

Hardness Testing of Thermal Cut Edges of Steel

ALEXANDER D. WILSON

ABSTRACT

Recent concerns for the quality of thermal cut edges (TCE) of steels used in bridge construction led to a research program funded by the American Iron and Steel Institute. The results of this program are reviewed. The program found that the hardness of the TCE was the most important variable influencing the quality of a TCE as measured by a bend test. Plate chemistry (carbon content), Charpy V-notch toughness, thermal cutting speed and plate temperature were also found important. A suggested technique for minimizing the variability in testing for TCE hardness, which utilizes localized grinding of the TCE location to be tested, is presented.

INTRODUCTION

Thermal cutting is a procedure that has been used in the manufacture and fabrication of steel for decades. The terminology *thermal cutting* covers oxygen fuel cutting, plasma cutting and other thermal processes that are used to cut steel products. Thermal cutting is particularly important in the production of plate steels where it is commonly used for the trimming of as-rolled plate to the required rectangular dimensions and for the stripping of plates to produce flanges and webs for bridge girders.

Alexander D. Wilson is with Lukens Steel Company, Coatesville, PA.

There has been recent concern for the quality of the edges of plates that have been thermally cut and used in bridge construction. The concern for bridge applications is due to the thermal cut edge remaining in service without any other attention. For example, the edges of flanges of a plate I-girder or a box section will remain in service in the as-cut condition. In reaction to this concern, the American Iron and Steel Institute (AISI) funded a research program to investigate thermal cutting of HSLA (high strength low alloy) steels used in bridge construction.¹ The report from the study identified the variables that influence the quality of thermal cut edges (TCE). These variables include ones that relate to the plate steels such as chemistry, thickness, and toughness and to the variables in the thermal cutting procedure such as cutting speed and plate temperature. The project also identified the hardness of thermal cut edges as an important variable. In the AISI project extensive Rockwell C hardness testing of TCEs was performed with considerable variability found on and between TCEs. The following report summarizes the AISI project results and establishes through new research a suggested procedure for hardness testing of thermal cut edges of steels where testing variability is minimized.

MATERIALS

The original AISI project evaluated the thermal cutting performance of A572-Grade 50, A588 and A36 steels. The production size plates were in thicknesses of 1 in., 2 in. and

Table 1.
Range of Chemistries for Plates in AISI Study

Element	Eight A572-50 Plates		Eleven A588 Plates		Two A36 Plates	
	Range of Study	A709 Grade 50 Spec.	Range of Study	A709 Grade 50W Spec.	Range of Study	A709 Grade 36 Spec.
C	.11-.23	.23 max.	.12-.19	.20 max.	.15	.26 max.
Mn	1.17-1.26	1.35 max.	1.02-1.22	0.75-1.35*	.97	.80-1.20
P	.012-.019	.04 max.	.008-.018	0.04 max.	.017	.04 max.
S	.006-.021	.05 max.	.009-.023	0.05 max.	.024	.05 max.
Si	.20-.35	.15-.40	.26-.59	0.15-0.50*	.23	.15-.40
Ni	.03-.19	—	.02-.30	0.50 max.*	.20	—
Cr	.05-.23	—	.54-.67	.040-0.70*	.19	—
Cu	.06-.31	—	.24-.43	0.20-0.40*	.32	—
Mo	.01-.05	—	.01-.04	—	.04	—
V	.05-.11	.01-.15*	.00-.08	0.00-0.10*	.00	—
CE	.38-.48	—	.46-.58	—	.39	—

$$CE = C + Mn/6 + \frac{(Ni + Cu)}{15} + \frac{(Cr + Mo + V)}{5}$$

* Slight difference with type.

