Strategies for Improving the Fatigue Resistance of Thermite Weldments

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ABSTRACT

The results of two parallel studies are reported both of which have the goal of improving the fatigue resistance of thermite welds. One study concentrates on the nature and distribution of shrinkage porosity in thermite welds using a radiographic technique. The second study concentrates on ways to improve the external geometry of thermite welds with special attention given to eliminating cold lap defects and improving the local geometry of thermite weld toe. The results to date suggest that the fatigue resistance of thermite welds failing from the base and web can be increased by improving the external weld geometry and the shape of the weld toe. Both studies suggest that better control of the thermal conditions during solidification is needed.

INTRODUCTION - SERVICE PROBLEMS WITH FIELD-WELDED RAIL JOINTS

Field-welded rail-joints are a frequent source of rail flaws in the North America (NA) railroad infrastructure; as such, they have a major impact on rail service reliability and a potential impact on safety. The increasingly heavy axle-loads characteristic of current and future North American railroad freight operation will only make this problem worse. Recent studies have suggested that defective field welds are currently a major problem for most railways. For example, a Class I railroad reports 14 service failures (broken rails) per day of which 40% are due to thermite welds, 40% are due to transverse defects under shell and 20% are listed as other. Broken field welds are reported as causing 10% of all derailments [1]. Thus, a practical and economic means of improving the fatigue-resistance of field welds is needed. To that end, the studies reported here are developing strategies for improving the fatigue resistance of thermite rail welds.

FIGURE 1 shows a transverse cross-section of a thermite weld in a railroad rail. Fatigue cracks frequently begin in the railhead at internal defects and in the rail web and base at external discontinuities associated with the weld toes. Rail head fatigue defects are much more frequent than rail fatigue failures originating at the web and base locations, but rail head fatigue cracks generally do not lead to service failures because they usually are found by NDE and removed before they can grow to critical size. For example, another Class I railroad reports that “mark-outs” (that is, detected and removed rail-head flaws) exceed actual broken rails (service failures) by a 2 to 1 ratio. In contrast, most service failures are caused by web and base external defects because fatigue cracks in these locations are more difficult to detect, and probably because triggering failure in this location requires less thermal stress since the imposed tensile flexural stresses are more than sufficient to cause fracture. Thus, most broken field welds (service failures) initiate at fatigue cracks in either the rail web or rail base locations.

Because of this situation, the fatigue behavior of thermite welds can be decomposed into two separate problems: fatigue crack initiation in the head at internal defects (notably shrinkage porosity) and fatigue crack initiation in the web and base at near-surface or external weld defects (notably cold laps). This paper will describe two ongoing research projects that deal with each of these separable fatigue problems in thermite welds.

IMPROVING THE FATIGUE PERFORMANCE OF THE BASE AND WEB OF THE THERMITE RAIL WELD

Prevalence of Rail Web and Base Service Failures

Analysis of 244 thermite weld service failures (events which cause broken rails) occurring over the last four years on the mentioned Class I railroad indicated that most field welds that failed were thermite welds and not flash-butt welds and that most service failures originated in the base and web of the rail as shown in FIG. 2.

Nature of Rail Web and Base Weld Flaws

As shown in FIG. 3, the weld defect most frequently causing fatigue crack initiation in the 244 weldment service failures was the “fin” or “cold lap.” This weld-toe welding-defect occurs most frequently in the web-to-base fillet because the thermite welding mold often does not conform exactly to the rail profile. The resulting gap between the mold and the rail permits weld metal to seep into the gap and solidify forming unfused regions often called “fins” or what will be termed here “cold laps”: see FIG. 4.

In a study by Dimitrakis [2], cold laps were found to reduce the fatigue life of fusion of weldments by greatly accelerating the formation and early growth of fatigue cracks. FIGURE 5 shows an idealization of a cold lap at a weld toe and indicates the important variables controlling its severity: weld toe flank angle (θ), cold lap depth (D) and cold lap root-radius (r). TABLE 1 below compares the predicted fatigue life for several choices of weld toe flank angle and cold lap depth. Cold lap root radius was not considered because it cannot be controlled and is generally very small. The initial length of fatigue crack was assumed to be quite small (0.002 of the plate thickness or 0.25mm for a 25mm thickness plate). The influence of the cold lap on crack growth depends very much on the distance of the crack tip away from the stress-concentrating apex of the cold lap. As seen in TABLE 1 even a very small cold lap much reduces the fatigue life. A 1mm cold lap reduces the fatigue life by 20%. Doubling the cold lap depth from 1 mm to 2mmm has little further effect. The effect of flank angle is also non-linear. Increasing the flank angle from 30˚ to 45˚ reduces the fatigue life by a factor of 2. A further increase of the flank angle to 60˚ further reduces the fatigue life but not by an additional factor of 2.

Clearly, in the absence of other, equally-severe weld-flaws; the fatigue life of a weldment could be much improved by the elimination of weld toe cold lap defects. If a weld toe cold lap were present, reducing the weld toe flank angle to as low a value as possible would appear to be somewhat beneficial.

Strategies for Reducing Thermite Weld-toe Fatigue Severity

Even in the absence of cold laps, most weld toes are serious, fatigue-crack-initiating stress concentrations. Using models developed by the authors for other fusion welded butt joints, the fatigue severity (fatigue notch factor, that is, K_f) of a thermite rail weld toe (FIG. 6) can be modeled by the expression:

$$\text{FatigueSeverity} = \left(1 + 0.27\tan\theta^{0.25}\sqrt{\frac{t}{r}}\right)\left(1 + 0.1054 S_u \sqrt{R}\right) - 1$$

Where:

t = Web or base thickness.

θ = Weld flank angle.

r = Weld toe radius.

R = Depth of the surface roughness of the weld toe notch root.

S_u = Tensile strength of the notch-root material.

Thus, reducing the flank angle, increasing the weld toe root radius, and/or decreasing the surface roughness of the web and base thermite weld toes should increase their fatigue resistance. This model suggests that fatigue resistance of thermite rail welds could be improved by:

- Eliminating cold lap defects.
- Reducing the flank angle (θ) to as low a value as possible.
- Increasing the weld toe radius (r) to as large a value as possible.
- Avoiding pores or other casting defects in the critical location (at the weld toe) and generally increasing the perfection of the as-cast surface there, that is, reducing the value of (R).

Current Studies

The Transportation Research Boards High Speed Rail IDEA program is sponsoring work in our laboratory to increase the fatigue performance of thermite welds by improving their external geometry in the web and base areas. FIGURE 4 shows the nature of the weld toe of a nominal thermite weld in the web-to-base fillet location. Note that the flank angle (θ) is roughly 90˚ (!), and note the presence of a cold lap. FIGURE 7 below shows the result of filling the mold to rail gap with a small amount of refractory paste sealant. This measure eliminates the cold lap defect, increases the weld toe radius and appears to provide a smooth, as-cast surface at the weld toe, the site of highest stress concentration and the expected site of fatigue crack initiation and early growth. Slightly increasing the initial gap between the rail ends from 25mm to 35mm insures that sufficient melt-back occurs to fuse beyond the weld toe defined by the 40mm weld bead width of the mold, particularly in the critical base-to-web fillet region. Other measures being investigated are reducing or eliminating the flank angle in the base-to-web fillet location by altering the profile of the thermite weld mold in this critical zone.

