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Automated Pin-Dot Marking Effects on A709-Gr50 Steel Plate Fatigue Capacity

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Automated Pin-Dot Marking Effects on A709-Gr50 Steel Plate Fatigue Capacity

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Abstract

During fabrication of multi-piece steel bridge assemblies, markings are often made on the steel surface to identify/track individual pieces or to provide reference for fabrication layout or later erection. Automated marking methods such as computer numerically controlled (CNC) pin-dot marking offer fabrication efficiencies; however, for marked steel sections subjected to frequent or repeated loading (i.e. bridge girders) many code specifications require experimental testing to verify any marking effects on fatigue capacity. In this study, the effects of automated pin-dot markings on the fatigue capacity of A709-Gr50 bridge steel are experimentally investigated from 13 specimens considering 2 marking frequencies (corresponding to marking speeds of 50in./min and 10in./min), 2 applied stress ranges (35ksi and 45ksi), and 2 material orientations (both longitudinal and transverse plate rolling directions). Results from the 13 high-cycle fatigue tests, along with other fatigue test results from the literature indicate that the surface markings from the automated marking systems have no effect on the fatigue capacity of the A709-Gr50 plate. All marked specimens achieved higher fatigue capacities than would be expected for unmarked specimens meeting the AASHTO fatigue detail category ‘A’ designation.

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Noernberg, M., and Prinz, G.S. (2017). “Automated Pin-Dot Marking Effects on Steel Bridge Component Fatigue Capacity.” *Journal of Constructional Steel Research*, Accepted

1. Introduction

During fabrication of multi-piece steel bridge assemblies, markings are often made on the steel surface to identify/track individual pieces or to provide reference for fabrication layout or later erection. While these markings can be made by various manual methods (crayons, tags, low-stress die stamps, etc.), automated marking methods offer potential fabrication efficiencies by creating rapid computer controlled indentations in the steel surface.

For marked steel sections subjected to frequent or repeated loading (i.e. bridge components) surface indentations from these automated markings have the potential to affect the component fatigue capacity. To account for marking effects, specifications often require additional experimental verification to ensure adequate fatigue performance. For example, in the American Railway Engineering and Maintenance-of-Way Association (AREMA) manual for railway engineering [1], piece marking methods that create an indentation on the steel surface must be demonstrated by testing to meet fatigue category '*B*' in the AASHTO LRFD Bridge Design Specification [2].

In AASHTO, the design load-induced fatigue resistance for detail category '*B*' takes the form:

$$\left(\Delta F\right)_n = \left(\frac{120\times 10^8}{N}\right)^{\frac{1}{3}} \geq 16\,ksi \qquad \text{(Eq. 1)}$$

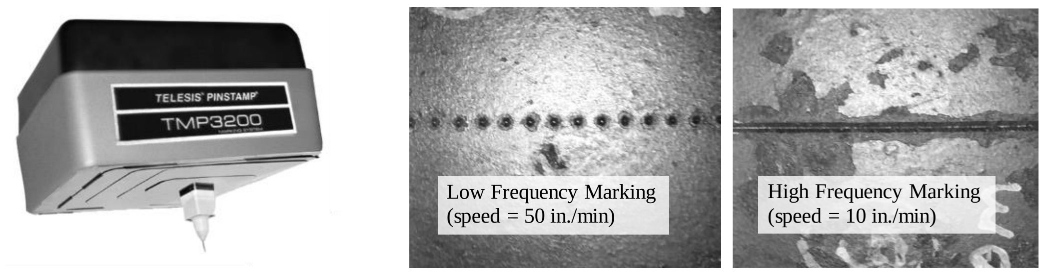
where $(\Delta F)_n$ is the allowable applied stress range and N is the number of cycles to fatigue failure. In order to satisfy compliance as a fatigue category '*B*' detail, fatigue tests must indicate a capacity greater than that provided by Equation 1.

Recent research efforts into the effects of automated piece-marking methods on plate fatigue capacities suggest little difference between marked and unmarked plate sections [3, 4]. In one study by [3] a total of 10 material coupons containing alphanumeric characters were fatigue tested, resulting in only 2 failures (which occurred at fatigue capacities expected for unmarked plate, fatigue detail category '*A*') and 8 runouts ranging from between 2.6 million and 9.3 million cycles. While the results from the marking systems described in [3, 4] indicate negligible fatigue effects for the limited number of samples tested, because certain features of these automated marking systems can change between manufacturer (marking depth, frequency, indenter type, etc.) each marking system must be verified prior to implementation in fatigue prone applications covered by the AREMA guidelines.