4 in. They represented the thickness levels that are used in bridge construction. The range of chemical analyses for these plates is summarized in Table 1. The A572-Grade 50 and A588 plates were intentionally chosen to provide chemistry levels near the higher alloy addition side of the specification range. For comparison, two A36 plates were also studied. The plates were evaluated in the as-rolled condition and some were also evaluated in the normalized condition. The range of longitudinal mechanical properties for these 21 plates are summarized in Table 2. Tensile and Charpy impact properties (CVN) are reported. A number of plates in this program had lower Charpy impact properties than would have been used in actual bridge construction. This was done to help emphasize any influence of CVN properties on TCE quality.

THERMAL CUTTING PROCEDURES

The primary thermal cutting process that was used in the AISI study was oxygen-fuel cutting using natural gas. The study also evaluated the use of propane and acetylene as the fuel gas and plasma cutting. The cutting variables that were examined were cutting speed and plate temperature. The cutting speeds that were examined were 6–24 ipm for 1-in. plates, 6–12 ipm for 2-in. plates and 4–10 ipm for 4-in. plates.

The plates were cut in ambient plate temperature conditions of 26–90°F representing the conditions that might be found in the steel mill or fabricators' shops. Additionally, certain plates were preheated to 200°F prior to cutting.

All plates were cut in the longitudinal direction (in the direction of rolling) and some plates were evaluated using transverse cutting. Cut lengths of any series of test conditions ranged from 40 in. to 120 in., thus allowing sufficient time for steady state cutting conditions to be achieved. For each of the plates that were evaluated, three and up to fourteen different cutting conditions were used. This resulted in a total of 109 different thermal cuts for evaluation.

EVALUATION OF THERMAL CUT EDGES

No surface cracking was found in any of the thermal cut edges in the AISI project. Therefore, additional methods were

used to develop a parameter to rate the quality of the edges. A three point bend test was developed that was used as a primary testing technique of the program. All of the thermal cutting trials in the program were evaluated by bend testing 3/8-in. thick × 6-in. long × 1-in. wide samples with the TCE in tension. The samples were tested in a guided bend apparatus, which used a 1½-in. thick plunger (3/4-in. radius) and a yoke with 2 3/8-in. wide opening. This sample and test fixture coincide with that used in the bend testing of weldments in the American Welding Society (AWS) Structural Welding Code. All of the TCEs that were evaluated met the 1000 microinch finish requirements of the AWS code as well. The bend test represents a very severe loading condition that is not representative of any loading that is found in a bridge. However, a rating scheme was developed to quantitatively rate the performance of TCEs in the bend test. The rating scheme that was developed is as follows:

Bend Test Rating

<i>Rating</i>	<i>Description</i>
0	Minimum surface indications with only a hairline appearance
1	Short cracks with a visible opening
2	Large cracks completely across the specimen width and/or a completely broken sample

Examples of these ratings are shown in Fig. 1.

In addition to bend testing, Rockwell C hardness testing was performed on all of the TCEs. This method also has some drawbacks with the primary one being that it provides significantly variable results, primarily due to the surface roughness inherent in TCEs. To try to address these concerns in the original AISI project, procedures were identified for evaluating the hardness of the edges. This preliminary procedure was as follows:

1. A sample was cut from the plate TCE.
2. All testing was performed using standard Rockwell hardness machine with 150 kilogram load and tested

Table 2.
Range of Mechanical Properties for Plates in AISI Study

	Eight A572-50 Plates		Eleven A588 Plates		Two A36 Plates	
	Range of Study	A709 Grade 50 Spec.	Range of Study	A709 Grade 50W Spec.	Range of Study	A709 Grade 36 Spec.
Yield strength, ksi	52–67	50 min.	51–72	50 min.	45–49	36 min.
Ultimate tensile strength, ksi	77–99	65 min.	77–108	70 min.	72–75	58–80
Elongation, %**	19–31	21 min.*	17–25	21 min.*	25–28	23 min.*
Avg. CVN, ft. lbs. @ +40°F**	20–135	15 min.	4–89	15 min.	27–37	15 min.

* In 2-in. gauge length.
** Includes some plates, which would have been heat treated if intended for actual bridge construction.

following ASTM E18-84 (except for surface roughness requirement).