The results to date are sketchy but promising. FIGURE 8 shows the four-point bend (R = 0) fatigue test results to date. All of the common thermite welding processes (labeled Process A, B , C and D) seem to give about the same fatigue resistance. One or two of the welds modified in this study failed at very short lives because of gross defects in the base caused by foreign substances, presumably material added to seal or modify the molds. We now insure the cleanliness of the setup by blowing out any debris at the base of the rail with compressed air just prior to welding. Several of the welds modified as described above have given considerably longer fatigue lives that normal thermite welds: see FIG 8.

IMPROVING THE FATIGUE PERFORMANCE OF THE HEAD OF THE THERMITE RAIL WELD

Past Studies

Our studies of the causes of fatigue crack initiation in the rail heads of thermite welds were begun with the study of Oderio [3] in which it was observed that detail fractures in tangent track had their origins in interdendritic shrinkage porosity: see FIG. 9. Thus, the amount and size of shrinkage pores in the head of thermite rail welds was believed to be the principal cause of fatigue crack initiation in the heads of thermite rail welds. Analytical studies by Fry [4] showed that the critical situation is a pore about 2mm below the running surface in the region where the residual stresses in the head become slightly tensile. Fry's study suggested that pores were far more serious than rigid inclusions and that the initial direction of crack growth for the pores, that is, the formation of a shell or a detail fracture might be related to the shape of the critical pore. A study by Withee [5] showed that for the same stress state, the largest pore is the more critical: see FIG. 10. Thus, the prior promising results obtained by "squeeze welding" (and/or vibrating) thermite welds[1] maybe best explained by the near elimination of weld metal in "squeezed welds." The near expulsion of weld metal greatly reduces the likelihood of a large pore existing in the welded rail head; however, the measured *distribution* of pore sizes in the small amount of weld metal remaining in the head of the squeezed rail weld was *not* affected.

Current Studies

Recently, we have developed a radiographic technique similar to that of Utrata [6] had have used it to measure the volume fraction and distribution of (shrinkage) micro porosity in thermite weld metal. The integrated effect of shrinkage pores (far too small to be imaged individually) is to increase the radiograph density in proportion to the volume fraction of pores existing in a given location. We section the welds in the plane of the web: see FIG. 1. The slabs of metal are then machined to the approximate dimensions: rail height x web thickness x 200 mm along the rail. The flat surfaces are machined and surface ground to reduce the web thickness dimension to 12mm. We devised a step penetramter that allows the technique to be calibrated to the nearest 0.25% porosity. Base metal contiguous to the weld is used as an internal standard for zero

[1] Thermite welds in which the rails being welded are forced together while the weld metal is still liquid.

porosity. The advantage of this technique is that it averages the porosity over the volume of the material radiographed and permits the porosity distribution in the entire weld metal section to be viewed. We have made these observations to date:

- There is a considerable variation in porosity from weld to weld. FIGURE 11 shows the porosity measured using the mentioned radiographic technique. The measured porosity in 10 thermite weldments varies from 0.4% to 1.3%.
- Fatigue cracks originating in the head have been observed to be associated with regions of high shrinkage porosity density – clusters of micro porosity.
- The density of porosity is not uniformly distributed. Greater concentrations are observed near the line of fusion where the rate of solidification is greater. Very high linear concentrations of shrinkage porosity and associated cracks and voids have been observed at the weld centerline. These defective areas may extend from the base to the web of the weld.
- Spherical gas porosity is infrequently observed.

DISCUSSION

Variability of Thermal Conditions

If one asks what conditions cause the critical defects citied in FIG. 3 one can identify the following possibilities:

- Unfavorable conditions for solidification (thermal conditions).
- Foreign matter (sand).
- Improper mold adjustment (e.g. cold laps).

TABLE 2 below lists the defects cited in FIG. 3 and assigns possible causes. One notes that thermal conditions would seem to play a role in most of the common fatigue-causing defects in both the rail head and rail base. The variables influencing thermal conditions include:

- Initial rail temperature and ambient air temperature: These temperatures would influence the outcome of preheating the rail and the rate heat extraction from the weld metal both while in the crucible and while solidifying in the mold.
- Preheat in conditions: Nature of the preheat flame, the duration of the preheat and the torch adjustment influence the heat imparted to the rail ends and the distribution of preheat temperatures along the height of the rail.
- Heat input: Tapping time, size of the thermite charge, volume of weld metal in the mold, that is, the size of the gap between the rail ends.

The chief defects causing fatigue failure in the base and web of the rail (cold laps) and the head of the rail weld (shrinkage porosity) would seem to depend partly or even wholly on the patterns and rates of solidification, that is, upon the thermal conditions during solidification. This idea is reinforced by the following observations.

We measured the width of the weld metal evident in radiographs of thermite welds in the location of the base-to-web fillet in 12 weldments, and the results are plotted in the histogram of FIG. 12. Two of these weldments had been welded in our laboratory (using a shorter than normal and longer than normal preheat), but the remainder were “mark-outs” donated by two Class I railroads. Prior to welding, the gap between the rail ends is generally 25mm. The width of the weld “collar” is determined by the mold and for the welds studied here was 40mm. Weld widths less than 40mm imply that the rails did not melt back to include the weld toe and that the weld metal would have to run around the ends of the rails to fill the mold and form the weld toe: this condition would (in our opinion) favor the formation of cold laps at the weld toe. Weld widths greater than 40mm would imply that the fused region included the weld toe and a distance beyond that. As seen in FIG. 12, about 25% of the welds studied did not have a weld width (at the weld center line) greater than 40mm.

FIGURE 13 shows half-profiles of the weld metal the 12 weldments studied. TABLE 3 lists the average weld widths, the standard deviations and the coefficient of variation (COV – mean divided by the standard deviation) at several distances from the rail base. It is interesting that:

- There is considerable variation in the weld widths at each elevation in the welds.
- The least variation in weld width at the rail base occurs at the rail base.
- Except for the rail base, the COV of the weld with is quite large, (20%).

We attribute this variation in weld width to a considerable (perhaps intolerable) variation of thermal conditions during solidification in 12 weldments studied here. If this is indeed a general problem, it is possible that improper thermal conditions are a major contributing factor in the formation of serious weld external defects such as cold laps in both the base and web of the rail and internal defects such as high concentrations of shrinkage porosity in the rail head.

CONCLUSIONS

- Most service failures caused by thermite weldments originate in the base of the rail. Elimination of cold lap weld-toe defects and subsequent improvements in the shape and perfection of the weld toes in the base and base-to-web fillet areas appears to improve the fatigue resistance of the thermite weld.

- While there are many more fatigue cracks detected in heads of thermite welds, they are usually removed before service failures occur and consequently cause fewer broken rails than fatigue cracks that initiate in the base of the thermite weld. Reducing the amount and size of shrinkage porosity is believed to be the best means of improving the fatigue resistance of the head of the thermite weld.
- Large variations in weld shapes and the implied thermal conditions during welding were observed for the 12-thermite welds studied using radiography. Improper thermal conditions are believed to contribute to the development of critical weld defects in both the base and head of thermite welds.