This research study investigates the fatigue performance of A709-Gr50 steel (commonly used in steel bridge applications) marked using automated marking methods. To quantify the effects of marking frequency on steel plate fatigue capacity, two levels of marking frequency are investigated. These marking frequencies represent the upper and lower bound capabilities of the Telesis TMP3200/470 marking system; however, existing experimental data from other automated marking systems is also considered for comparison. The study begins with a brief overview of the automated marking system, followed by a description of the specimen fabrication and testing methods. Next, results from the fatigue testing are discussed and conclusions are presented.

2. Automated Marking System Overview

Figure 1(a) shows the marking head of the Telesis TMP3200/470 which was used for this study and Figure 1(b) shows an A709-Gr50 steel plate sample with two marking dot frequencies corresponding to the upper and lower bound dot-frequency capabilities of the system. The automated Telesis TMP3200/470 system uses a single marking pin, which depending on the pin size can create indentation depths of between 0.102 mm (0.004 in.) and 0.457 mm (0.018 in.). In addition to variable marking depth, the pin-dot system can vary marking frequency, up to 200 dots-per-inch, forming seemingly continuous indentation marks in the steel surface (see Figure 1(b)).



(a) (b)

Figure 1. (a) Telesis TMP3200/470 marking head and (b) marked steel surfaces

2.1. Specimen Fabrication and Testing Methods

To investigate the effects of the automated pin-dot marking system on the fatigue capacity of A709-Gr50 steel plate, a total of 13 coupon specimens representing 2 marking frequencies (50in./min and 10in./min), 2 applied stress ranges (35ksi and 45ksi), and 2 material orientations (both longitudinal and transverse plate rolling directions) were fatigue tested. Figure 2(a) shows the coupon specimen geometry, which was chosen to satisfy the ASTM A370-16 specification for mechanical testing of steel products [5]. To ensure consistent pin-dot marking between each specimen, marking lines were scribed in a piece of ½ in. A709-Gr50 steel plate prior to the cutting of each coupon geometry (see Figure 2(b)). As shown in Figure 2(b), a total of 4 lines were scribed in the plate prior to fabrication of the coupon specimens; accounting for both transverse and longitudinal plate rolling directions as well as the highest and lowest pin-dot marking frequencies possible, to bound any marking effects. Table 1 presents the A709-Gr50 material properties, including the mill tested chemical composition.

All specimens were fatigue tested in a Walter+Bai servo-hydraulic bi-axial fatigue testing machine under uni-directional loading, resulting in an applied mean stress equal to half of the applied stress range. To reduce the required testing time, a loading rate of 20Hz was used for each test specimen. Note that the two applied stress ranges of 35ksi and 45ksi were chosen to allow comparison with the finite-life fatigue capacities from the AASHTO '*A*' and '*B*' fatigue detail categories [2].

Table 1. Mill test chemical composition and mechanical properties

	C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Al	Cb
Chemical Composition [% by weight]	0.09	1.30	0.01	0.004	0.0015	0.019	0.01	0.03	0.006	0.05	0.028	0.033

Yield Strength (σ_y) [ksi]	61.7
Ultimate Strength (σ_{ult}) [ksi]	71.6
Elongation [%]	26