3. No surface preparation of the cut edge was used.
4. All testing was performed at the mid-thickness location of the plate.
5. An attempt was made to make the hardness test or indentation in the valleys of the grooved surfaces.
6. Seven measurements were made, the highest and lowest values were eliminated and the mean and standard deviation established from the remaining five.

An example of the variability that was encountered in these hardness tests is displayed in Fig. 2. In this presentation the results of both quarterline and centerline are shown.

To provide additional information on the depth of the thermal cut edge, microhardness testing was performed on a

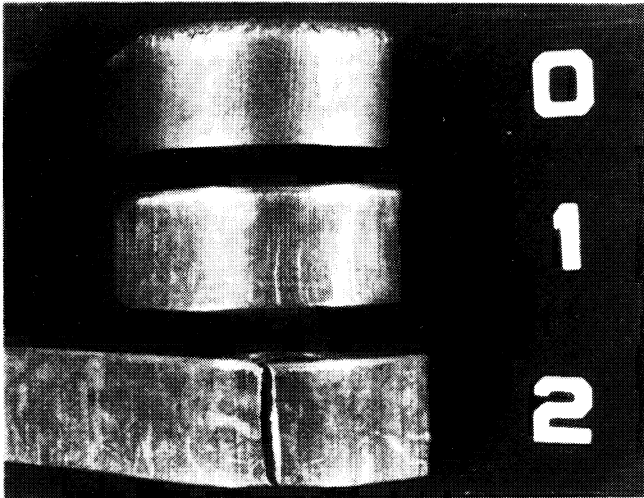


Fig. 1. Typical examples of bend test ratings in AISI study.

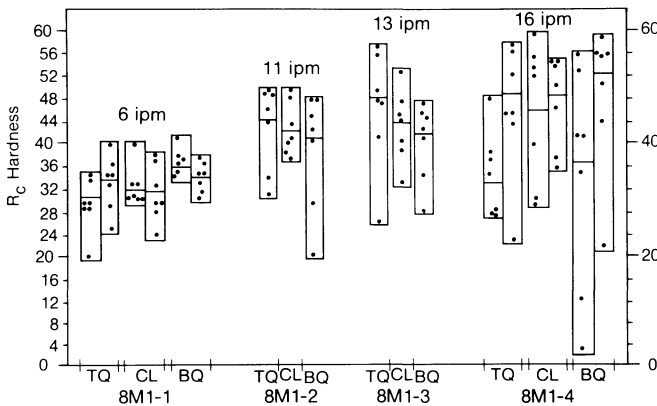


Fig. 2. Hardness testing results of thermal cut edges at four different cutting speeds. Results at centerline (CL), bottom (BQ) and top (TQ) quarterline locations, with duplicate surveys at 6 and 16 ipm. Note variability. Five point average shown by horizontal line.

cross-section of the TCE across the heat affected zone. These studies showed the following general trends:

1. Hardness levels very near the TCE tended to vary widely from very low to very high levels.
2. The depth of hardened material is greater near the top of the TCE nearest the cutting torch.
3. Richer chemistry plates tended to have harder and broader heat affected zones as shown in Fig. 3.
4. Higher cutting speeds led to narrower heat affected zones with higher hardness levels.

RESULTS OF AISI PROJECT

The results of the bend testing of all the thermal cut edges were evaluated using both graphical and statistical methods. The evaluations showed a number of trends and identified

