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# Effects of Silicon Nanoparticles on the Transient Liquid Phase Bonding of 304 Stainless Steel

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Transient liquid phase (TLP) bonding of 304 stainless steel with nickel based filler metal, BNi-9, was performed to study the influence of silicon nanoparticles (NPs) on the mechanical and structural properties of the bonding area. It was found that silicon NPs act as a melting point depressant in the brazing process; the formation of silicon TLP induces the dissolution of elements of the metal filler and promotes a uniform distribution in the bonding area. Silicon NPs induce the development of smaller eutectic structures in the melting zone; it has been related to microhardness measurements, which are lower when the silicon NPs are used in the brazing process.

**KEY WORDS: Brazing; Nanoparticles; Silicon; Stainless steel**

## 1. Introduction

Stainless steels are essential for medical, chemical, food processing, and biotechnological applications because of their excellent corrosion resistance and hardness at room temperature. For most applications, stainless steels require bonding of components when reparation of damaged components is needed or fabrication of special geometries is required. Under certain conditions, stainless steel components are damaged because their mechanical properties are reduced or exist zones susceptible to corrosive attacks[1]. These adverse effects usually occur in bonding areas[1,2].

There are three processes for repairing or joining metal-pieces; namely, fusion welding, diffusion bonding and brazing[2,3]. Brazing is an alternative technique for joining components made from special alloys[4−6]. However, brazed joints often contain hard and brittle intermetallic phases, which decrease the mechanical and corrosion properties of the bonding areas[3,7−9]. An alternative to prevent the formation of intermetallics is the use of transient liquid phase (TLP) bonding (also named as diffusion brazing)[3,7,10−12], which consists of a complete isothermal solidification of the TLP that exists temporarily during the brazing process. In the TLP bonding, the brazing metal filler should contain melting point depressants (MPD) elements such as boron, silicon and phosphorous[3,10,13,14]. MPD elements should exhibit high solubility in the base metal, which will reduce the growth of intermetallics. Currently, for development of the TLP bonding process, some alternatives have been used such as the use of nanoparticles as effective agents for retarding or avoiding the growth of intermetallic compounds[15−17].

The aim of this work was to evaluate the effect of silicon nanoparticles (NPs) used as an additive in the TLP bonding of 304 stainless steel. It was found that the formation of TLP on cracks of 304 stainless steel promoted the following: 1) forming a liquid capable of increasing the wettability between microcracks and internal micropores, 2) improving capillary forces between the filler metals and the TLP and 3) modifying the development of deleterious intermetallic phases.

## 2. Experimental

### *2.1. Synthesis of silicon NPs and characterization of the brazing filler metal*

Silicon nanoparticles were synthesized from silicon powders (35 μm, Aldrich) using high energy ball milling at 350 r/min for 8 h. The structure and morphology of the NPs were characterized by high resolution transmission electron microscopy (HR-TEM) in an FEI Titan microscope. The brazing filler metal selected for

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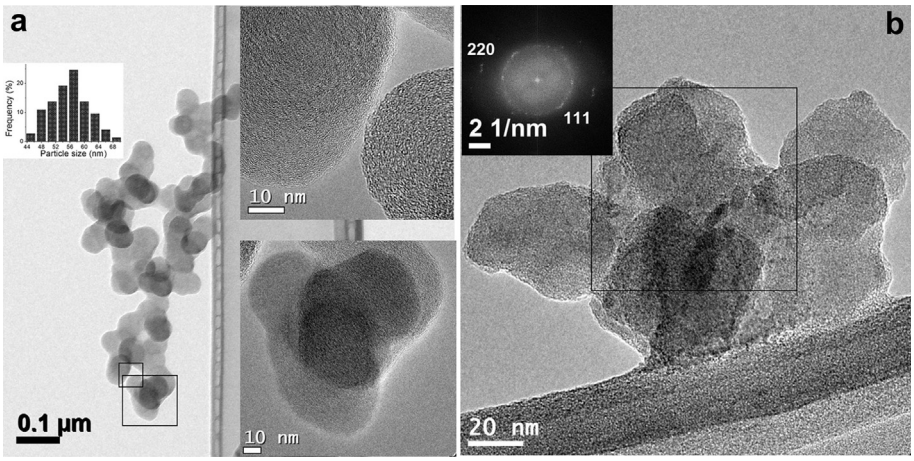


