# Effect of surface roughness on the diffusion bonding of Incoloy MA 956

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Oxide dispersion strengthened (ODS) alloys are promising structural materials for high temperature applications. There are two kinds of ODS superalloy: nickel based and iron based. Commercial nickel-based ODS superalloy include Inconel MA 753, MA 755 and MA 6000. Iron-based ODS superalloy include Incoloy MA 956 and MA 957. Compared with nickel-based alloys, iron based ODS alloys have higher melting points and improved corrosion resistance properties. Incoloy MA 956 was first developed as an aerospace superalloy, and now used in a range of industrial applications. It combines excellent strength and fabricability with outstanding resistance to prolonged exposure up to 1300 °C. Its exceptional properties result from the MA (mechanical alloying) process by which it is made. Very fine yttrium oxide particles are incorporated into a highly corrosion resistant ferritic FeCrAl matrix. The high Al content of the matrix leads to the formation of the tightly adherent, slow growing alumina scale during exposure at high temperatures, which provides excellent resistance to aggressive gaseous environments. The oxide particles are much less susceptible to coarsening than precipitates and remain as discrete particles at temperatures near the melting point of the matrix [1]. Development of a suitable joining technology is essential for ODS alloy because components with complicated cooling design, such as blades and vanes as well as combustion chambers, cannot be made by other methods. Solid-state diffusion bonding does not create melting zone at the joint interface. Agglomeration or coarsening of oxide particles may be avoided and joints having mechanical properties that match base material could be obtained [2]. Although some work was carried out on the diffusion bonding of Incoloy MA 956 [3], the investigation was only on the effect of bonding pressure. The success of bond formation and joint quality depends largely upon the intimate contact between the mating surfaces. It is commonly believed that smoother the surface, better the joint quality. However, there is some evidence that some roughness in surface helps the joint formation [4, 5]. Therefore, with this in mind a study was undertaken to evaluate the effect of surface roughness on the diffusion bond quality of MA 956 alloy.

The chemical composition of alloy MA 956 is given as follows (in wt%): 0.05 C, 0.3 Si, 20.5 Cr, 0.5 Ni, 0.28 Co, 0.45 Ti, 5.5 Al, 0.07 N, 0.5 $Y_2O_3$, bal. Fe. The material was in the form of hot extruded rods that had been heat treated at 1603 K for 1 hr. The heat treatment produces very coarse grains with a high grain aspect ratio. The high grain aspect ratio imparts an additional strengthening effect upon the material and largely improves the creep rupture strength [6]. Macrostructure of MA 956 was observed by immersing the material in the solution of 30 ml $H_2SO_4$ plus 10 ml HCl and 40 ml $H_2O$ for 10 min. The microstructure samples were electrolytically etched using a solution of 10 vol% HCl and 90 vol% ethanol. The three basic grades of preparation commonly used in diffusion bonding are polishing, grinding, and lathing. They give progressively rougher surfaces and each will bond at a different rate. To investigate the effect of roughness on bonding MA 956, two surface machining methods were used. One was lathing only, which gave the average surface roughness of 0.65 $\mu$m. The other was lathing plus grinding and the average roughness was 0.062 $\mu$m. After machining, these materials were cleaned in an ultrasonic bath with acetone for 10 min, and then dried in hot air. Diffusion bonding was carried out immediately after the cleaning to avoid the recurrence of thick surface oxides. Bonding pressure and time were set at 72 MPa and 60 min separately. Bonding temperature was 1100 and 1125 °C.

In order to retain ODS material properties in the joining zone, no significant change in the coarse grain structure with the high grain aspect ratio is allowed. The macrostructure of the joints is shown in Fig. 1. For all the bonding conditions investigated, only slight deformation of about 0.2% could be observed. After bonding, the macrostructure of MA 956 was almost unchanged. The grain size and direction also remained the same in the joint region. The interface remained a uniform straight line without any distortion. For samples with finer surface roughness, no unbonded area was observed in the joints. Its microstructure is shown in Fig. 2. No continuous oxide films were found at the interface. The limited residual oxides were spheroidized and of small size. Clean metals were thus exposed and metallic bonds came into being.

As shown in Fig. 1(b), large unbonded area was observed in the joints bonded with rougher surface. There are four typical microstructures in the interface of one joint (Fig. 3). This indicates that bonding process does not advance evenly throughout the faying surface. These four types of microstructure are with the following features:

1. One in which large voids exist (Fig. 3(a)). The initial void height is quite large (about 10–12 $\mu$m) expected from the surface roughness profile.