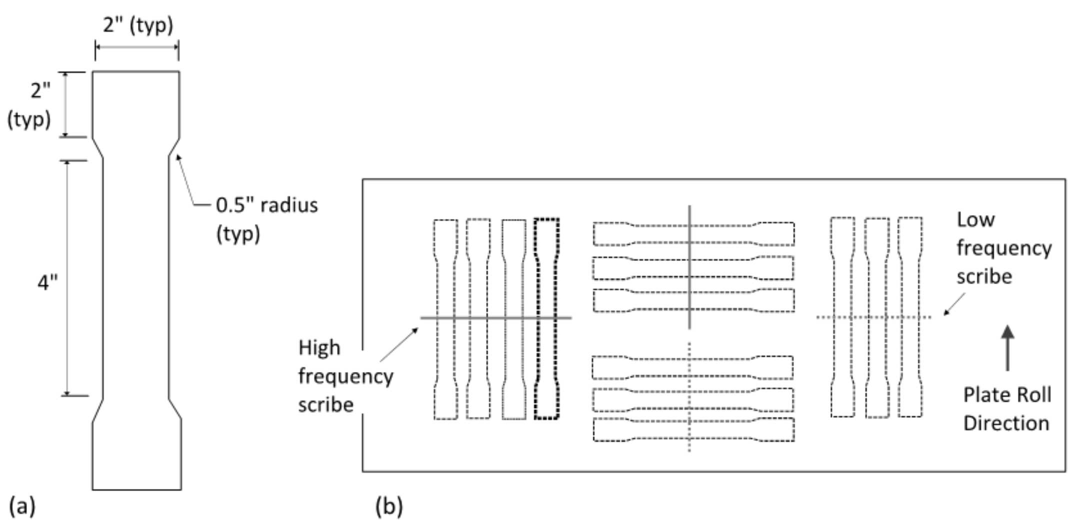


Figure 2. (a) Steel coupon geometry (b) coupon material orientations from rolled A709 plate

Table 2 shows the fatigue test matrix describing specimen material orientation, marking frequency, loading rate, and the resulting fatigue capacity. All fatigue capacities presented in Table 2 will be discussed in detail in the following 'Fatigue Test Results' section.

Table 2. Experimental test matrix

Specimen Number	Pin-dot Marking Frequency	Material Orientation	Applied Stress Range [ksi]	Loading Rate [Hz]	Number of Cycles	Failure (X)/ Runout (O)
1	LF[a]	L[c]	35	20	1,697,702	X
2	LF	L	35	20	4,000,180	O
3	LF	T[d]	35	20	3,500,000	O
4	LF	T	45	20	1,639,460	O
5	LF	L	45	20	516,758	X
6	LF	T	35	20	5,428,137	O
7	HF[b]	L	35	20	3,500,000	O
8	HF	L	45	20	626,000	X
9	HF	T	35	20	2,563,032	O
10	HF	T	45	20	3,086,352	O
11	HF	T	45	20	1,787,587	O
12	HF	L	35	20	11,779,782	O
13	HF	L	35	20	4,780,220	O

a. Low frequency marking speed (50 inches/min)
b. High frequency marking speed (10 inches/min)
c. Specimens fabricated in the longitudinal plate rolling direction
d. Specimens fabricated transverse to the plate rolling direction

2.2. Measured Indentation Depth

To characterize the surface marking depth and allow comparison of fatigue results with other automated marking systems, a modified micrometer was used to measure indentation depth. Measurements taken from the fatigue specimens indicate an average marking depth of 0.168 mm (0.0066 in.) with 0.135 mm (0.0053 in.) and 0.191 mm (0.0075 in.) as the minimum and maximum recorded depths respectively. It is reasonable to assume that fatigue results from plates marked by other automated systems (falling within the marking frequencies tested) will be similar, as long as the automated indentations are of similar depth.

2.3. Effect of Surface Marking on Through-Thickness Material Hardness

Metallographic analyses on a marked specimen cross-section and micro-hardness measurements were used to determine the effect of the surface markings on local material damage. Any effects from local material damage may provide insight into resulting fatigue effects. A cross-section of the indented surface (from Specimen 11 having high-frequency markings) was polished to a surface roughness of 1μm using diamond abrasives and etched with 5% Nitol solution (5ml HNO_3 per 100 ml ethanol) to highlight the steel microstructure features. Following the metallographic preparation, an array of Vickers micro-hardness measurements were taken near the marked surface. Figure 3 shows the resulting Vickers hardness contours on the specimen cross-section. From Figure 3, Vickers hardness values above 200 are localized near the pin-dot marking surface (within ~1mm of the steel surface) surrounding the entire indentation. These hardness values greater than 200 indicate localized compressive residual stresses above yield, which may help offset any deleterious stress concentration effects caused by the surface defect.