ACKNOWLEDGEMENTS

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TABLE AND FIGURE CAPTIONS

TABLE 1 -- *Effect of cold-lap depth and weld toe flank angle on fatigue crack growth in an axially loaded butt weldment.*

TABLE 2 -- *Common fatigue-causing weld defects and their probable causes.*

TABLE 3 -- *Variation in weld-metal width as a function of distance from the base of the rail measured in radiographs of near centerline sections of 12 thermite rail welds.*

FIG. 1 -- *Cross-section of thermite weld in a railroad rail. Fatigue cracks frequently begin in the railhead at internal defects and in the rail web and base at external discontinuities associated with the weld toes. The cross-section of the slab of metal machined for the*

radiographic studies is also shown here. The direction of the X-rays would be horizontal in this figure.

FIG. 2 -- *Analysis of 244-thermite service weld failures. Base and web-to-base fillet are the most frequent failure locations.*

FIG. 3 -- *Analysis of 244 thermite service weld failures and the frequency of certain fatigue initiating weld defects. Cold laps are the most frequent defect causing fatigue failure.*

FIG. 4 -- *Weld toe at base-to-web fillet of a normal thermite weld. Left: lower magnification macro-photograph. Right: higher magnification view showing apex of cold lap*

FIG. 5 -- *Two-dimensional model of a weld-toe cold-lap. The weld-toe flank-angle (θ), the cold-lap depth (D), the cold-lap root-radius (r) and the azimuth angle around the cold-lap root-radius (ϕ) are indicated.*

FIG. 6 – *Idealization of thermite weld toe geometry*.

FIG. 7 -- *Weld toe at web-to-toe fillet of modified thermite weld. Left: lower magnification macro-photograph. White material is fused sealant. Right: higher magnification view showing a reduced flank angle and a reasonably smooth surface at the weld toe.*

FIG. 8 -- *Four-point bending fatigue testing results (R = 0). Processes A, B, C and D are the standard Orgo-thermit, Railtech, and Stanley thermite welds. The "modified" welds are the results for experimental thermite welds described in text. The arrow indicates a run-out specimen. The power curve fitted to the data for Process A exhibits the expected –1/3 slope characteristic of fatigue crack growth.*

FIG. 9 -- *Interdendritic shrinkage porosity [3] in the railhead of tangent track thermite weldment.*

FIG. 10 -- *Porosity measured using the radiographic technique developed in 10 thermite weldments.*

FIG. 11 -- *Effect of pore size on fatigue resistance of laboratory smooth specimens of thermite weld metal [5] from normal thermite welds and from thermite welds squeezed or vibrated during the solidification of the weld metal. The fatigue life is independent of treatment and solely a function of the size of the largest pore.*

FIG. 12 -- *Measured weld widths in the web-to-base fillet of 12 thermite welds.*

FIG. 13 -- *Scale drawings of half profiles of weld metal evident in 10 radiographs of the weld sections described in text. The dashed line is the weld centerline. The light area represents weld metal. The bottom of each image is the base of the rail. The top of the image is the running surface.*

TABLES

TABLE 1 -- *Effect of cold-lap depth and weld toe flank angle on fatigue crack growth in an axially loaded butt weldment.*

Condition	Percentage of Fatigue Life
Flank angle (θ) = 30˚	**100%**
Flank angle (θ) = 45˚	56%
Flank angle (θ) = 60˚	44%
Cold lap depth (D) = 0	**100%**
Cold lap depth (D) = 1mm	20%
Cold lap depth (D) = 2mm	15%

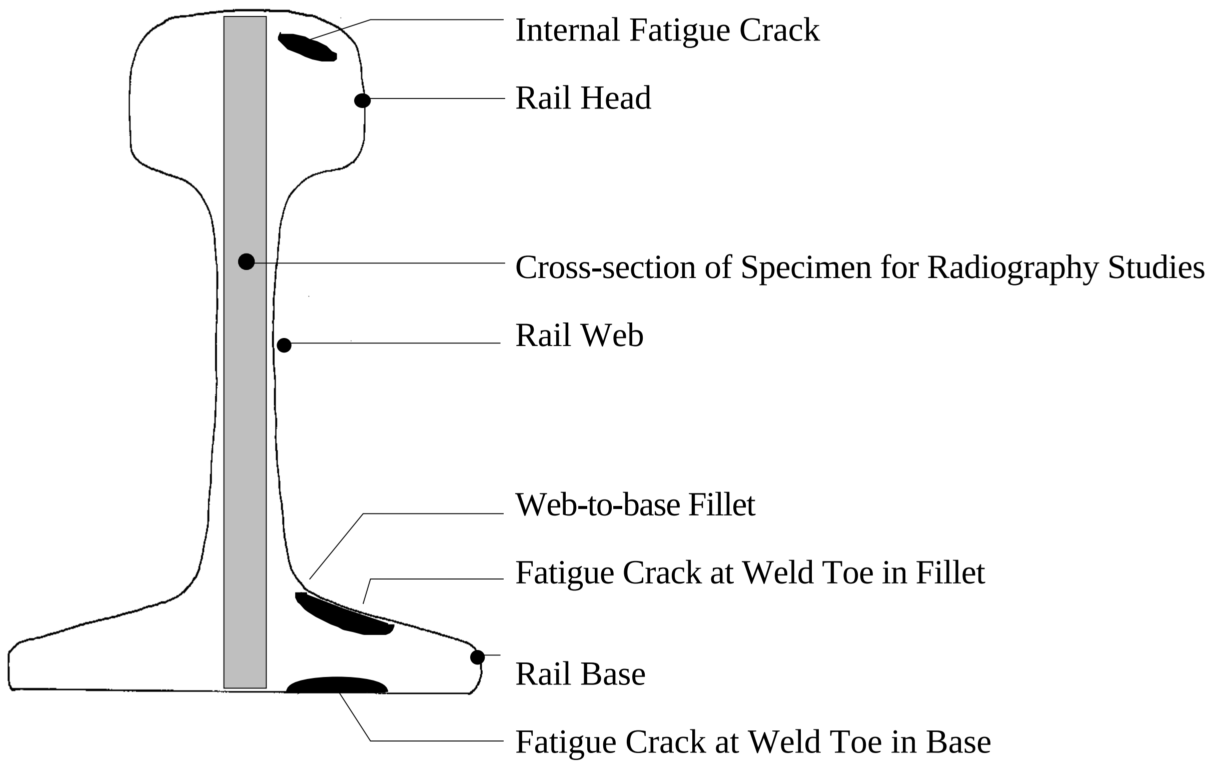
TABLE 2 -- *Common fatigue-causing weld defects and their probable causes.*

Defect	Percentage of service failures	Wholly or partly caused by:		
		Solidification thermal conditions?	Foreign substance?	Mold adjustment?
Cold lap	32.8	✓		✓
Slag	20.5	✓	✓	
Porosity	15.6	✓		
Hot tear	12.3	✓		✓
Columnar grains in head	4.1	✓		
Lack of fusion	3.7	✓		
Hot pull-apart	3.7	✓		
Grindburn	2.5			
Sand burn in	2.0		✓	
Inclusions in head	0.8	✓	✓	