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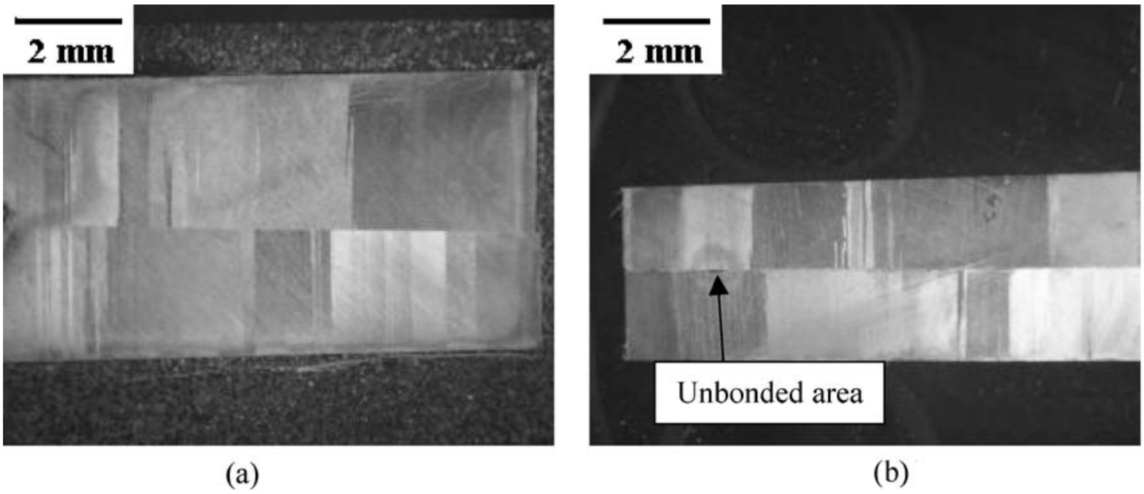


*Figure 1* Macrostructure of the joints: (a) Finer surface, 1100 °C, 72 MPa, 60 min and (b) Rougher surface, 1125 °C, 72 MPa, 60 min.

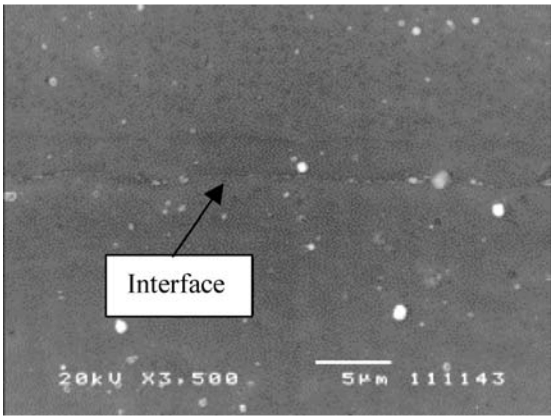


*Figure 2* Microstructure of Fig. 1(a).

Power-creep and diffusion mechanisms were not enough to entirely close the voids. These resultant voids were rounded, indicating that diffusion had smoothed out most irregularities. In the area between the voids, no oxides were observed and bonding interface is indistinguishable. This may prove that a certain amount of asperity is necessary to disrupt surface oxide film and produce clean metal.

2. One in which porous thick films and large particles were included, as shown in Fig. 3(b). The EDS result of the bright film showed it rich in Al and O and found to be oxide film. In bonding of MA 956, the heating took place in vacuum environment, and the oxidation on the surfaces was greatly reduced. However, there may still be some air trapped in the cell

