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A micromechanical model of the cracking failure on structural steel components during hot-dip galvanizing

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ABSTRACT

This paper describes a model that explains the failure during hot-dip galvanizing of structural steel components. This is an occasional problem found by galvanizers, which involves a high level of structural responsibility, and it has been considered as a stress corrosion cracking process by all experts. Considering this statement as a starting point, a complete experimental characterization of each step of the galvanizing process and its effect on the failure has been performed. The results of these tests are used to elaborate a complete model of micromechanisms which explains and describes step by step the cracking process up to failure during galvanizing. Two cases were considered, depending on whether the Sn content in the galvanizing bath was lower than 0.5% Sn or more than 0.5% Sn. Besides, two mechanical conditions are necessary to maintain the cracking process, which are:

1.- The stress intensity factor K_I should be higher than a threshold value, K_{Iscc}.
2.- The stress intensity factor K_I should increase during all the immersion in liquid Zn.

These mechanical conditions were used to formulate additional recommendations to prevent cracking failure during galvanizing.

1. Introduction

Structural steel failure or cracking during hot-dip galvanizing is a phenomenon which was first identified as long ago as the 1950's [1–3]. Nevertheless, the problem only started to receive attention from the scientific community in the 1980's, initially in Japan [4,5]. The problem became more widely recognized in the 1990's when the frequency of the occurrence of the cracking failures increased as a result of the addition of up to 1% Sn to galvanizing baths in order to control Zn coating thickness on Si-killed steels [6,7].

In general, it has been established that failure during hot-dip galvanizing shows the following characteristics [7]:

- It is occasional.
- This type of failure can occur during the galvanizing of all structural steel grades with a yield strength up to 500 MPa.
- Cracks are mostly intergranular and are highly branched.
- The origin of the cracks is typically the heat-affected zone of welds, or the mechanically deformed parts of the components which have been cold-deformed, punched or drilled [8].
- All cracks are filled with a Zn layer from the galvanizing bath, which usually presents high concentrations of Pb, Sn and even Bi, which are minor components of the liquid metal bath.
- Failure appears only during galvanizing. After galvanizing there is no delayed embrittlement. If a steel component has not suffered cracking during galvanizing it will behave in exactly the same manner as the component in the as-received conditions.
- This type of failure is, at the moment, not adequately considered in the standards.

There have been several research projects which have studied this problem in Japan [4,5,9], Europe [7] and America [10,11], and some good review articles have been published [12]. They conclude that failure during galvanizing is mainly a liquid metal assisted embrittlement process where other aggressive agents, such us hydrogen, to which steel is exposed during pickling and fluxing prior to galvanizing, do not play an essential role in crack propagation [4,7,12]. As a consequence, failure during galvanizing is a stress corrosion cracking process, in which a susceptible steel grade, internal or externally applied stresses

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and an aggressive environment, i.e. the galvanizing bath, are simultaneously present.

These projects have contributed greatly to the prevention of large scale failures, offering useful recommendations to the galvanizing workshops which have led to a reduction in the number of failure cases since 2006. Nevertheless, the specific micromechanisms of the failure process have not been described yet. There is no complete explanation of how the different components of the liquid galvanizing bath interact with the steel base to produce and propagate cracking.

This paper shows a complete experimental program that includes:

a) A real life, full scale case study (Section 2.1).
b) A conventional mechanical characterization on a selection of structural galvanized or non-galvanized steels which can suffer embrittlement (2.3).
c) A study of the surface of these steels (2.4.1).
d) A study of the hydrogen absorption of these steels during galvanizing (2.4.2).
e) The characterization of the toughness properties of the selected steels (2.5).
f) A study of the cracking behavior during hot-dip galvanizing (2.6).

As a result of this experimental program, a micromechanical model of the failure during hot-dip galvanizing is shown (Section 3). Finally recommendations to galvanizers on preventing cracking drawn from this model are proposed (Section 4).

2. Experimental program and results

2.1. A case study at real scale

Arcelor-Mittal supplied a piece of structural steel EN 10025-3:2006 S420N from an IPE 750 profile with semi-plates welded to their extremes, as shown in Fig. 1a). This beam, which had been submitted to galvanization in order to promote cracking, showed a failure in one of the two welding zones between the web and the semi-plate. After carefully cutting this zone of the profile, an extracted sample which was encapsulated (Fig. 1b)), polished and finally etched with nital 5% during 5 s, could be analyzed and examined in a Scanning Electron Microscope (SEM) with Energy-Dispersive X-ray Spectroscopy (EDS). SEM observations showed the existence of three cracks, as can be seen in Fig. 1c), the central one being much bigger than the others.