TABLE 3 -- *Variation in weld-metal width as a function of distance from the base of the rail measured in radiographs of near centerline sections of 12 thermite rail welds.*

Distance above base of rail (mm)	Average width of weld metal (mm)	Standard deviation (mm)	COV (%)
0	53.6	6.6	12%
12.7	46.4	9.4	20%
25.4	44.5	9.7	22%
31.7	44.7	10.0	22%
88.9	44.5	8.7	20%
139.7	45.1	8.9	20%
158.8	50.8	14.5	28%
184.1	66.0	14.3	22%

FIGURES



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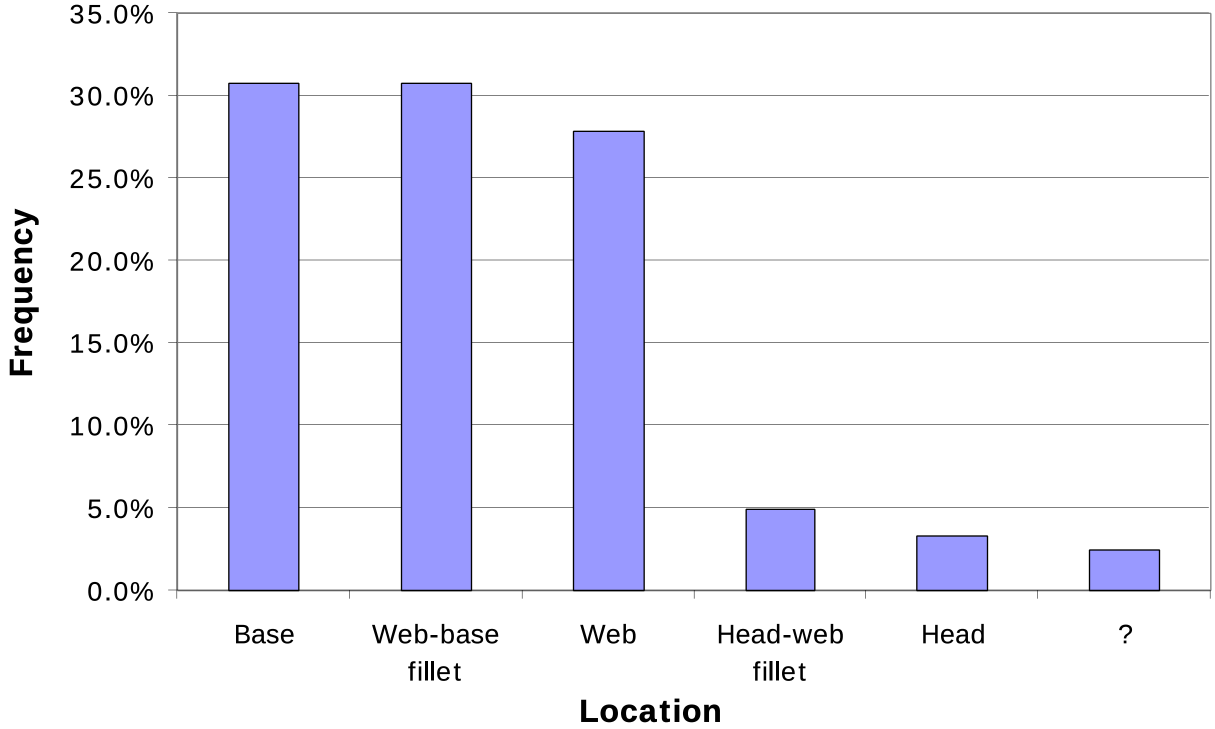

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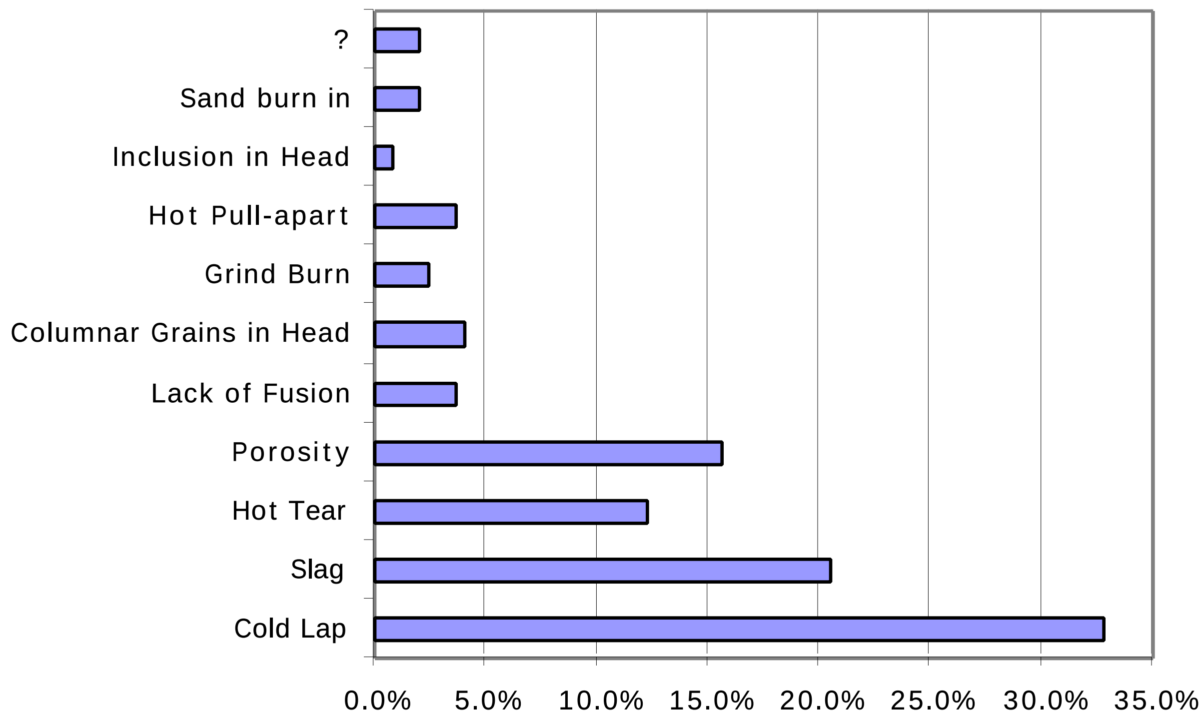

