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Experiments On Delayed Failure During Galvanizing Of Flame-Cut Structural Steels

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ABSTRACT: Cracks have occasionally been found after hot-dip galvanizing of flame-cut structural beams. A project has been completed at CANMET to find the causes of this problem. Experiments have been designed to measure the time-to-failure of notched samples under near-constant load. Cracking during galvanizing is caused by liquid-metal embrittlement, and occurs for critical combinations of stress and susceptible material. Sources of stress are residual stresses including those from flame cutting, and thermal stresses from thermal gradients during hot dipping. Material susceptibility is related primarily to surface hardness, and correlates well with micro-hardness measured at 100µm depth. Remedial measures to eliminate cracking require either reduction of the hardness below a critical level (270 Vickers), or reduction of residual and thermal stresses.

1 INTRODUCTION

Hot-dip galvanizing is a tried-and-true cost-effective method to prevent corrosion of structural steel members. However, cracks are occasionally found in galvanized sections, notably at flame-cut copes in I-beams [Langill and Schlafly 1995]. The problem is found in only a small proportion of cases, but when it occurs it is costly and disconcerting. To address this problem, a project was undertaken at MTL/CANMET to investigate the source of the cracking and to suggest ways to ameliorate it.

It has been known for many years that steel can be embrittled by exposure to a number of low-melting metals. This phenomenon has been blamed for a variety of failures of engineering components [Lynch 2003], and has given rise to lively debate on the basic cause of the embrittlement. Arguments have been advanced in favour of either a decohesion or an enhanced plasticity mechanism. Both mechanisms involve localized weakening of interatomic bonds in the steel, and recent electronic structure calculations have led to criteria for the embrittlement power of liquid metals [Legris et al. 2002]. It is not surprising that steel is embrittled by zinc as it is by mercury, gallium, cadmium, lithium, and indium [Kamdar 1983] (although the recent work by Legris et al. removes mercury from this list but adds tin, lead, and bismuth). It is fortunate that the severity of the embrittlement is low enough to allow hot-dip galvanizing to be the successful process that it is. However, under certain conditions liquid zinc has been observed to cause cracks in steel, and it was the intent of this work to identify and quantify the factors involved.

2 EXPERIMENTS

The approach used in this work was to measure the time to failure of a stressed steel specimen immersed in liquid zinc. The specimen chosen was a bend bar of Charpy dimensions (10x10x55 mm). A special jig was designed using a soft loading system comprising a stack of Belleville washers that would maintain the load approximately constant during immersion, allowing for thermal expansion and small deflections before crack initiation. With this jig (Fig. 1), a typical applied load of 800 kg would relax by about 15% with a deflection of 0.5 mm.

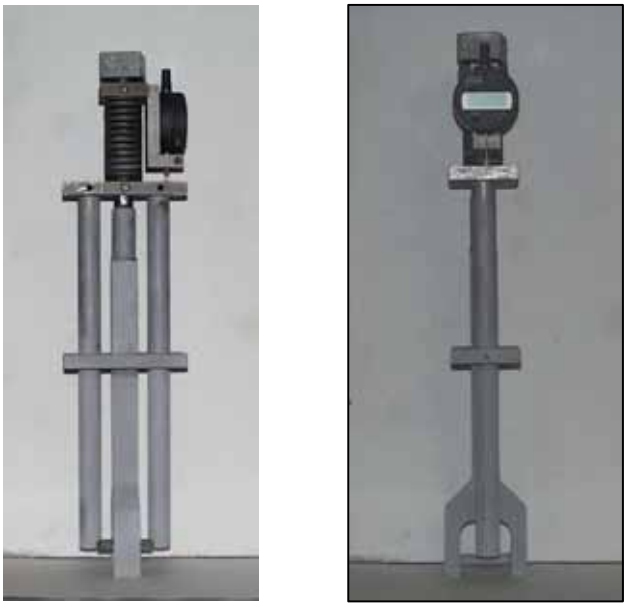

Fig. 1. Three-point bend jig.

