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Improvement of adhesive bonding of grit-blasted steel substrates by using diluted resin as a primer

Binhua Wang[a,b], Xiaozhi Hu[b,*], Pengmin Lu[a]

[a] Key Laboratory of Road Construction Technology and Equipment, MOE, Chang'an University, Xi'an 710064, PR China
[b] School of Mechanical and Chemical Engineering, University of Western Australia, Perth, WA 6009, Australia

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ABSTRACT

This study reveals the micro-structural details on the metal substrate surface prepared by grit blasting, and then proposes a simple resin pre-coating method aiming at full wetting of the substrate surface for stronger adhesive bonding. The resin pre-coating solution consisting of around 90% acetone and around 10% resin without hardener is used as a primer, which can be sprayed or blushed onto the grit-blasted metal substrate. The acetone solution can carry resin deep into micro-cavities created by grit blasting and effectively coat and wet micro-debris so that micro-voids or gaps between the adhesive joint and metal substrate can be removed. Since the resin pre-coating does not contain hardener and remains wet, the wettability of the substrate is also improved. The normal epoxy adhesive with hardener can then be applied onto the substrate surface. Despite having the primer-like function, the proposed resin pre-coating method still maintains the simplicity of one epoxy resin system. Based on the current study, a resin and acetone solution without hardener does not seem to have adverse effects on the final bonding strengths of adhesive joints, although acetone is known to have detrimental effects on resin and hardener adhesive systems. Four different surface conditions are examined, each having 14 specimens: (1) Grit-Blasted (GB) surface, (2) GB-surface with ultrasonic cleaning, (3) GB-surface with resin Pre-Coating (PC) only, and (4) GB-surface with both ultrasonic cleaning and PC. 25% improvement in the shear strength has been achieved by the resin pre-coating method, even without ultrasonic cleaning, in comparison with 8% improvement after ultrasonic cleaning. These results show GB-surface with PC is beneficial to adhesive bonding, which can be adopted for structural applications even if thorough substrate surface cleaning on site is not possible. The improved wettability of metal substrates after resin pre-coating contributes to the maximum possible utilization of the contact areas over the roughened substrate surfaces and thus leads to the enhanced adhesive bond strength.

1. Introduction

Adhesive bonding of metals and fibre composites has been widely used in various composite structures, where the interfacial bond strength is the key concern. Steel, among various metal substrates, is the most heavily used structural material in automobile industry, marine engineering, civil infrastructure, and oil and gas industries. In the past decade, carbon-fibre reinforcement of steel structures has attracted increasing attention because of its high strength and similar elastic modulus [1–4]. Adhesive joining of carbon-fibre composites to steel structures is also convenient and flexible, showing a promising future in wide applications [5–7]. However, the shear stress transfer between carbon-fibre composites and steel substrates and thus the interfacial bond strength is the limiting factor to the success of carbon-fibre reinforcement [8]. Due to the huge dissimilarities of material compositions and properties at the adhesive and steel substrate interface, adhesive bond failure along the adhesive/steel interface is known to be the dominant failure mode, which can significantly reduce the effectiveness of carbon-fibre reinforcement.

To ensure strong interfacial bonding, grit blasting or grinding has been commonly used to prepare the steel substrate to have rough, fresh and more reactive contact surface areas between the adhesive and substrate. The strong interfacial bonding on a grit-roughened substrate can also enhance micro- mechanical interlocking between the poxy adhesive and steel substrate [9–12]. Other methods such as chemical etching [13–15] and atmospheric plasma [16–20] are also used in well-equipped factories and laboratories. Furthermore, grit-blasted metal substrates can be ultrasonically cleaned in laboratories to ensure the best possible bonding conditions [21]. However, in many real engineering applications, chemical etching and ultrasonic cleaning cannot

* Corresponding author.
E-mail address: xiao.zhi.hu@uwa.edu.au (X. Hu).

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be adopted on site due to the limitation of equipment and work environment [22,23]. As a result, grit-blasting preparation of steel substrates followed by air blowing remains the most common and practical method for adhesive bonding of steel structures [24,25]. The down side of this substrate surface preparation process is that the best possible adhesive joining conditions may not be achieved because micro-debris and broken grit particles, embedded in the metal substrate or trapped inside micro-cracks created by repeated plastic deformation during the grit-blasting process, cannot be completely removed by air blowing. Furthermore, it can be difficult to achieve complete wetting on the grit-roughened substrate surface due to the presence of micro-cavities generated from grit blasting.

In this paper, we present a simple resin pre-coating method, which can be used to achieve a near perfect wetting condition on site using a single resin and hardener adhesive system without a commercial primer. Four different surface conditions are examined in this study. They are: (1) Grit-Blasted (GB) steel surface, (2) GB-surface with ultrasonic cleaning, (3) GB-surface with our proposed resin Pre-Coating (PC), but without ultrasonic cleaning, and (4) GB-surface with both ultrasonic cleaning and PC. Our preliminary results show GB-surface with PC only is sufficient, which implies thorough substrate surface cleaning on site is not necessary for adhesive bonding. This can be useful for many structural applications when chemical etching and ultrasonic cleaning cannot be used due to the limitation of equipment and work environment on site.

2. Method and surface preparation

2.1. Interfacial zone from grit-blasting & role of resin pre-coating

Adhesive failure between steel substrates or between carbon-fibre face sheet and steel-substrate, as illustrated in Fig. 1, can be described by two most likely crack growth paths. (1) Adhesive failure or cracking along the bonding interface between steel substrate and adhesive joint, and (2) cohesive failure or cracking within adhesive joint. In the case of carbon-fibre face sheet and steel substrate, the interface between carbon-fibre face sheet and epoxy adhesive joint is fairly strong as carbon fibre itself contains around 30 vol% of epoxy.