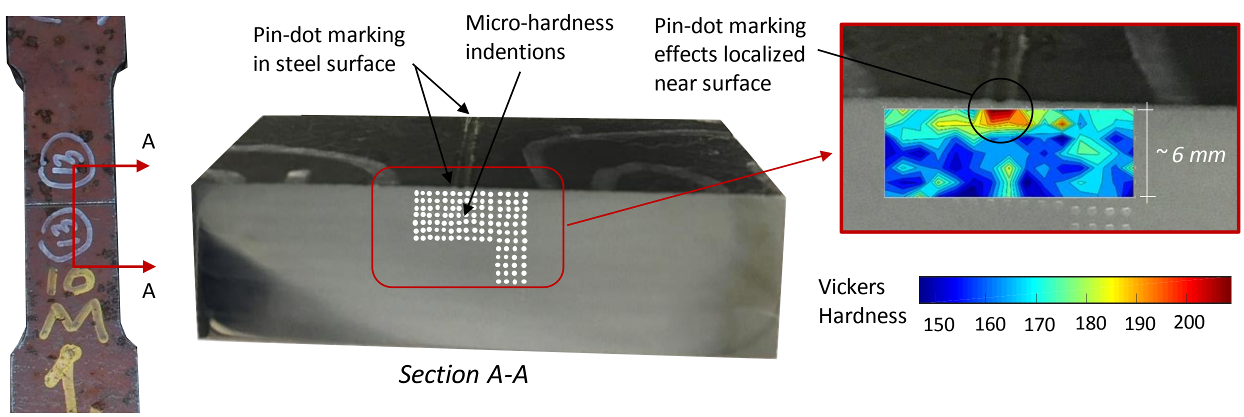


Figure 3. Polished cross-section of indented steel surface and Vickers micro-hardness contours.

3. Fatigue Test Results

All specimens tested indicate a fatigue capacity above that expected for unmarked plates (fatigue detail category '*A*'). Specimen 1 was the only observed fatigue failure at the 35ksi stress range, which occurred at 1,697,702 cycles. For reference, the expected fatigue capacity of an unmarked plate loaded at 35ksi and 45ksi is 583,090 and 274,348 cycles respectively. Fatigue failure of specimens 5 and 8 (loaded at the 45ksi stress range) occurred after 516,758, and 626,000 cycles respectively. Other tested marked steel specimens resulted in runouts with applied cycles ranging from between 1,639,000 cycles and 11,700,000 cycles. These runout test results do not indicate failure, but rather provide a lower bound on the potential fatigue capacity of the specimen. Figure 4 plots the fatigue failure and runout test results along with the results from [3] and the AASHTO '*A*' and '*B*' detail category S-N curves. In Figure 4, all fatigue test results appear above the detail category '*A*' S-N curve, indicating higher fatigue capacity. Marking frequency did not appear to have any effect on fatigue capacity, but it is interesting to note that all fatigue failures occurred in specimens oriented parallel with the plate rolling direction.

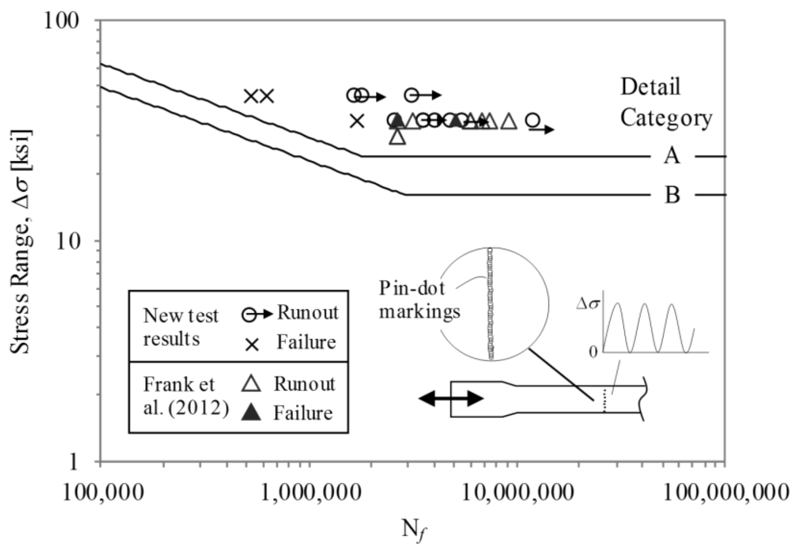


Figure 4. Comparison of test results with fatigue detail category S-N curves

All fatigue failures occurred near the material coupon transition radius, away from the applied markings, indicating that fatigue testing of marked specimens without the radius would likely result in a higher fatigue life than measured in this study. Figure 5 shows the location of fracture initiation for the three fatigue failures of Specimens 1, 5, and 8. Investigation of the specimen fracture surface indicates a fatigue fracture initiation at the specimen corner (near the radius transition), propagating inward until a critical crack length was reached (see again Figure 5). All specimens failed away from the section containing pin-dot markings.