In early phases of the work, specimens were prepared with or without a notch and for various heat treatments of the steel. That work led to the conclusion that the strength of the steel, in particular the hardness, was a crucial variable in determining cracking susceptibility. These properties are influenced by both steel composition and thermomechanical process history. In the work reported here, the focus was on evaluating the effect of the condition of the steel surface on cracking susceptibility. The as-received steel was cut by a flame or plasma torch, and some of the surfaces were softened by thermal treatment. Specimens (without a notch) were then machined and tested with the cut surface on the tension side of the bend bar.

Fifteen steels of a range of chemistries, represented by the two examples in Table 1, were studied in the course of this project. Carbon equivalents (CE_{IIW}) ranged from 0.23 to 0.62, and yield strengths (as-received) from 281 to 803 MPa.

Table 1. Chemical compositions of two of the steels studied

Steel	*C*	*Mn*	*Si*	*Ni*	*Cu*	*P*	*S*	*Cr*	*Sn*	*Mo*	*Al*	CE_{IIW}*
5	0.17	0.79	0.24	0.19	0.39	<0.006	0.017	0.19	<0.006	0.03	-	0.378
HY-80	0.13	0.25	0.26	2.10	0.18	0.013	0.022	1.20	0.015	0.29	0.019	0.622

* $CE_{IIW} = C+Mn/6+(Ni+Cu)/15+(Cr+Mo+V)/5$

The experimental procedure involved: ***cleaning*** (ultrasonic followed by acetone and water rinse); ***pickling*** (at 80°C in 15%HCl); ***fluxing*** (at 70°C in 200 g/L $ZnCl_2.3NH_4Cl$); ***drying*** (in air at 100°C); ***loading*** (to a pre-determined load in a pre-heated jig); and ***immersion*** in a bath of liquid zinc (99% Zn, 1% Pb to represent "Prime Western" grade). The deflection was monitored using a digital dial gauge (see Fig. 1) and the time to failure (defined as 0.5 mm deflection) was recorded.

3 RESULTS

A typical deflection-time curve (raw data) is shown in Fig. 2. The deflection remains virtually constant until failure in this case which occurred by rapid crack growth; in other cases, the deflection dropped gradually corresponding to creep deformation. In both cases, attainment of 0.5 mm deflection was defined as failure, labeled "Crack" in the former case and "No Crack" in the latter.

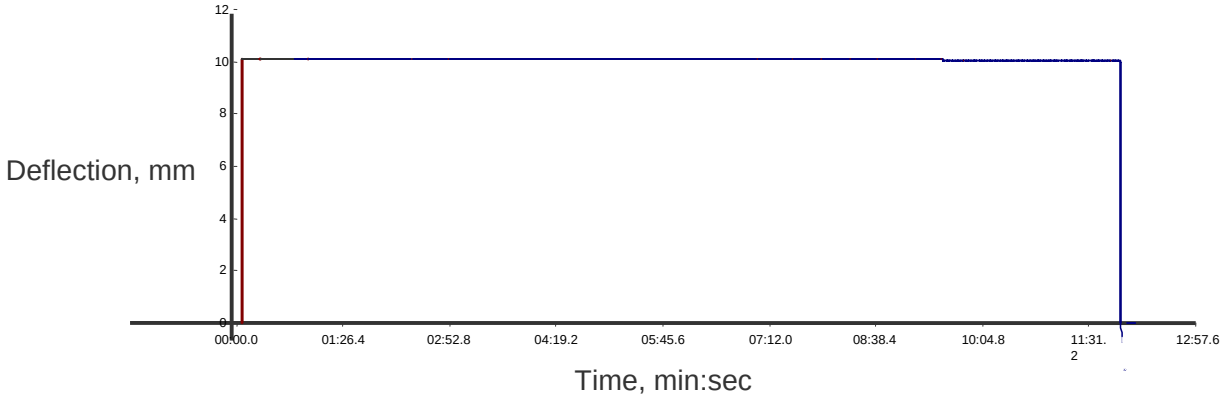

Fig. 2. Typical record of deflection after time of immersion in zinc bath.

