma_{gb} + M\left[\Delta\tau_0 + \Delta\tau_{ss} + \left(\Delta\tau_D^2 + \Delta\tau_{ppt}^2\right)^{1/2}\right] \quad (1)$$

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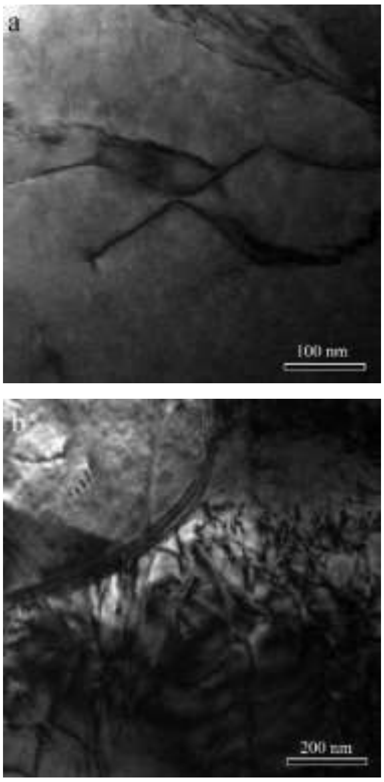


Figure 2. TEM Images for the (a) BM, and (b) SZ

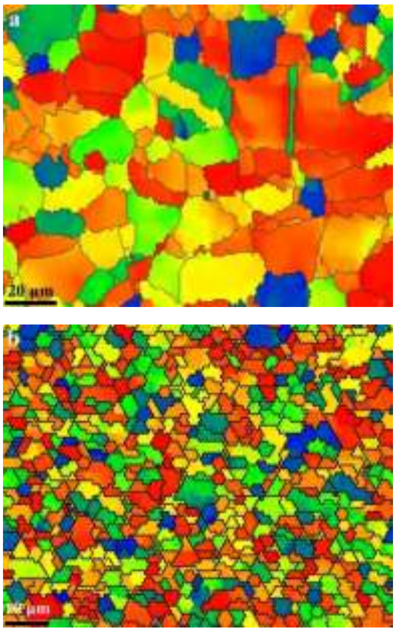


Figure 3. Taylor factor maps for the (a) BM, and (b) SZ

From Equation 1, $\sigma_y$ depends on the values of different strengthening items such as the grain boundary strengthening ($\Delta\sigma_{gb}$), the solution strengthening ($\Delta\tau_{ss}$), the dislocation strengthening ($\Delta\tau_D$), the precipitation strengthening ($\Delta\tau_{ppt}$), and the strengthening due to the texture (M) which is usually defined by Taylor factor. In addition, in Equation 1, $\Delta\tau_0$ stands for the pure metal strength. As Monel 400 does not contain precipitates, the strengthening mechanisms for it will as follows: $\Delta\sigma_{gb}$, $\Delta\tau_D$, and effect of M, which are going to be discussed.

In this study, the SZ had average grain size of 3.8 µm, which was finer than that of the BM, i.e., 18.4 µm. In addition, the HAGBs in the SZ were 85% of the total grain boundaries, where in the case of BM it has been reduced to 67%. In addition to the finer grain sizes in the SZ compared to the BM, the amount of HAGBs has been increased. Thus, the total amount of the HAGBs in SZ was larger than that of the BM. These HAGBs act as the obstacles against the dislocation movement, and hence cause higher $\Delta\sigma_{gb}$ or $\sigma_y$ (higher hardness). Moreover, TEM images (see Figure 2) showed higher dislocation density in the case of SZ compared to that of the BM, which results in higher $\Delta\sigma_{gb}$ or $\sigma_y$ (higher hardness).

The effect of texture on the $\sigma_y$ occurs as the M parameter in Equation 1, which is usually considered as the Taylor factor. The higher Taylor factor means higher M value, and hence causes higher $\sigma_y$ or higher hardness. From Taylor factor maps, (see Figures 3 (a) and (b)) it was found that the average Taylor factor for the SZ was higher than that of the BM (3.13 for SZ and 2.96 for BM). Thus, it seems that the texture had a considerable effect on the strength value. In summary, the main strengthening mechanisms causing higher $\sigma_y$ or lower hardness values in SZ compared to the BM were the grain boundary, dislocation mechanisms, and texture effect.

## 4. Conclusion

In this study, Monel 400 alloy was welded by FSW, and the resulted microstructure and mechanical properties were compared with those of the base material. FSW causes formation of the finer grains, larger amounts of high angle grain boundaries, higher dislocation densities, and larger Taylor factors. Therefore, the main strengthening mechanisms causing higher hardness values in SZ compared to the BM were the grain boundary, dislocation mechanisms, and texture effect.