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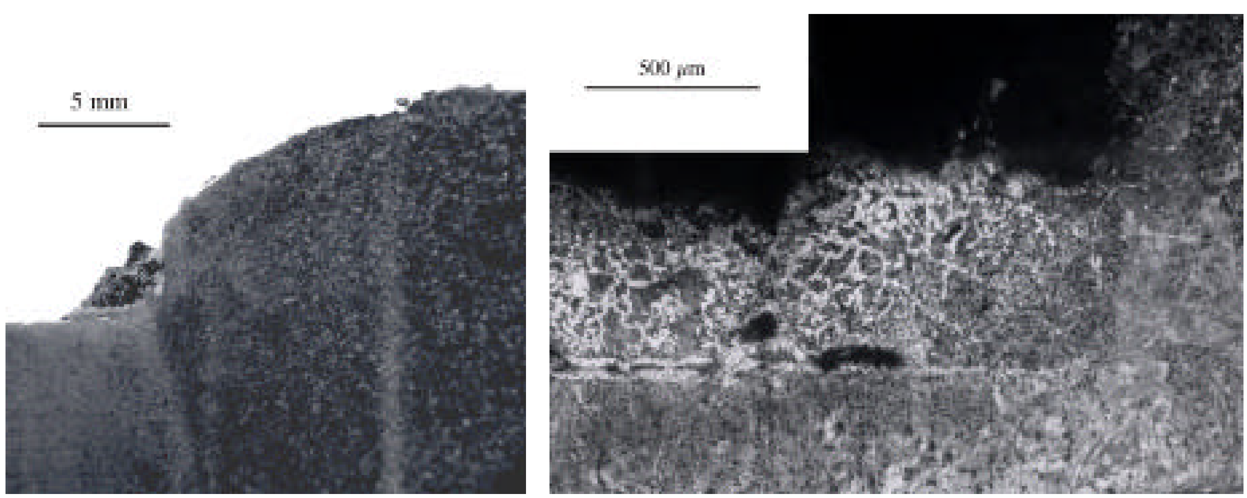

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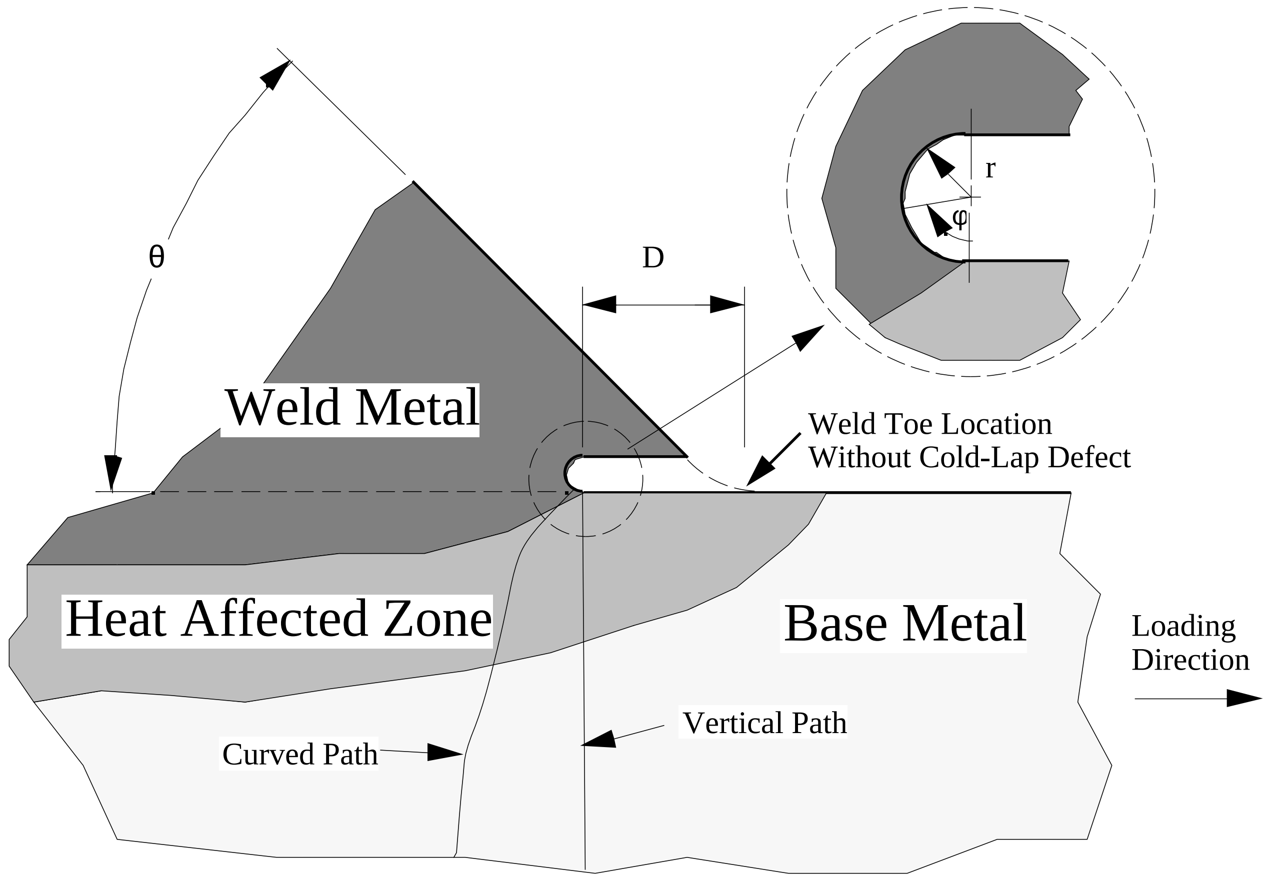

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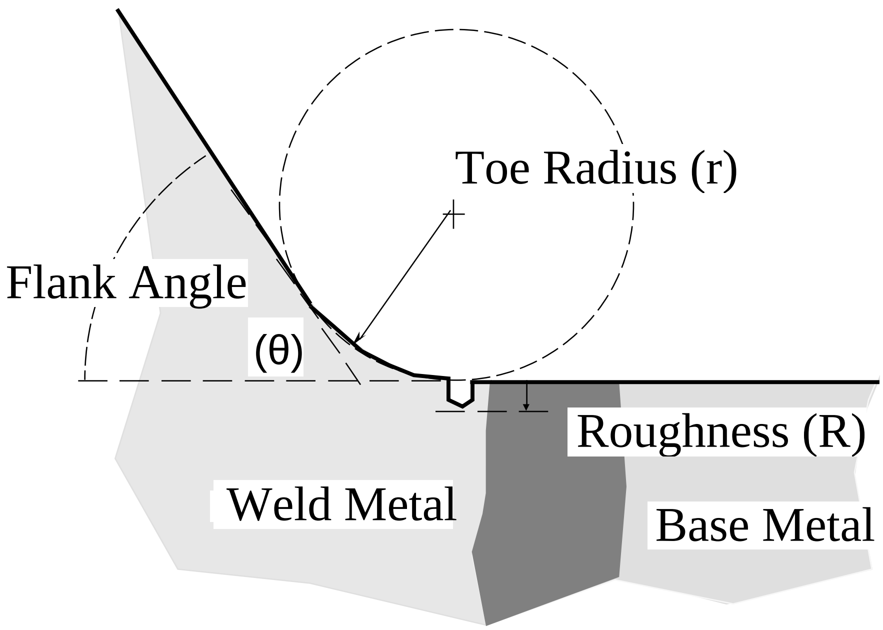