Delayed failure results (time-to-failure as a function of applied load) for the HY-80 steel are shown in Fig. 3. The points refer to different conditions of the tensile surface (as received, or cut, or cut and thermally softened; see legend and description in next paragraph); the mode of failure is by cracking

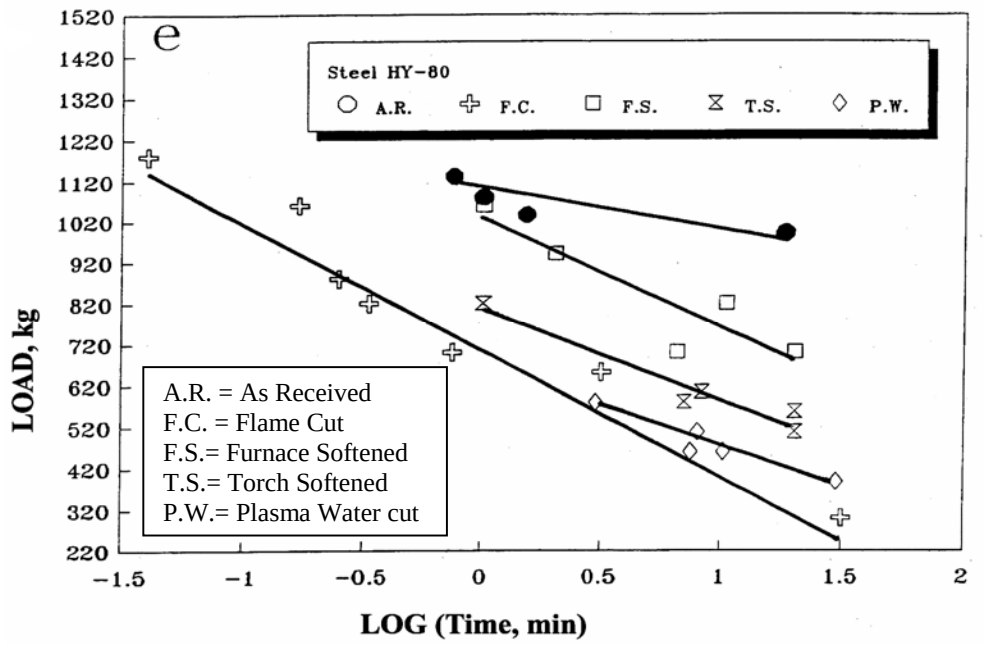

Fig. 3. Delayed failure results: time-to-failure at different applied loads. Open points: Crack; filled points: No Crack (i.e. failure by plastic deflection in creep).

for open points, and creep (no crack) for filled points. It is evident that the surfaces that have been hardened by thermal cutting are more susceptible to failure by cracking than the surface of the as-received material, which failed by creep at higher loads than for the specimens that cracked.

Previous work had shown that hardness is a key variable in determining susceptibility. Hardness profiles were measured below the surface of the materials in the as-cut condition and after various thermal treatments intended to soften the surface. Softening treatments were: torch softening (T.S.) by heating to cherry red (650-900°C) with an acetylene torch and air cooling; and furnace softening (F.S.) by heating at 650°C for one hour in a furnace. The micro-hardness as a function of depth below the cut surface for the HY-80 steel is shown in Fig. 4. It is evident that the thermal treatments have significantly reduced the hardness at the surface, although not to the level of as-received material for this steel (HY-80).