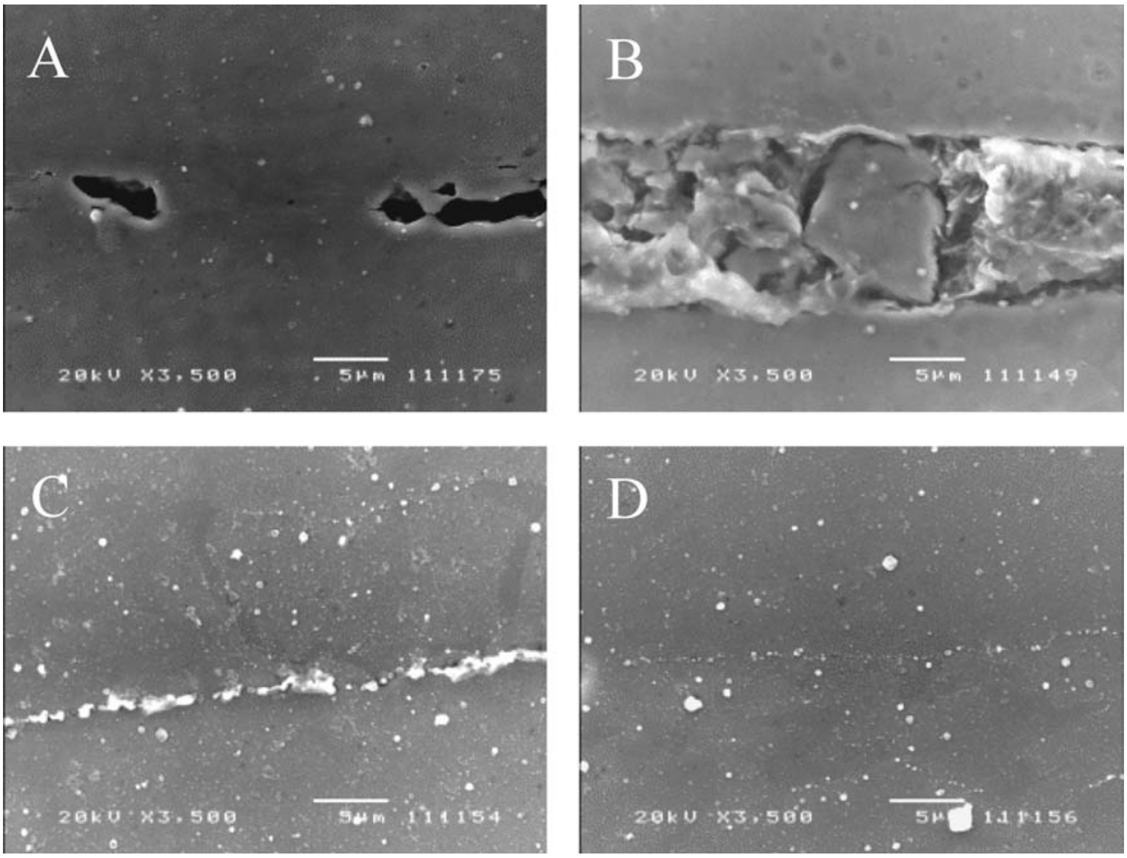


*Figure 3* Diversified microstructure of Fig. 1(b).

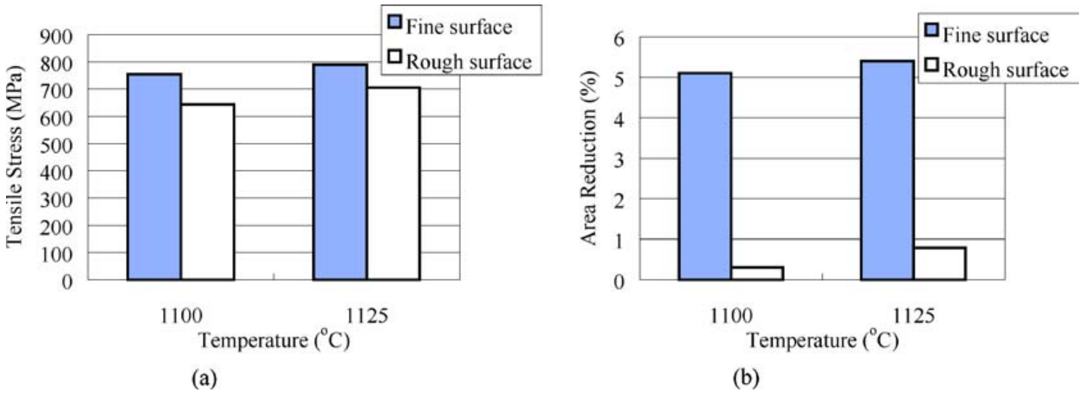


*Figure 4* Mechanical properties of joints: (a) Tensile strength and (b) Area reduction.