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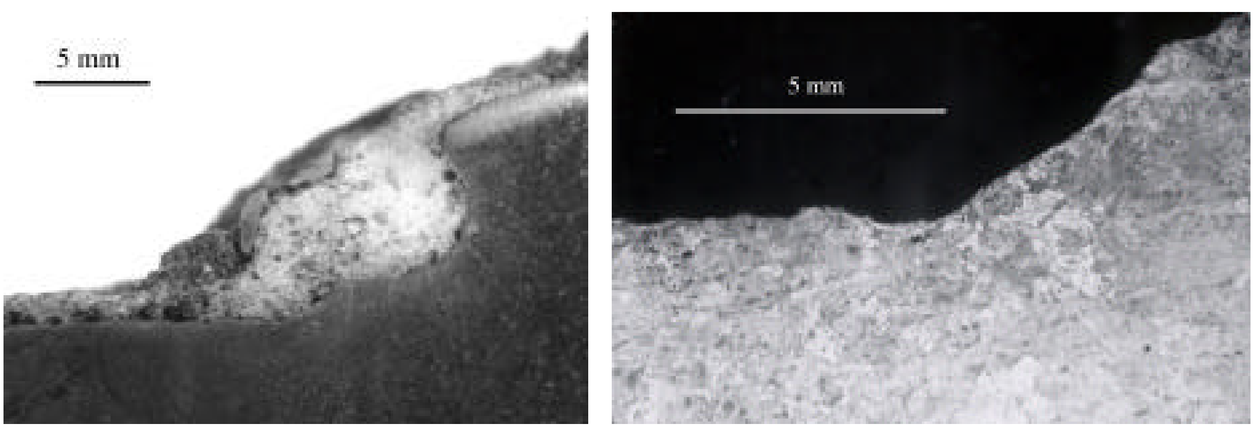

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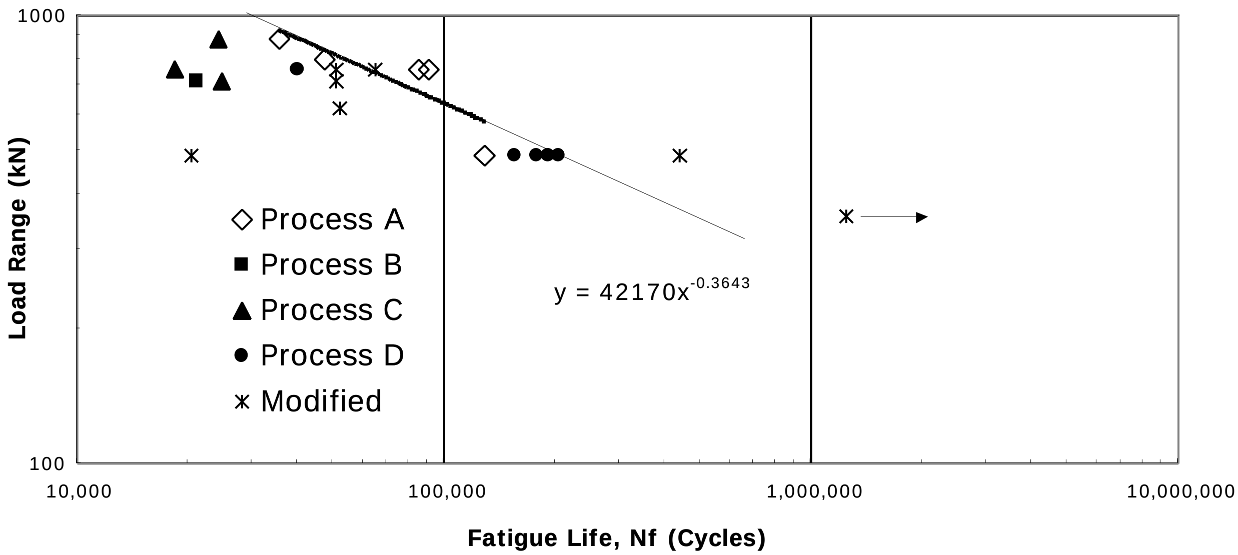

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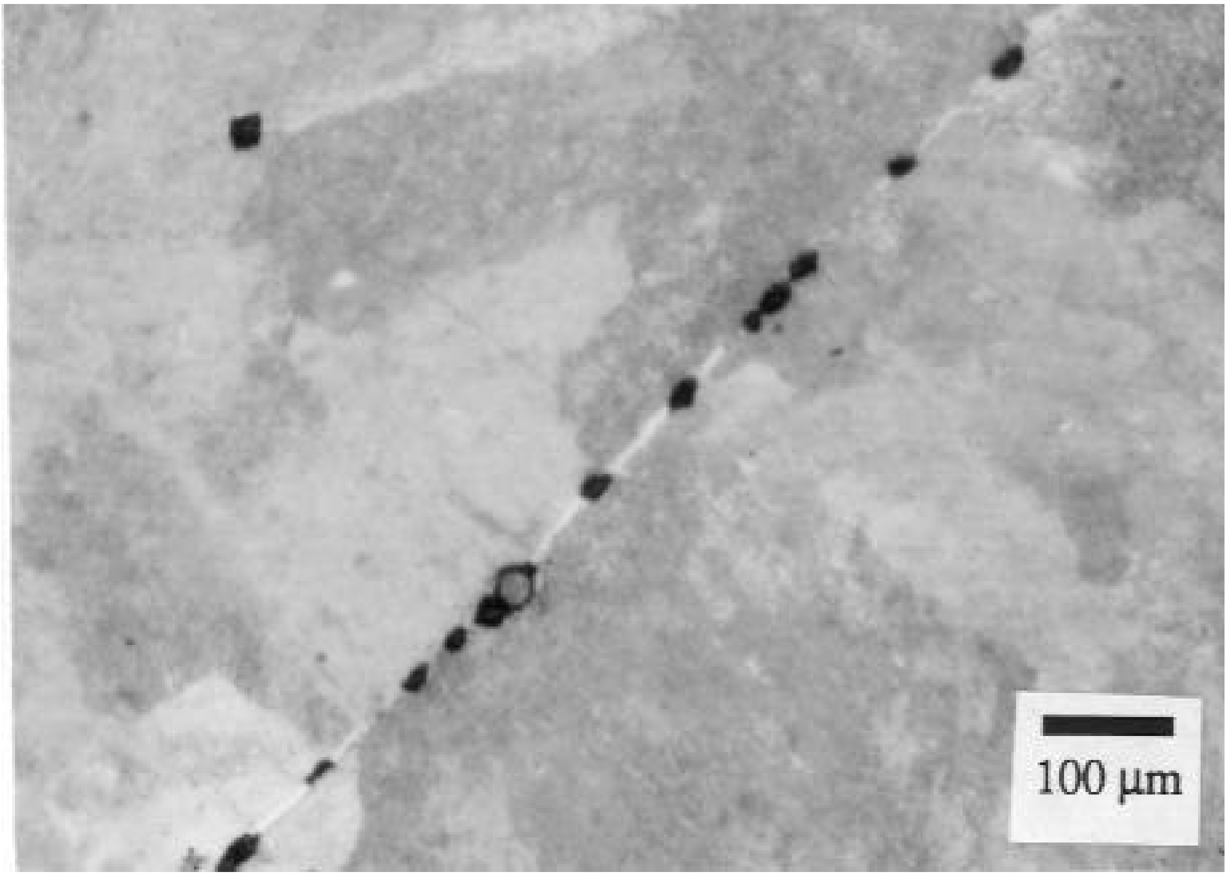

