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Low-velocity impact behavior of vitreous-enameled steel plates

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ABSTRACT

In the present work vitreous enamel, a special class of ceramic–glass material, was used as a coating for thin steel plate. The impact behavior of rectangular steel plate and coated steel plate (enameled steel plate) was studied by means of both experimental tests and numerical analysis. Experimental tests revealed the onset and growth of plate instability in the case of impact both on steel plates and on enameled steel plates. The instability was mainly located on the free edges and was particularly evident on the longer side of rectangular plates. The impactor initial energy that caused the instability onset in the case of enameled steel plate was about six times higher than the one that induced the instability in the steel plates. Numerical simulations were performed to better understand and study the experimentally observed instability phenomenon. Four numerical models were developed in order to study the influence of plate thickness and residual stresses acting on the enameled steel plates on plate instability. Results of numerical simulation revealed that residual stresses acting on enameled steel plated increased the value of force that caused the instability onset. Further numerical simulations showed that the increase of residual stresses acting on enameled steel plates highlighted the values relative to the instability force increase according to a non-linear trend.

1. Introduction

The vitreous ceramic coatings used in this work belong to the class of enamels for metallic substrates known as porcelain- or vitreous enamel coatings. Although these coatings are the oldest among known coatings for metals (the first examples appeared around 3000 years ago), we still know very little about their mechanical and tribological behavior. A wide spectrum of industrial and domestic applications currently makes use of these coatings (e.g. the treatment of components for household use, the protection of interior walls of reactors for chemical processes, the protection of mechanical components of aircraft turbojets). Vitreous-enameled metals are non-equilibrium composites, since the enamel (a ceramic–glass material characterized by a predominantly amorphous structure whose percentage typically ranges between 85% and 95% [1]) never exactly matches the metal (steel) over a range of temperatures. Since glass is a brittle material, and it almost always fails in tension, enamels are designed to be in a state of compression with respect to the metal on which they are applied [1,2]. This is accomplished by compounding the enamels so that they have a lower overall thermal contraction and expansion than the metal, so that in cooling the enamel layer is placed under compression and the metal under tension. All enamel–metal composites, therefore, contain residual stresses which influence the overall physical and mechanical properties of the system.

Vitreous enamel coatings are also characterized by the presence of gas bubbles in the coating thickness (percentage of bubbles, known as blistering, typically range between 15% and 30%), and their surface is characterized by high values of hardness (up to 800 HV) and low roughness (lower than 0.5 μm). Compared to other coatings for metals, such as thermally sprayed ceramic ones, vitreous enamel coatings are characterized by a chemical and not only physical adhesion to the substrate achieved by a graded interface that is developed during the coating firing process. From the functional point of view, vitreous enamel coatings have an excellent resistance to chemical corrosion processes [1,3–5] and a good resistance to tribological phenomena such as abrasive wear [4,5]. All these features can be totally lost or partially reduced by external phenomena, such as transversal loads, and in particular by low-velocity impacts. In fact, such events can cause both the onset/growth of cracks and the spalling of the coating, thus decreasing the surface integrity and exposing the metal substrate to environmental attacks.

This paper discusses experimental tests of both steel and enameled steel plates that were subjected to low-velocity impacts. Experimental results on both steel and enameled steel plates showed a structural instability when the initial kinetic energy of

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the impactor was greater than a certain threshold. It was also observed that in the case of enameled steel plates the instability onset energy was 6 times higher than in the case of steel plates. In both cases, steel plates and enameled steel plates, the instability took place, as a local instability, at the center of the longest edges and it was highlighted by a great change of specimen geometry, from the flat shape to the butterfly one, Fig. 1.

A survey of the literature on this subject has shown a lack of experimental and theoretical studies about such instability. In fact the only paper that refers to the instability phenomenon considered here was published by Belluzzi in 1952 [6]. Experiments done by Belluzzi revealed the instability phenomenon in both rectangular and circular metal plates. Belluzzi related this instability phenomenon to a complex mechanism of load transfer within the plates. The author hypothesized that the transversal load leads to the development of compression membrane forces acting in the plane of the plate. The author also developed semi-empirical mathematical relations to predict the instability load, although he never completed the study. No references have been found about the impact behavior of enameled steel plates.