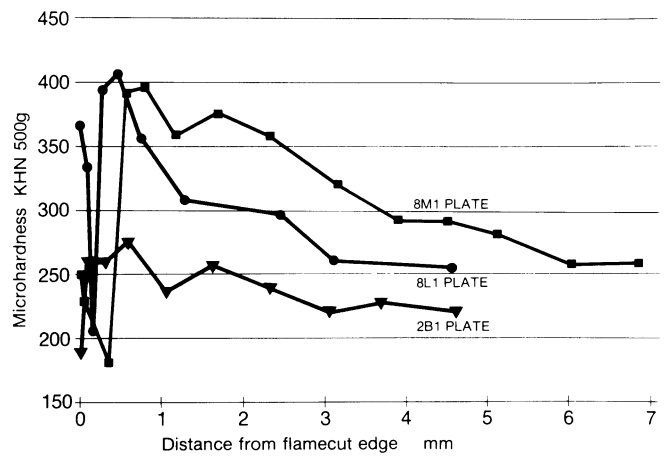


Fig. 3. Typical microhardness traverse for three different steels: 8 MI-A588 with a CE = 0.42; 8LI-A588 with a CE = 0.37; 2BI-A572 with a CE = 0.35.

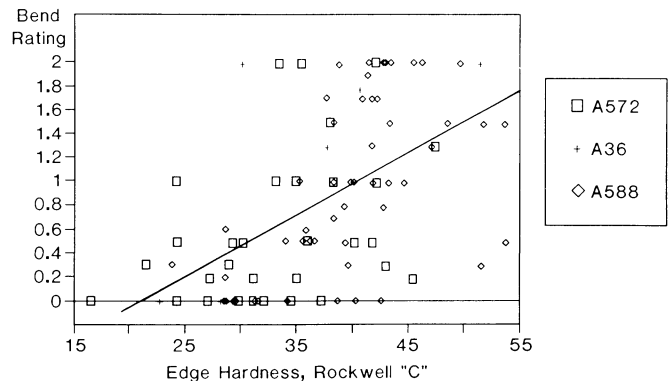


Fig. 4. Graph of average bend test rating versus thermal cut edge hardness (as-cut) for all data from AISI program. Best fit line shown: Bend Rating = $-1.13 + 0.053 H_{Rc}$ with an $R^2 = 0.30$ and Standard Error of estimate of 0.61.

the key variables influencing bend testing performance. A regression equation was determined using standard regression analytical methods. The regression equation for all of the AISI data was as follows:

$$\text{Bend Rating} = 0.36H_{Rc} + 7.3(\%C) + 0.0077T + 0.048V_C + 0.0047E_V - 1.42$$

$$R^2 = 0.55 \quad \text{Standard Error} = 0.50 \quad F \text{ Ratio} = 21.9$$

H_{Rc} = TCE hardness, Rockwell C

$\%C$ = Carbon content, w/o

T = Temperature of cut, °F

V_C = Cutting speed, ipm

E_V = CVN energy at +40°F, ft. lbs.

Additional regression equations were established for other subgroups of the data based on thickness or steel grade. Although there were slight differences in the order of importance of the variables in each subgroup, five key variables were identified as being most important in the AISI program. They were the hardness of the thermal cut edge, the carbon content of the plate, the temperature of the steel when it was cut, the cutting speed and the CVN toughness properties of the base plate. The chemistry levels such as carbon content and the CVN properties are already controlled for bridge steels through applicable ASTM and AASHTO specifications. Cutting parameters such as plate temperature and cutting speed are varied depending on the manufacturing practices that are used in each fabricating shop. The hardness of the thermal cut edge was found to be the most statistically important parameter.

However, as Fig. 4 shows, there is significant variability in the data when trying to directly correlate bend rating with the hardness of the edge. This further compounds the problem in its use as a quality control test as noted previously in Fig. 2. Furthermore, when the distribution of all the hard-