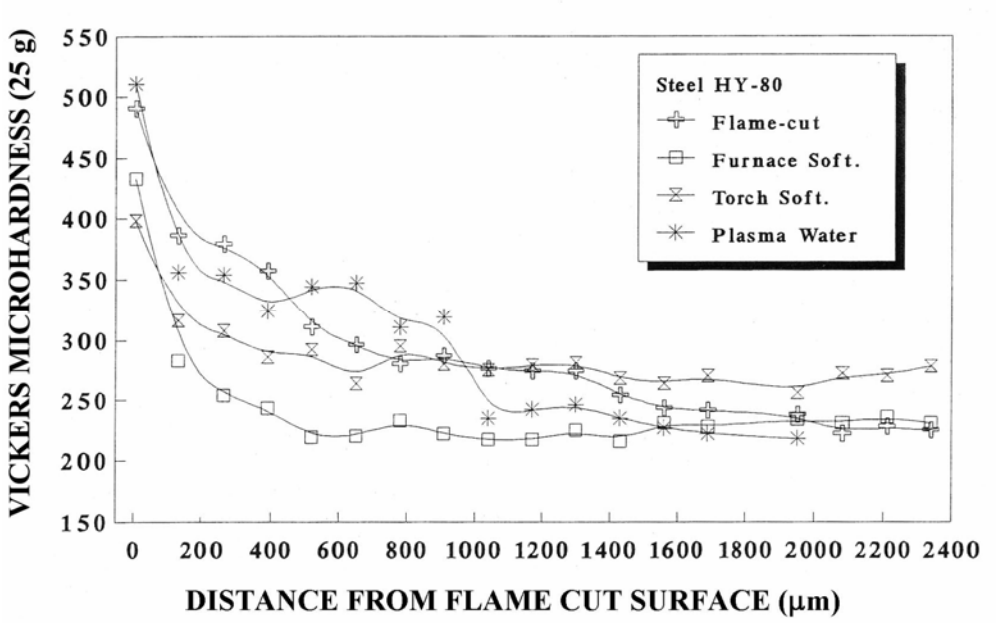

Fig. 4. Micro-hardness (Vickers 25 g load) near the cut surface of HY-80.

Results of delayed failure tests of the type shown in Fig. 3 are reported in Table 2. This table gives the micro-hardness at a depth of 100 μm below the surface, and indicates (in square brackets) the

Table 2. Yield strength and micro-hardness of two of the steels studied

		Micro-Hardness (HV_{25}) at 100 μm depth [cracking response]				
Steel	*YS (MPa)*	*A.R.*	*F.C.*	*F.S.*	*T.S.*	*P.W.*
5	304	139 [N.C.]	360 [C.]	180 [N.C.]	160 [N.C.]	-
HY-80	585	230 [N.C.]	430 [C.]	330 [C.]	340 [C.]	440 [C.]

Code: A.R = As Received; F.C. = Flame Cut; P.W. = Plasma Water cut; F.S. = Furnace Softened; T.S. = Torch Softened; N.C. = failure with No Crack; C. = failure with Crack

cracking response observed at a time-to-failure near 10 min. For steel 5, the flame-cut surface failed by cracking, but the thermal softening treatments were sufficient to generate failure by creep deformation (N.C., i.e. no crack appeared at a deflection of 0.5 mm). For HY-80, softening was not sufficient.

Results for the fifteen steels studied in this project are summarized in Fig. 5. The abscissa in this figure is the CE_{IIW}, which is relevant as an indicator of the maximum as-cut hardness; note the trend to increasing microhardness with increasing CE_{IIW}. There is a trend to increased cracking with increased