**Fig. 1** TEM images of silicon NPs obtained by high energy ball milling: (a) amorphous round shaped NPs, (b) quasi-crystalline NPs. Insets in (a) show HR-TEM images of different areas of the micrograph (right) and a histogram of particle size distribution determined by TEM (left). Inset in (b) shows the SAED pattern of the quasi-crystalline NPs.

this work was BNi-9; it was characterized by differential thermal analysis (DTA) using a Pyris Diamond Tg/DTA equipment, X-ray diffraction (XRD) in a Phillips X'Pert 3040 diffractometer and scanning electron microscopy (SEM) in a Phillips XL30 microscope.

### *2.2. Generation of cracks in stainless steel and their impregnation with silicon NPs*

In order to study the brazing process and the effects of silicon NPs, cracks were generated in 304 stainless steel rods of Φ10 mm × 60 mm by bending them with a mechanical testing machine; these fractures were inspected by SEM. For the impregnation of the cracks with NPs, a mixture of 0.5 g of silicon NPs in 200 ml of ethanol was sonicated for 1 h. Subsequently, the steel with cracks was placed in the dispersed silicon NPs and sonicated for 30 min. This sonicating time promotes the diffusion of silicon NPs inside the microcracks.

### *2.3. Brazing of cracked 304 stainless steel*

In order to evaluate the effect of silicon NPs in the brazing process of the stainless steel, the BNi-9 filler metal (Nicrobraz, Wall Colmonoy) was used in the cracked rods with and without silicon NPs impregnation. The brazing process was conducted in a sealed tube furnace under an Ar gas flow of 0.1 L/min at the brazing temperature of 1200 °C for 10, 20, 30 and 60 min; the heating and cooling rates were fixed at 10 °C/min. Additionally, in order to determine the reactivity of the silicon NPs on the cracked stainless steel, the impregnated cracks were subjected to the same conditions described above, at 1000 and 1200 °C. The resulting samples were characterized by SEM and optical microscopy. The microhardness measurements were performed in a Vickers/Knoop hardness tester by Wilson Instruments Tukon 2100B using a load of 500 g with a pyramidal indenter. 15 microhardness measurements were realized in each zone, namely melting zone, isothermal zone and base metal.

## 3. Results and Discussion

### *3.1. Characterization of silicon NP and BNi-9 filler metal*

The morphology and structure of the silicon NP were studied by HR-TEM. Fig. 1 shows TEM micrographs of the silicon NP synthesized by ball milling. It was found that the sample consists of two kinds of nanoparticles. Fig. 1(a) displays a bright field image of one kind of NPs that were found in the sample. The round shaped NPs with sizes among 45−70 nm can be

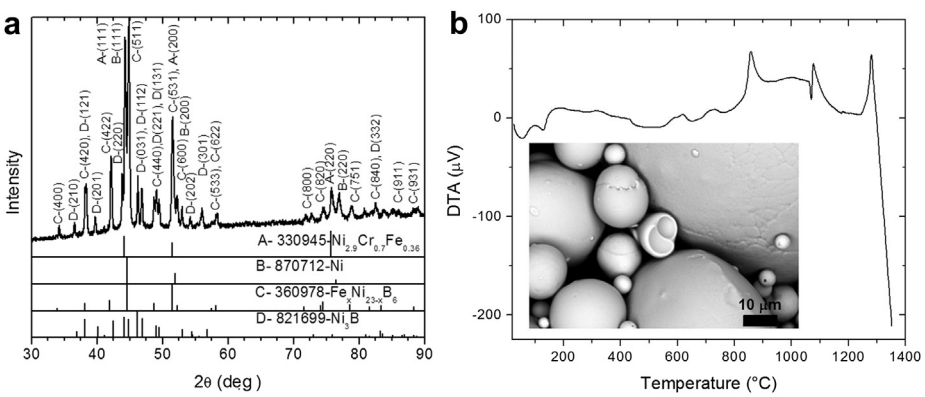


**Fig. 2** Analyses of the BNi-9 filler metal: (a) XRD pattern, (b) DTA; the inset showing a SEM image.