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Experimental investigation for anti-slipping performance of stainless steel slip-resistant connections with particles embedded in connected plates

Zixuan Chen, Yang Peng, Wang Su, Feng Qian, Jun Dong *

College of Civil Engineering, Nanjing Tech University, 30# Puzhu South Street, Nanjing 211800, PR China

HIGHLIGHTS

- Embedded particles can effectively improve the slip factor of anti-slipping connections.
- S45990 stainless steel beads are suitable for S30408 stainless steel plates.
- Distribution of particles significantly impacts the slip factor of the connections.
- The critical anti-slipping load is recommended for engineering applications.

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ABSTRACT

Stainless steel has significant potential in high-durability structural applications owing to its superior corrosion resistance. However, efficient fastener connections similar to slip-resistant connections are lacking in stainless steel structures. Conventional treatments fail to obtain sufficient slip factors on stainless steel plates owing to the passive film on its surface. This paper proposes an innovative anti-slipping concept using particles embedded in the stainless steel plate surface. Static experiments illustrate that S45990 stainless steel beads with diameters of 2 mm can be applied to 5-mm-thick S30406 stainless steel plates. The ultimate slip factor of connections with seven beads and one preloaded stainless steel A4-80 bolt is 1.4.

1. Introduction

Stainless steel has been widely used in decorative engineering because of its outstanding corrosion resistance, beautiful appearance, and unique mechanical properties [1]. However, its incorporation into major structures can also be beneficial in terms of the entire life cycle of the structure, energy conservation, and emission reduction that can be achieved using recycled materials [2,3]. Stainless steel structures therefore have a particularly bright future in marine, bridge, and nuclear power engineering, as well as in other applications that demand structural durability [4].

Current design codes for stainless steel are essentially based on the rules for carbon steel [5]. However, with regard to stainless steel structures, the design specifications for slip-resistant connections, a widely used form of steelwork connection, are not included in American Specification (ASCE) [6], the European Code (EC3) [7], and Chinese Specification (CECS) [8]. The insufficient slip factor is the most important reason for the limited use of stainless steel slip-resistant connections. The slip factor of steel slip-resistant connections subjected to friction surface treatments such as shot, grit blasting, zinc spray-metallizing, or alkali-zinc silicate painting is typically between 0.3 and 0.5, [9–11].

However, an effective slip factor is difficult to obtain using the available surface treatments. In a series of tests conducted by Wang et al. [12], surface processing by abrasion blasting, wire drawing, scoring, and non-processing was found to produce poor slip resistance and a slip factor lower than 0.2 in connections of austenitic S30406 stainless steel plates. This indicated that mechanical treatments fail to improve the slip factor of stainless steel slip-resistant connections. Aoki et al. [13] studied the slip resistance of slip-resistant connections with painting and molten metal spray, achieving slip factors of 0.55 and 0.6 separately. These results have contributed to the formulation of design rules for Japanese Specification [14], but the two treatments have high

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* Corresponding author.
E-mail address: dongjun@njtech.edu.cn (J. Dong).

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environmental requirements in order to protect the corrosion resistance performance of stainless steel, which will pose significant difficulties in ensuring suitable quality control, efficiency, and cost. As such, these methods are not popular in other parts of the world [15,16].

This paper therefore introduces an innovative concept aimed at achieving more efficient fastener connections in stainless steel structures that uses embedded particles to improve the anti-slipping performance of stainless steel plate.

2. Anti-slipping concept based on embedded particles

2.1. Influence of passive film on the slip factor of stainless steel

The surface characteristics of stainless steel differ from those of carbon steel. Fig. 1 shows a comparison between a stainless steel surface and carbon steel surface [17]. The passive film on the surface of stainless steel results in a small slip factor for slip-resistant connections and prevents surface rusting.

Different understandings regarding the mechanism of friction have led to many different friction theories [18,19]. The following two main theories have been developed to describe metal surface friction:

2.1.1. Mechanical theory

This theory is based on the notion that friction is dependent on surface roughness, and thus, the friction force is derived from the interlocking of asperities. However, this theory regards metal surface asperities as rigid bodies and cannot explain why the friction coefficient of a metal surface is increased by superfinishing. This has led to a more complete metal friction mechanism (adhesion theory) becoming more widely accepted in modern tribology.