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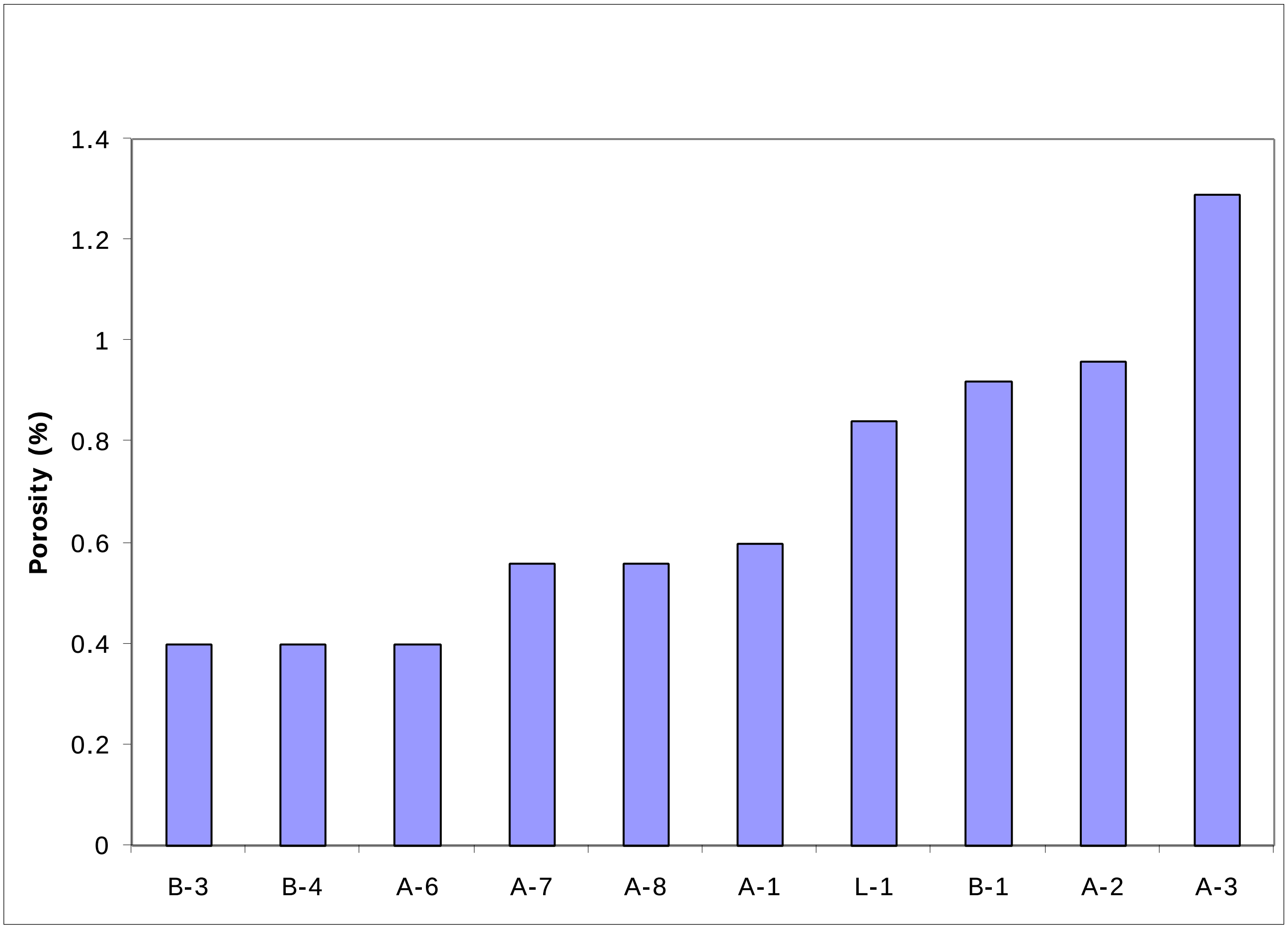

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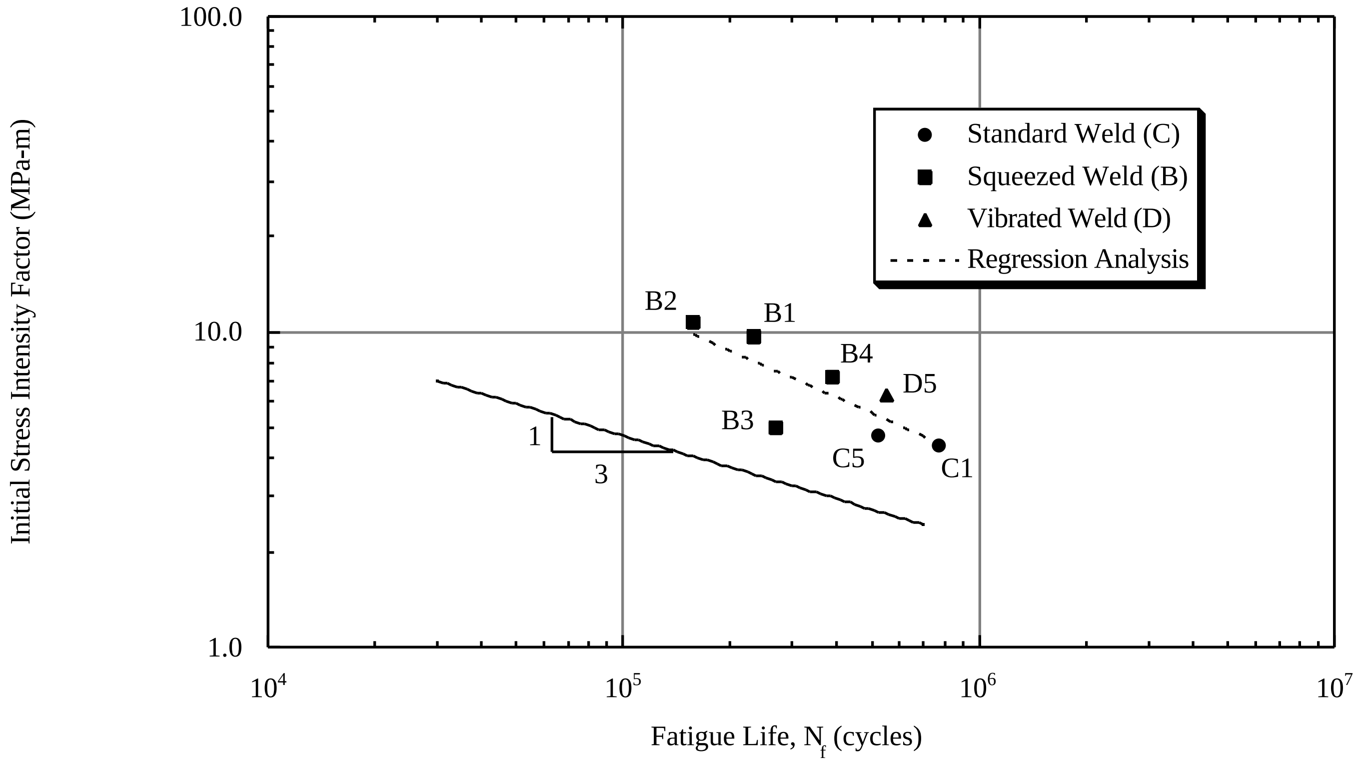