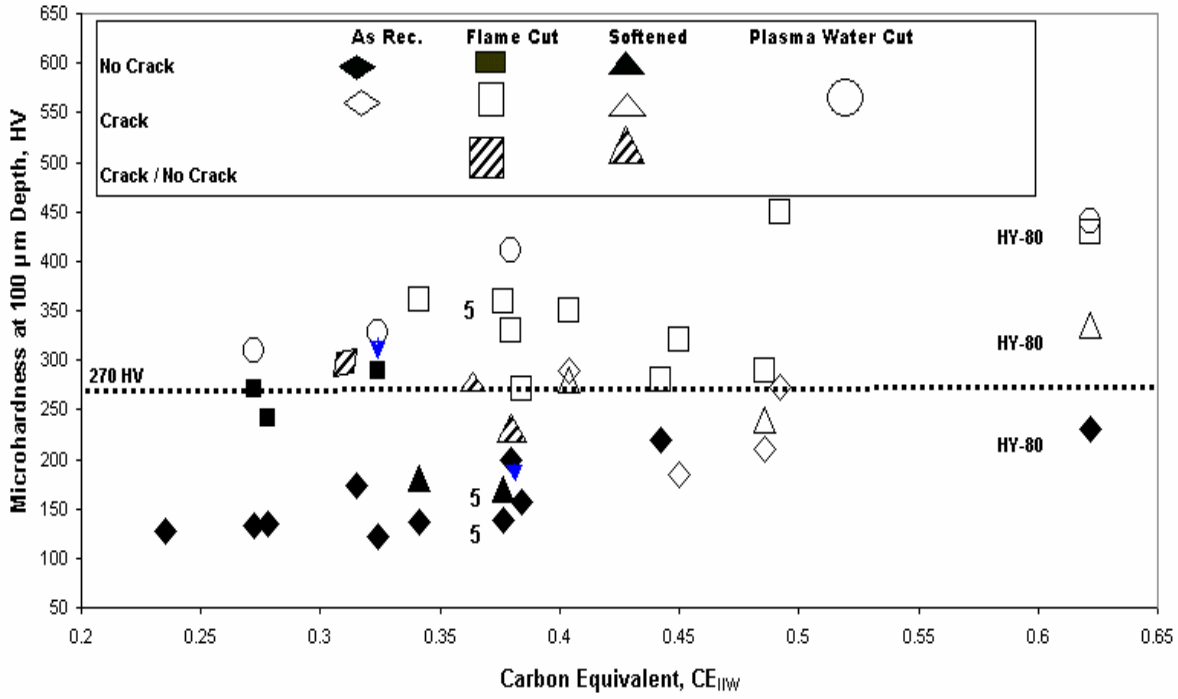

Fig. 5. Cracking susceptibility (mode of failure by 0.5 mm deflection under load for time-to-failure near 10 min) as a function of microhardness for fifteen steels of a range of carbon equivalents. Open points: specimens cracked; filled points: specimens did not crack. Mixed behaviour is shown by half-filled points. Points for steels 5 and HY-80 are labeled.

hardness, and for hardness levels above about 270 HV failure tends to occur by cracking. This is consistent with earlier work in which it was noted that higher-strength (harder) steels were more prone to cracking. From the standard correlation between hardness and tensile strength, the value of 270 HV corresponds to a tensile strength of about 850 MPa, i.e. a yield strength of about 725 MPa (105 ksi) for a Y/T ratio of 0.85.

4 DISCUSSION

Cracking of steel during galvanizing displays the well-known features of all environment-assisted cracking, i.e. it occurs for critical combinations of stress, environment, and material. It has been found in this work that a steel must have a hardness near the exposed surface of a bend bar of at least 270 Vickers to sustain high enough stress when immersed in zinc to fail by cracking. Of course, the presence of stress concentrators such as notches might make steel of lower hardness susceptible to cracking, as has been shown by Legris et al. (2000) to occur for steel immersed in lead. Immunity is not absolute for hardness below 270 Vickers, but the trend of increasing susceptibility with higher hardness is clear. It must be remembered when considering galvanizability of a structure that the hardness may be unnecessarily increased through poor control of fabrication processes involving cold

working, flame cutting, and welding, and that the locally hardened regions are often located in regions of stress concentration. Thus, composition alone cannot be used as an indicator of hardness.

The detailed mechanism of cracking observed during galvanizing in these experiments remains to be investigated. Since a layer of solid zinc-iron intermetallics forms on the surface by a chemical reaction, the steel is exposed to liquid zinc only momentarily. Owing to the observed delay in cracking during which thickening of the solid layer increases, it is likely that the sequence of events in crack initiation and propagation involves a complex combination of solid-state diffusion and rupture of the intermetallic layer to deliver zinc atoms to the crack tip. The details are unclear.

5 CONCLUSIONS

1. A simple technique has been developed to investigate cracking during immersion in a galvanizing bath, in which the stress can be varied over a wide range and the effects of surface condition of the material can be investigated.
2. The susceptibility of a steel to cracking during galvanizing increases with hardness, and a hardness level of 270 Vickers has been identified as critical.
3. A practical way to reduce cracking is to soften the surface by thermal treatment.

ACKNOWLEDGMENTS

This work was funded by members of ILZRO, the International Lead Zinc Research Organization, under the technical direction of F. Goodwin and A. Stoneman. Many staff members of MTL/CANMET participated in the work, and their efforts are gratefully acknowledged.

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