2.1.2. Adhesion theory [20]

The adhesion theory of friction postulates that the friction force is constituted of the resistance force from the adhesion effect and the ploughing effect. The adhesion effect is shown in Fig. 2(a). The surface asperities yield and deform under vertical pressure, which may bring about a sudden increase in temperature, leading to cold-weld junctions. This friction force originates from the shear resistance of the cold-weld junctions. The friction force of the adhesion effect is related to the shear strength of material. The ploughing effect is depicted in Fig. 2(b). The surface asperities embed into the surface under vertical pressure. This friction force comes from ploughing of the surface by asperities. The ploughing force is related to the depth of the indentation and the yield strength of material.

The embedded depth of asperities decreases with increasing yield strength of the material, whereas the ploughing force is inversely proportional to the square root of the material's yield strength. In other words, materials with higher yield strength have a smaller ploughing force [21]. Therefore, the friction force of the metal surface is primarily the result of the friction force from the adhesion effect, and the friction force from the ploughing effect can be ignored. The slip-resistant connections used in carbon steel structures resist shear owing to the friction force between contact surfaces of the carbon steel plates [22]. With machinery and painting treatments, the number of asperities on a carbon steel surface can be increased, thereby increasing the cold-weld junctions. The friction force from the adhesion effect increases, leading to an increase in the slip factor of the carbon steel slip-resistant connection.

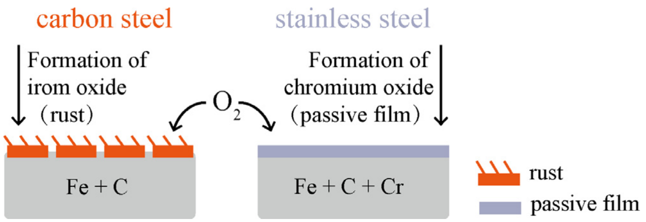

Fig. 1. Comparison of stainless steel and carbon steel surfaces.

The passive film over a stainless steel surface is significantly harder and stronger than the stainless steel substrate. The passive film also has excellent self-healing capability, which implies that it will regenerate quickly through oxidation immediately after surface processing [23]. This film does not yield easily and prevents the contact surfaces of stainless steel plates from exhibiting a significant adhesion force [24], which makes it difficult to achieve a sufficient slip factor for slip-resistant connections.

2.2. Anti-slipping concept of embedded particles

We abandon the old idea of increasing the slip factor by increasing surface roughness of the stainless steel using conventional treatments and propose an innovative concept for achieving effective anti-slipping properties using embedded particles. As shown in Fig. 3, this involves using vertical pressure to embed hard particles in two opposing plates to a certain depth. Stainless steel preloaded bolts are used to maintain the clamping force, ensuring that the particles remain effectively embedded within the two stainless steel plates. The embedded particles are similar to blind bolts and can provide sufficient stable shear resistance between the stainless steel plates.

The contact stress status of a single particle embedded into the surfaces is shown in Fig. 4(a). The following anti-slipping failure modes are possible:

- Failure mode 1: the particle undergoes fracture under shear stress, as shown in Fig. 4(b);
- Failure mode 2: the particle is crushed by the plates owing to increasing extrusion stress, as shown in Fig. 4(b);
- Failure mode 3: the contact zone on the plate surface is crushed owing to increasing extrusion stress, as shown in Fig. 4(b);
- Failure mode 4: the plates are ploughed by the particle, producing significant relative displacement, as shown in Fig. 4(c).

The failure modes 1, 2, and 3 are similar to the failure modes of blind bolt connections under shear force. The slip resistance depends on the strength of the particles and stainless steel surface. The fourth failure mode is similar to the ploughing effect in tribology. Before failure, the deformation of the anti-slipping connections is noticeable. Owing to the stacking material in front of the particles on the plate surface, the slip resistance can increase considerably. The slip resistance from the fourth failure mode is larger than that from the other modes.

The contact region between the particle and the plate surface is in the triaxial pressure state, which causes the materials around the contact region to strongly resist yielding. Thus, the slip resistance increases with the increase in the material yield strength. In addition, the slip factor can be adjusted over a considerable range through the control of the particle properties such as size, shape, hardness, and strength.

To obtain suitable particles, experiments on the embedding procedure of particles were conducted under vertical loads. In addition, experiments on the anti-slipping procedure of connections were conducted under shear loads in this study so as to evaluate the performance of the innovative anti-slipping concept. These experiments also provided the maximum slip factor of single-shear preloaded bolt connections by changing the