To reach a deeper understanding of the cited phenomenon, and to describe the mechanical behavior of both steel and enameled steel plates, numerical structural analyses were developed. Numerical simulations of steel plates confirmed the hypotheses by Belluzzi, even if in the case under study material non-linear plastic behavior was observed. A good agreement between the maximum load measured during impact test on steel plates and the instability load from numerical analysis was observed. Also in the case of enameled steel plates, it was observed that the maximum load measured during impact test and the instability load from numerical analyses, that takes into account residual stresses, are in good agreement. By means of the numerical analyses it was also possible to highlight the influence of residual stresses acting on the enamel–metal composite on the instability load.

2. Materials and methods

2.1. Materials and experimental approach

Rectangular steel plates, 150 mm × 100 mm, made of very low carbon steel (DC04ED), were used as specimens for laboratory tests. One type of specimens were uncoated steel plates and a second type of specimens were very low carbon steel plates coated by vitreous enamel (also called enameled steel plates). The steel plate thickness was 0.8 mm while the average coating thickness was 200 μm per side. A special purpose enamel [5], technically used to protect the heating elements of rotary heat exchangers (ljungström type) in thermal power plants [7], was used as the material for coating. Enamel raw material was produced in water slip form by ball milling process [1]. Particulates of frits in the slip had a mean size of 0.40 μm ± 0.1 μm. Enamel slip was applied over the steel specimen surfaces by wet-spray technology. Steel specimens covered by enamel slip were dehydrated and then fired at 870 °C for 6 min 30 s, obtaining a composite known as enameled steel. During the firing process the enamel raw material melts and interacts with the metal substrate, thus enabling the formation of a continuous varying structure. As shown in the micrograph of the transversal section in Fig. 2, the interface zone between the substrate and the external layer is made of a complex material system where the vitreous enamel and the metal constituents are mixed. In particular, three main regions can be identified, starting from the bottom of Fig. 2A: a first region is made of metal, the second region is the interphase where both metal constituents and enamel components are mixed, and the third region composed of the vitreous enamel material. The presence of metallic dendrites that hinder the substrate and the external layer passing through the interphase region should also be noted, Fig. 2B.

For the low-velocity impact test on both enameled and not enameled plates, the same fixing support, designed according to ASTM [8], was used, Fig. 3. A steel plate with a rectangular opening (125 mm × 75 mm) unilaterally supports the rectangular specimens. Three guiding pins ensure the correct positioning of tested plates so centering them with respect to the opening. Four levers with rubber tip prevent the upward motion of the plate during impact. The test apparatus was equipped with a laser sensor for measuring impactor velocity just before the collision.

The impactor was instrumented with a piezoelectric load cell to measure the contact force, and its overall mass was 1.22 kg. The impactor end-contact geometry was a hemisphere with a diameter of 12.7 mm. The methodology adopted for the calculation of both impactor displacement and absorbed energy, at the impact stage, was also performed according to ASTM [8]. Low-velocity impact tests were developed considering different energy levels (from 3 J to 33 J). The experimental protocol was articulated by first impacting the steel plates and then the enameled steel plates, see Table 1 for the full test plan.

In order to perform numerical analyses the physical and mechanical properties summarized in Table 2 for both low carbon steel and vitreous enamel coating materials were considered. In particular, the mechanical performance of low carbon steel was assessed by tensile tests according to UNI EN 10002. The mechanical properties of vitreous enamel material (E and ν) were estimated

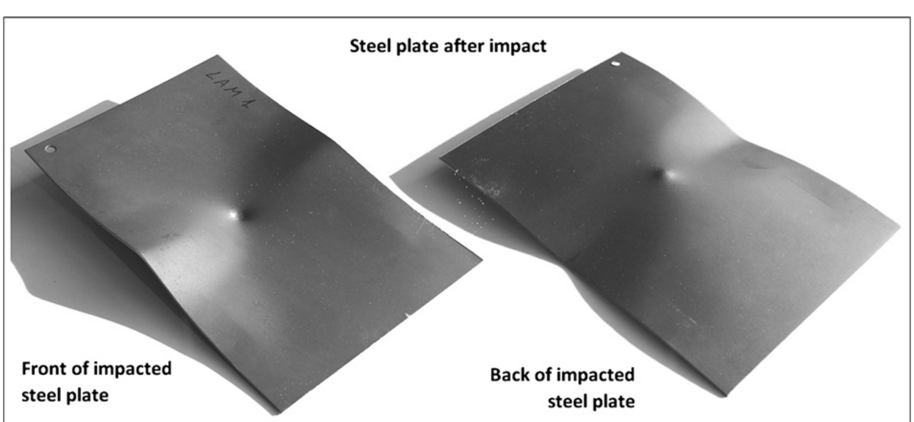

Fig. 1. Examples of post-instability shape of a steel plate specimen.