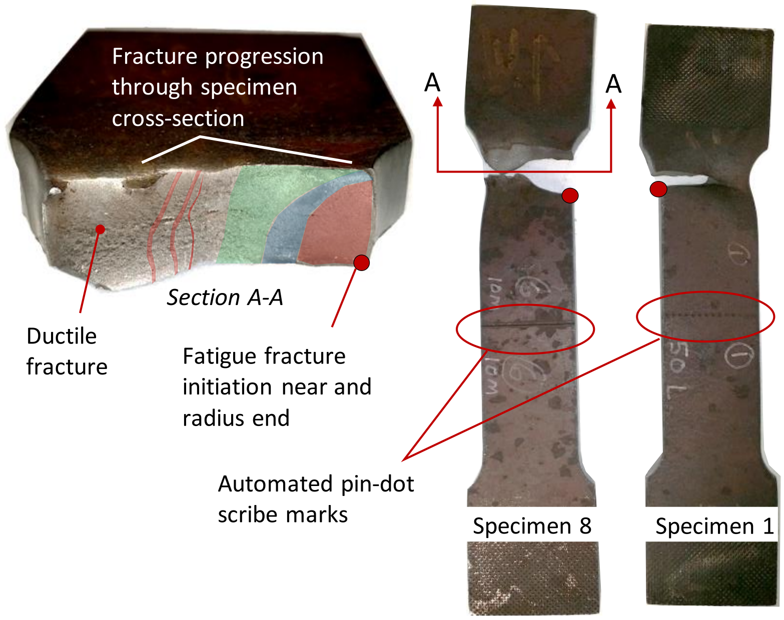


Figure 5. Location of fracture initiation for Specimens 1 and 8 and fractured steel surface.

Table 3 compares the capacity ratios of the tested marked specimens with expected values from the AASHTO fatigue detail categories. Also shown in Table 3 are the fatigue data from [3] for A709-GR50 steel having alphanumeric character markings. From Table 3, the average fatigue capacity (considering measured runout values as the specimen fatigue capacity) from the tested piece-marked specimens was 11 times greater than that expected from an unmarked steel plate (detail category A) subjected to uniaxial fatigue loading. The marked steel specimens (from both the newly tested specimens and those found in the literature) had measured fatigue capacities of 23 times those expected from a 'B' fatigue detail, on average. From Table 3 the smallest ratio between measured and expected capacity was 1.9 for detail category 'A' and 3.9 for detail category 'B'.

Table 3. Comparison between measured and design fatigue capacities

	Specimen Number	Stress range [ksi]	Number of Cycles, N	N/B[a]	N/A[b]
	1	35	1,697,702	6.1	2.9
	2	35	4,000,180	14.3	6.9
	3	35	3,500,000	12.5	6.0
	4	45	1,639,460	12.4	6.0
	5	45	516,758	3.9	1.9
	6	35	5,428,137	19.4	9.3
	7	35	3,500,000	12.5	6.0
	8	45	626,000	4.8	2.3
	9	35	2,563,032	19.5	9.3
	10	45	3,086,352	23.4	11.2
	11	45	1,787,587	13.6	6.5
	12	35	11,779,782	42.1	20.2
	13	35	4,780,220	17.1	8.2
Measured values from Frank et al [3]	A1[3]	30	2,700,241	6.1	2.9
	A2	35	2,672,452	9.5	4.6
	A3	35	6,000,028	21.4	10.3
	A4	35	7,513,600	26.8	12.9
	A5	35	9,241,204	33.0	15.8
	N1	30	2,674,040	6.0	2.9
	N2	35	3,181,753	11.4	5.5
	N3	35	6,009,136	21.5	10.3
	N4	35	5,079,358	18.1	8.7
	N5	35	6,826,604	24.4	11.7

a. Ratio of cycles tested to cycle capacity values for AASHTO detail Category B

b. Ratio of cycles tested to cycle capacity values for AASHTO detail Category A

4. Conclusions on Pin-Dot Marking Fatigue Effects

In this study, the effects of automated pin-dot markings on the fatigue capacity of A709-Gr50 steel plate were investigated by fatigue testing a total of 13 marked coupon specimens. These specimens represent 2 marking frequencies (corresponding to marking speeds of 50in./min and 10in./min), 2 applied stress ranges (35ksi and 45ksi), and 2 material orientations (both longitudinal and transverse plate rolling directions). Results from the 13 fatigue tests, along with other fatigue test results from the literature indicate that the surface markings from the automated impact marking systems have no effect on the fatigue capacity of A709-Gr50 plate. All marked specimens tested achieved higher fatigue capacities than would be expected for unmarked specimens meeting the AASHTO fatigue detail category '*A'* designation.

5. References

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[5] ASTM (2016). "Standard Test Methods and Definitions for Mechanical Testing of Steel Products, "A370-16 (West Conshohicken, Pa)