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Mechanical testing of steel/aluminium–silicon interfaces by pushout

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Abstract

The functionality of structural light alloy castings can be improved by inserting into them, upon moulding, local iron base reinforcements. To acquire a better knowledge of such bimetallic assemblies, samples were prepared by immersing a mild steel bar (5 mm in diameter) in aluminium base Al–Si alloy melts held at 730 °C. After melt solidification, the bimetallic samples were cut into 5 mm thick slices and pushout testing was performed on these slices. Characterization of damaging corresponding to different load level before complete debonding allows the determination of the failure mode. Crack initiation occurs at the specimen bottom face in the intermetallic reaction layer, important damage occurs before complete debonding and no brittle failure is observed. The results highlight the necessity of analysing pushout tests with a more integrated approach taking into account shear stress distribution along the interface such as interfacial crack growth.

Keywords: Aluminium and alloys; Titanium and alloys; Adhesion by chemical bonding; Push-out tests

1. Introduction

There is major interest (weight saving and low-cost production) in replacing cast iron and steel automotive components by light weight aluminium castings to improve vehicle performance and efficiency [1]. However, a key problem is to form a sound bond between the steel insert and the aluminium casting alloy. Indeed, when using conventional die casting the insert is simply embedded in the light alloy after its solidification. Hot dipping process is a way to produce a sound metallurgical bond at the interface [2,3].

Despite the usefulness of bonding steel to aluminium alloys, some difficulties may arise from the possible development of brittle intermetallic compounds at the steel/aluminium interface [4]. Moreover, little work has been published on the mechanical properties of such interfaces [5].

This paper is an attempt to link the chemistry of the reaction zone at steel/aluminium silicon alloys interface with mechanical behaviour. Therefore, special care was taken to control and characterize (before and after loading) the metal/metal interfaces. As no ASTM test exists for such assemblies, pushout testing was chosen to investigate their mechanical strength.

Combining pushout test results with the characterization of the interface zone before and after loading has led us to propose a failure mode for the steel/light weight aluminium alloy assembly. Mechanical testing of joined materials being a hot topic in many fields of materials science, the relevance of pushout test to characterize bimetallic assemblies is also discussed.

2. Experimental procedure

Bimetallic samples were processed from an AS-13 foundry alloy (composition in wt%: 12.6 Si, 0.42 Fe, <0.02 Cu, Mg, Mn, Ni, Ti, Zn) and from inserts rods made of mild steel (composition in wt%: 0.2 C, 0.85 Mn, 0.4 Si, 0.045 P, 0.045 S and Fe balance). The steel rods (5 mm in diameter) all received the same surface preparation by mechanical abrasion leading to a mean surface roughness of 3 μm. Moreover, just before the insertion process, steel and aluminium alloy pieces were degreased in an ultrasonic bath of dichloromethane. Bimetallic sample

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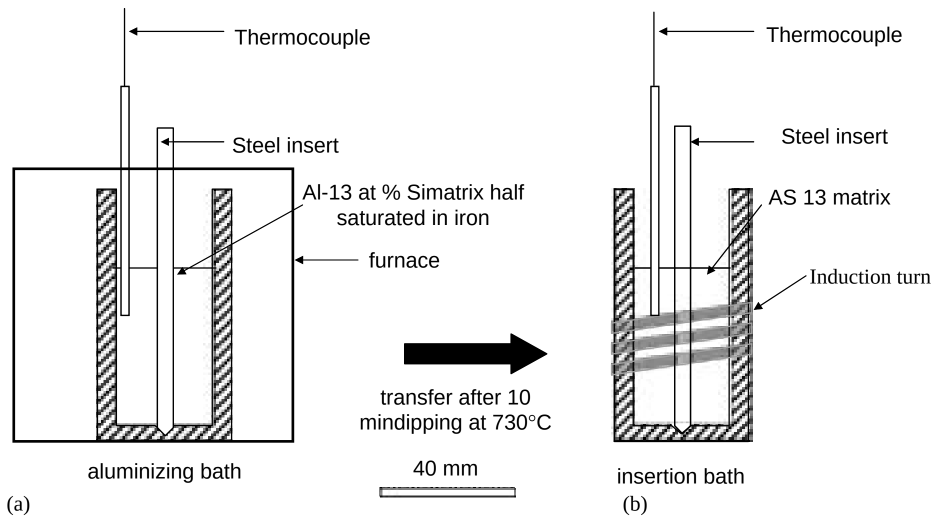

Fig. 1. Manufacturing process of bimetallic sample: (a) aluminizing step, (b) transfer to the insertion bath.

were produced in two successive steps: aluminizing and insertion as shown in Fig. 1.