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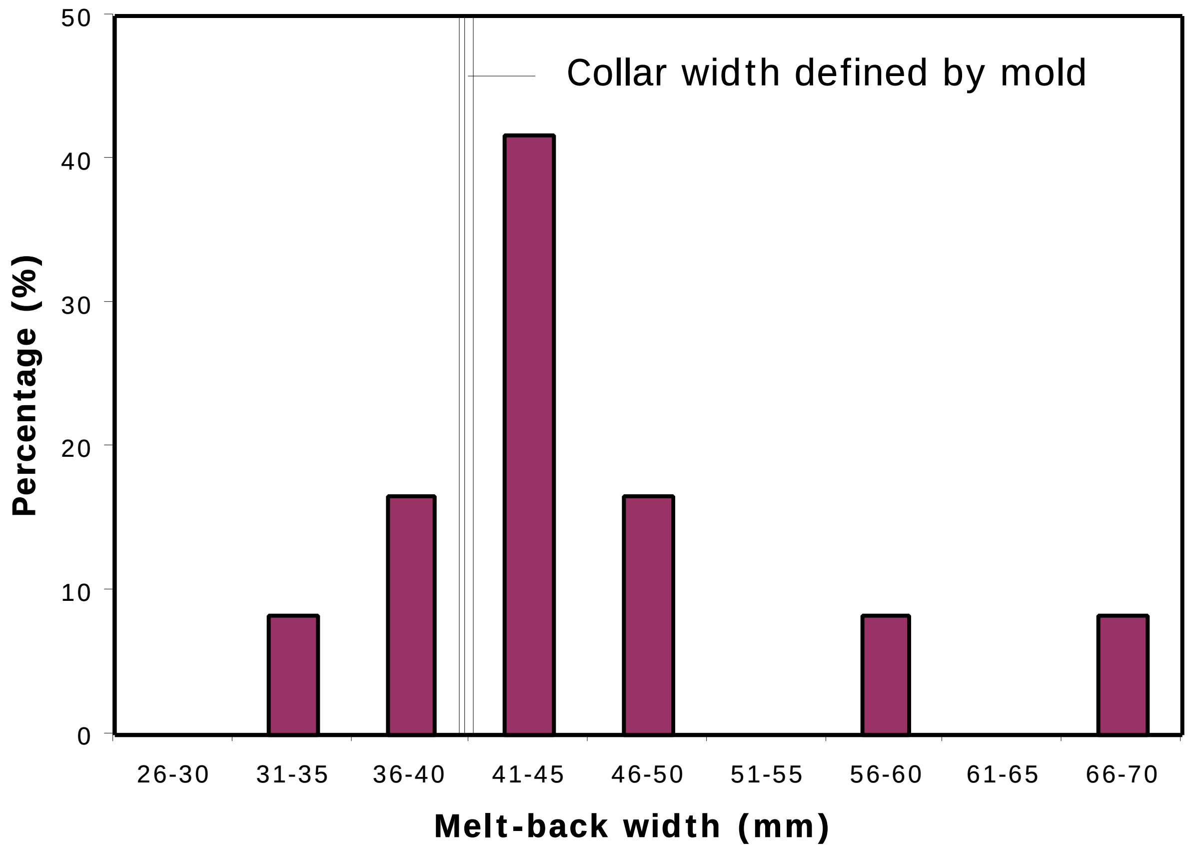

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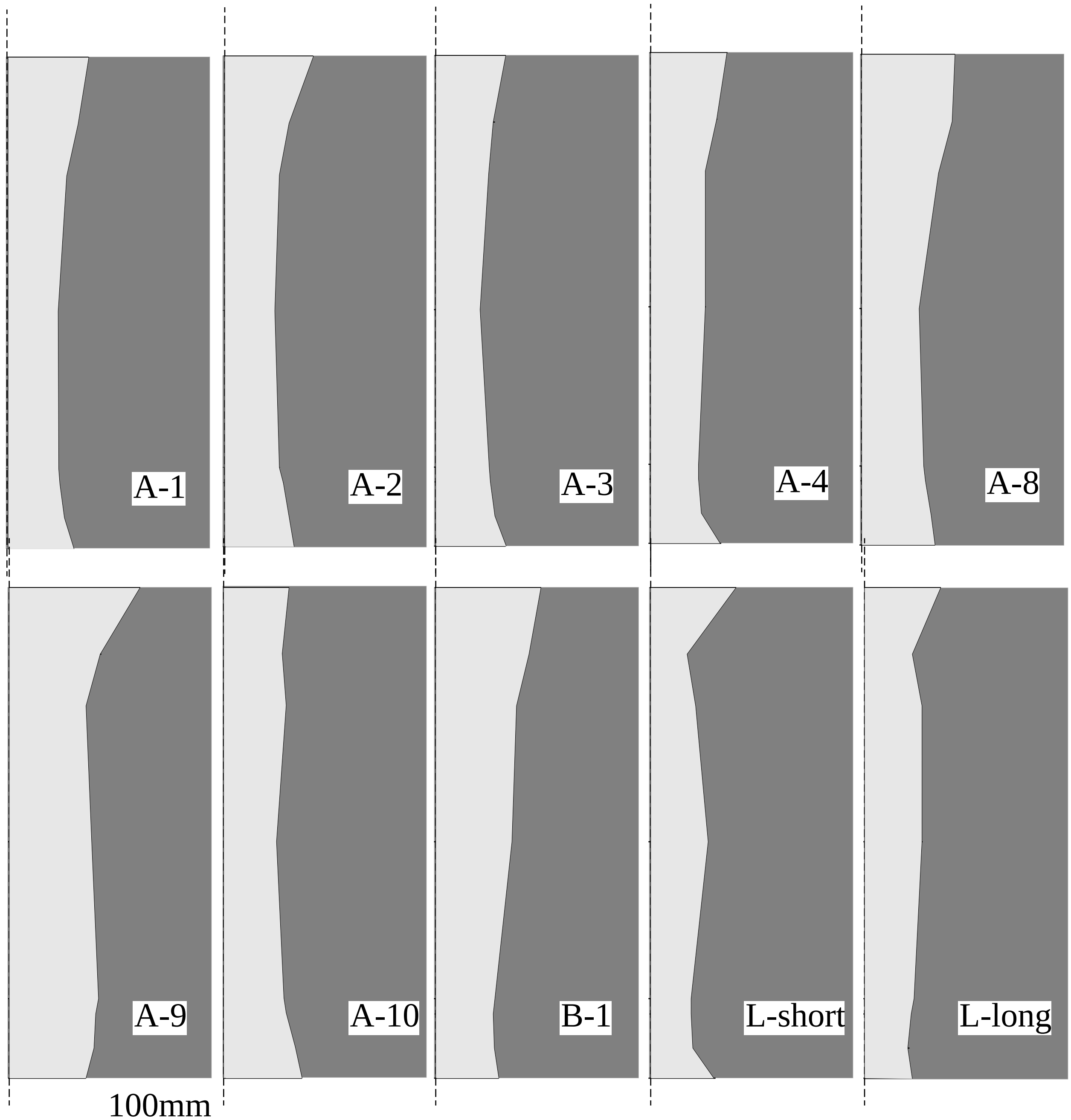

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