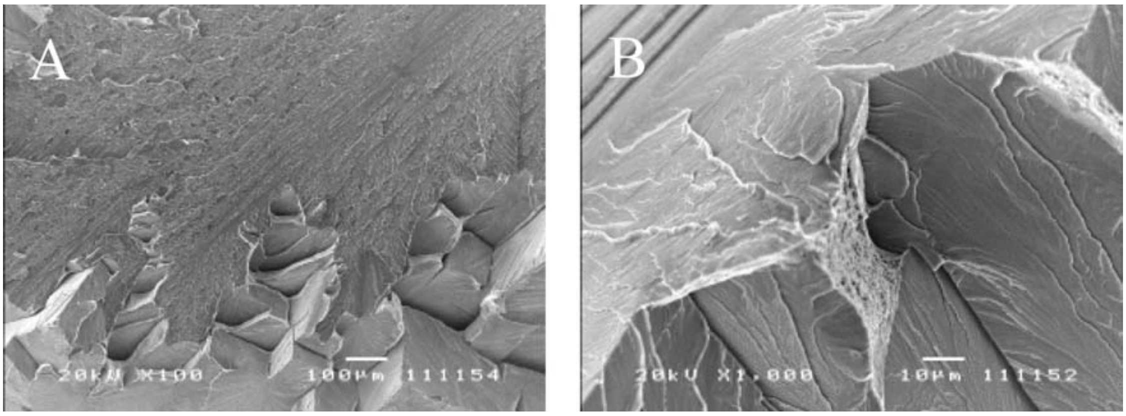


*Figure 5* Fractograph of joint bonded with finer surface at 1100 °C.

formed by the asperities of the specimens. Rougher the surface is, more air is trapped and the thicker oxide film is formed during bonding. EDS result of the large particle is nearly the same with that of base material. These particles may be the crushed asperities due to the limited compressive ductility.

3. One in which coarse oxides are present at the interface, as shown in Fig. 3(c). The metal grains may have partially crossed the interfaces. These regions could be thought of as poor bonds.

4. One in which almost full bond is obtained (Fig. 3(d)). Almost no oxides are found. The interface nearly disappeared in this region. Bond is with a microstructure hardly distinguishable from that of the adjacent parent metal. These regions were soundly bonded and with parent material properties.

Fig. 4 shows the influence of roughness on joints mechanical properties. It can be seen that joints bonded with rough surface are with almost no ductility. This is expected from the macrostructure, because even under such a low magnification, unbonded area could still be clearly seen. Although certain roughness is helpful to break the oxide film and full bond is also obtained at some regions, compared with the whole bonding area, it is just a very small part.

The fractograph of the joints bonded with finer surface is shown in Fig. 5. The fracture began to occur in certain crystallographic planes. Large area of transgranular shear fracture was observed in Fig. 5(a). There were also small regions of ductile failure at the junction of cleavage facets (Fig. 5(b)), just as in the as-received material. It may be because without the residual oxide,

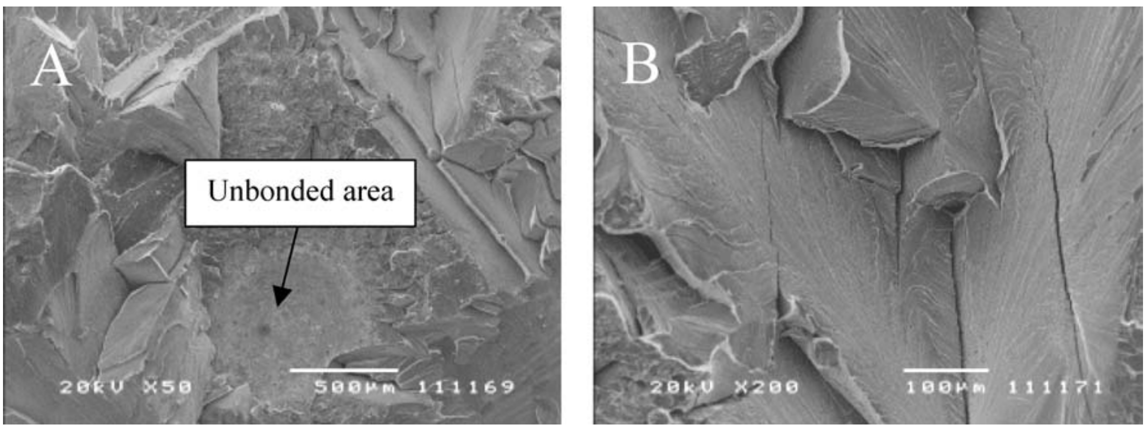


*Figure 6* Fractograph of joint bonded with rougher surface at 1100 °C.

grains can grow across the interface and the interface is no longer a weak link.

In the fractograph of the joint bonded with rougher surface, large area with striated appearance was observed (Fig. 6). In that area, the remnants of machining marks could still be seen. It was the unbonded area, where some inclusions rich in O were found. In some area, the joint failed in transgranular brittle mode. Small regions of ductile failure were found at the junction of cleavage facets. Both the metallographic examination and the mechanical property evaluation show that the surface preparation is critical for bonding MA 956. For 60 min duration a 0.06 um finish will be needed.

In summary, the surface preparation is critical for the successful bonding of MA 956. A certain amount of roughness is helpful to disrupt surface oxide film and produce indistinguishable bonding interface. However, a very rough surface would leave large voids that may be difficult to eliminate and thus degrade the joint quality.

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