2.1. Steel rod aluminizing

The first step of the sample manufacturing process consists of dipping (under air) mild steel rods in a cylindrical crucible containing an Al–Si mixture based on a commercial AS-13 (Al–13 wt%Si) alloy. Pure silicon chips (electronic grade purity 99.9995 wt%) were added to the AS-13 liquid bath in order to adjust its silicon content at 13at%. Iron was then added at a level corresponding to half saturation (5.5 wt% at 770 °C) to favour the growth of a uniform reaction layer without excessive iron dissolution, as reported in [6] (final composition of the melt in wt%: 13.46 Si, 5.5 Fe, <0.02 Cu, Mg, Mn, Ni, Ti, Zn). In the following this first liquid will be named aluminizing bath. Dipping temperature was measured with a precision better than $\pm 0.2\,^{\circ}C$ by plunging in the melt a K-type (Ni/Cr) thermocouple. Note that with a bath heated at 770 °C, immersion of the insert led to a 30–40 °C decrease in temperature. Therefore, interface reactions in this first step are considered to develop at a temperature of $735 \pm 5\,^{\circ}C$.

2.2. Transfer to the insertion bath

After 10 min dipping at $735 \pm 5\,^{\circ}C$, the hot aluminized insert was pulled out of the bath and immediately transferred in a new crucible, heated at 620 °C by RF coupling and containing a commercial AS-13 alloy to produce the final reinforced bimetallic casting. The transfer duration from one bath to the other was such that the AS-13 alloy coating the steel rod had no time to solidify. The bottom of the crucible containing the insert bath was machined and a device put on its top so that the steel insert was perfectly vertical. In the following this liquid will be named insertion bath. The RF power supply was turned off and the aluminium alloy was allowed to cool and solidify around the insert 20 s after plunging the aluminized steel rod in the second bath. The temperature of the AS-13 melt in this second bath was also measured with a K-type thermocouple. In that case, the temperature did not notably change when the aluminized insert was dipped.

After solidification, the bimetallic samples were sawn with a diamond coated wire, into slices with a thickness from 3 to 8 mm, the cross-section of these slices being perpendicular to the rod axis. End sections of each cylinder were diamond polished to a finish better than 1 μm for examination by optical microscopy (OM), scanning electron microscopy (SEM) and electron probe microanalysis (EPMA). Other slices were used for pushout testing as shown in Fig. 2. The tests were performed by using an INSTRON 1195 testing frame equipped with a compression load cell of 100 kN capacity. The insert was pushed by means of a flat-bottomed STUB steel cylinder (ball bearing steel) with a diameter of 4 mm, i.e. 1 mm less than the steel insert. The cross-head displacement rate was of $0.2\,mm\,min^{-1}$. The relative displacement of the indenter compared to the AS-13 matrix was measured by using a modified extensometer (see Fig. 2). This experimental equipment makes it possible to remove the influence of the machine compliance on the displacement measurements, therefore, only the compliance of the indenter remains. The tested slice is placed on a flat supporting surface, the insert being centred on a drilled hole of 6 mm diameter (Fig. 2).

3. Interface chemistry

Examination by optical micrography of the bimetallic samples end sections (labelled zero) indicates that the interfacial reaction zone, formed after the complete process of insertion, consists of two different intermetallic layers (see Fig. 3). EPMA characterization indicates the following phase sequence from steel rod to aluminium alloy matrix: (i) a 3–4 μm thick η-Al_5Fe_2(Si) layer and, (ii) a 9–10 μm