Fig. 1d) and Table 1 are representatives of the main findings in the examination of this case study of failure during galvanizing at real scale. The main findings were the following:

1. High concentration of Sn at the crack path (galvanizing bath composition: 98% Zn, 1% Sn, 1% Pb and 0.1% Bi), which increases with the crack advance to the tip.
2. In these zones of high Sn concentration, FeSn intermetallic compound was found (Table 1).
3. Crack propagation along ferritic sub-grain boundaries was detected.

2.2. Material selection for the experimental program

Corus-Tata and Arcelor-Mittal supplied the steel grades summarized in Table 2 to study failure during galvanizing. All of them are low alloy structural steels that are usually galvanized and have been reported as susceptible to suffer failure during galvanizing, according to reference [7]. Their complete chemical composition can also be consulted in [7]. Their Si + 2.5P content, see Table 2, provides a classification of the reactivity of the steels with the galvanizing bath (Sandelin effect [5]). Class 3 steels are adequate to be galvanized in all Zn baths and class 2, reactives, can only be galvanized in special Zn baths with additions of 1% Sn and 0.1% Bi.

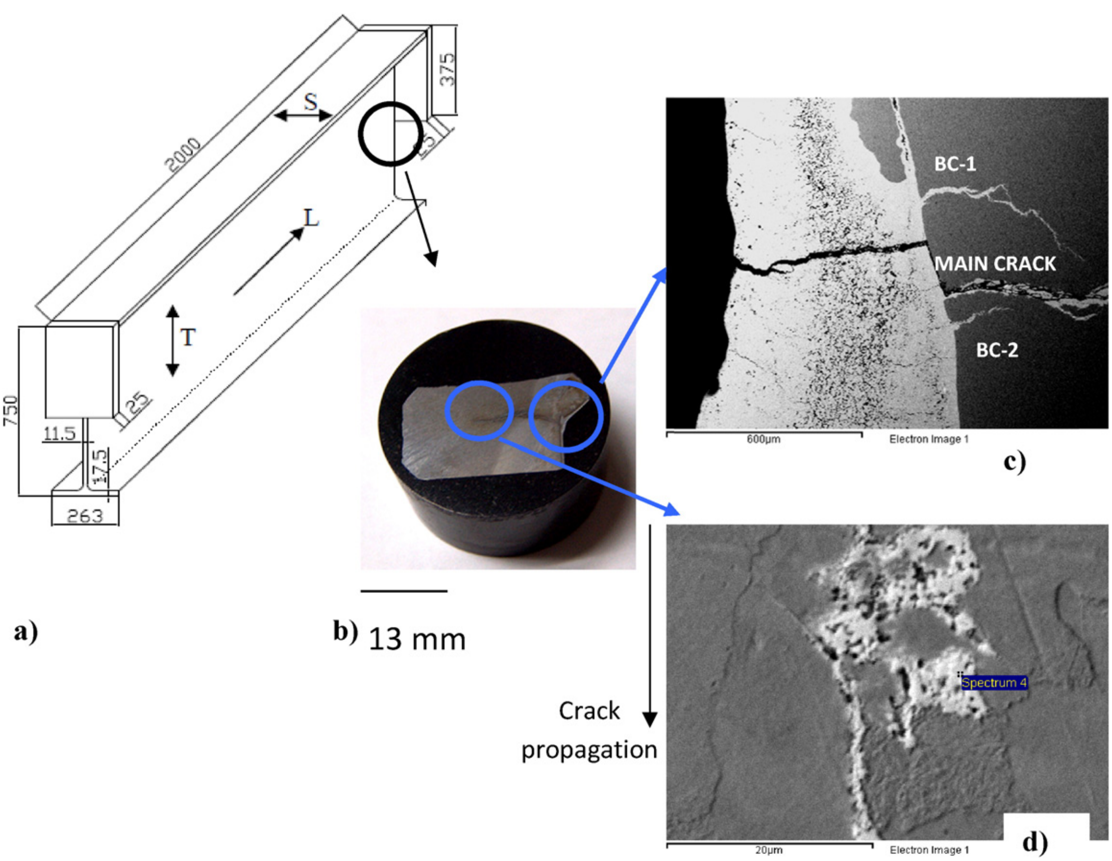

Fig. 1. Scheme of the extraction of the piece of steel with a failure during galvanizing: a) scheme of the original steel component; b) zone of the profile to be studied; c) general SEM micrograph of the origin of the 3 cracks; d) micrograph of a zone near to the crack of the case study of failure during galvanizing.