In general, the interfacial shear strength of an adhesive joint is controlled by the interface between the steel substrate and epoxy adhesive because of the huge variation in material properties. That is the reason why a steel substrate surface needs to be roughened through grit blasting, and then cleaned thoroughly by ultrasonic cleaning to achieve the best possible surface condition for adhesion [4,26]. It is noted that micro-dirt on a grit-blasted surface needs to be removed [27,28], otherwise the benefits of grit blasting will be compromised. While small test samples can be ultrasonically cleaned in laboratory, it cannot be adopted for large engineering structures on site. The most likely option in practice may be air blowing by compressed air although it is not as effective as ultrasonic cleaning.

In order to have a good understanding of the interfacial bonding and controlling mechanisms, the enclosed area along the adhesive/steel interface in Fig. 1 is enlarged and illustrated by a hypothesised interfacial zone model in Fig. 2. As a result of grit-blasting, a steel substrate surface is no longer flat, but turned into an “interfacial zone” of certain depth, as in Fig. 2(a). Sticky epoxy with hardener may not be able to penetrate deep into micro- fissures or cracks. Furthermore, micro-dirt on the grit-blasted surface is not desirable for good surface wetting, as schematically illustrated in Fig. 2(b).

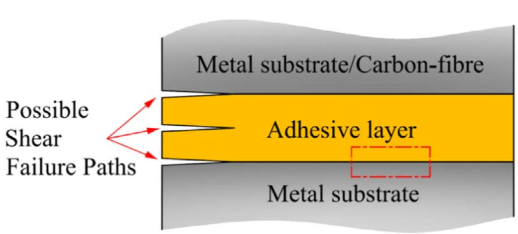

Fig. 1. Three possible crack paths or failure modes in epoxy joint between steel substrates. The adhesive failure, or interfacial cracking, can occur along both interfaces.

It would be an ideal scenario that epoxy or resin can completely wet the micro-dirt and micro-particles and penetrate deep into all micro-cracks within the interfacial zone, as shown in Fig. 2(c). Afterward, the normal well-mixed epoxy with hardener can be applied, as in Fig. 2(d). Diffusion during the curing process should lead to the final uniform curing, as in Fig. 2(e), as long as the interfacial zone is not too deep and the resin pre-coating is not too thick.

Complete wetting of the steel substrate is critical to the bonding strength of adhesive joint [9,29], which is unfortunately hard to achieve on site because of the relatively “dirty” substrate surface condition. What is shown in Fig. 2 outlines the possibility of achieving perfect substrate wetting on site without the need of thorough surface cleaning.

Acetone is widely used in laboratory as a cleaning agent because of its excellent surface wettability. Resin without hardener can be easily dissolved in acetone, which can then be taken deep into those micro-fissures of the interfacial zone by the acetone-resin solution, as illustrated in Fig. 2(c). In this study, resin pre-coating is used to achieve the complete wetting of a grit-blasted steel substrate even if micro-dirt and grit-particles exist within the interfacial zone. The fresh steel substrate surface after grit blasting is also temporarily protested by the resin pre-coating so that the on-site engineers have more time to complete the adhesive bonding.

2.2. Materials and sample preparations

Flat mild steel bars of dimensions $6000\times25\times3$ mm^3 supplied by Midalia Company were cut into the dimensions of $40\times25\times3$ mm^3. Commercial Selleys Araldite Super Strength bi-component composed of resin and hardener was selected for bonding the steel substrates. Grit-blasting was carried out by using GMA Premium Blast garnet with the grit size of 30–60 (as marked by the supplier) under a pressure of 5 bar for 10 s. During the process of grit-blasting, the nozzle with the inner diameter of 7 mm was almost located at an angle of approximately 90° and kept a distance of about 50 mm from the surface of steel substrate. Acetone was used to clean the steel substrates. The diluted resin/acetone solution contains 10 wt% of resin. Various wt% of resin solutions have been tested [8], and it appears the 10 wt% resin/acetone solution gives the best adhesion under the short-term test conditions adopted in this study.

Four different surface preparation methods were considered in this study, i.e. (i) Grit-Blasting (GB), (ii) grit-blasting followed by ultrasonic cleaning in acetone at the room temperature for 30 min (GB/Cleaning), (iii) grit-blasting followed immediately by the pre-coating of 10 wt% of resin (GB/Pre-Coating (PC)), and (iv) grit-blasting followed firstly by cleaning and then PC (GB/Cleaning/PC).

Before the above surface preparations, as-received steel substrates were first ultrasonic cleaned in acetone at the room temperature for 30 min to remove any surface dust and possible oil contamination. The cleaned substrates were then grit-blasted for 30 s, followed by surface cleaning by compressed air. The steel substrates were then divided into four groups, for the four different surface preparation tests. All specimens were allowed to dry the room temperature for 10 min.

Shear strengths of the adhesive joints with different surface conditions were obtained by the common single lap shear (SLS) tests. The dimensions of assembled specimens used in SLS tests are showed in Fig. 3. The bond area was 13 mm×25 mm and was held by a small spring clamp during the curing process. The curing temperature was kept at 40 °C in an oven for 20 min for the first curing period and 60 °C for 10 h for the following curing period. Fourteen samples were prepared and tested for each substrate surface condition.