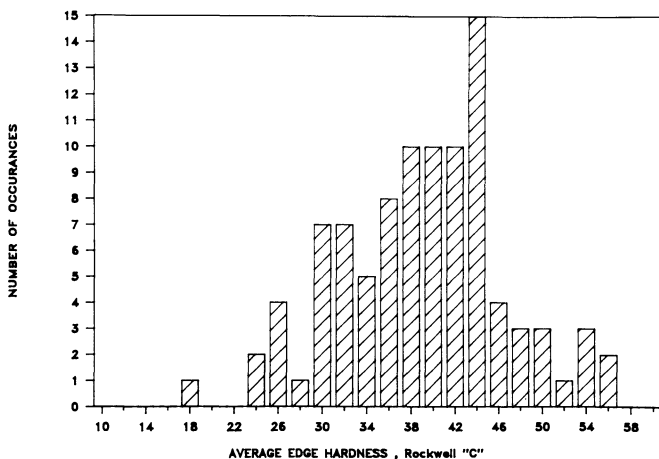
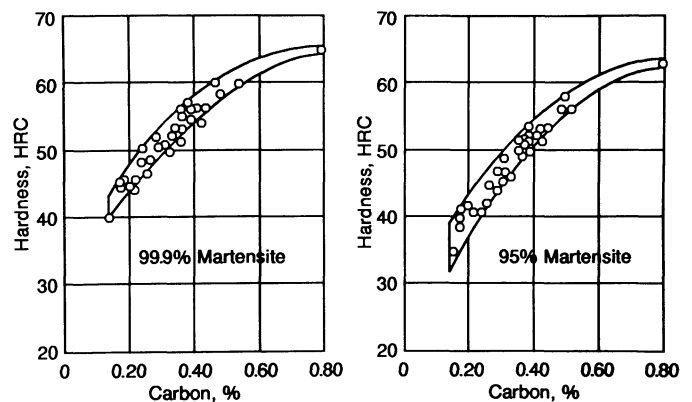


Fig. 5. Distribution of average thermal cut edge hardness (as-cut) for all evaluations in AISI program.

Table 3. Summary for 41 Samples from 15 Plates of Grinding Study			
	Rockwell C Hardness		
	Average of All Data	Minimum Value	Maximum Value
As-Cut Average			
7 pt. Calc.	36.0	21.2	47.4
5 pt. Calc.	36.1	21.4	47.3
As-Cut Std. Dev.			
7 pt. Calc.	6.3	2.4	14.1
5 pt. Calc.	3.8	0.6	10.9
Ground Average			
7 pt. Calc.	33.6	18.5	45.2
5 pt. Calc.	33.6	18.7	45.4
Ground Std. Dev.			
7 pt. Calc.	2.0	0.5	4.7
5 pt. Calc.	1.0	0.3	3.3
Comparison of As-Cut and Ground			
(As-Cut)-(Ground) Avg.			
7 pt. Calc.	2.3	-6.0	12.6
5 pt. Calc.	2.5	-6.2	14.4
(As-Cut)-(Ground) Std. Dev.			
7 pt. Calc.	4.3	-0.6	11.5
5 pt. Calc.	2.8	-1.0	9.0

ness results in this program is examined in Fig. 5, the wide range of results is apparent. In particular, as shown in Fig. 5, the average hardness results range from 18 to 56 Rockwell C. This is a broad range particularly when one considers that the hardness of as-quenched martensite for steels with these chemistry levels should normally be between 35 and 45 Rockwell C as demonstrated in Fig. 6, taken from the *ASM Metals Handbook*.² The very hard readings are a result of pickup of carbon content in localized areas during the burning process. The very low data are a result of the



*From ASM Metals Handbook

Fig. 6. Hardness of as-quenched martensite as a function of carbon content. From ASM Metals Handbook.

loss of carbon in localized areas on the thermal cut edge and low percentages of martensite being present. This variability was also confirmed by the microhardness results reported previously. The variability in these edge hardness results suggests that alternative methods were needed to obtain a more consistent measure of quality of the thermal cut edges.

EFFECT OF SURFACE PREPARATION

The greatest problem in accurately measuring hardness of TCEs is the edge roughness that is inherent in the thermal cutting process. Furthermore, localized areas on the TCEs have either higher or lower carbon content due to the cutting process and add to the variability in the hardness measurements. Therefore, a sampling of cuts from the previous AISI study were evaluated using localized grinding of the thermal cut edge. By testing a smooth surface, newly developed portable hardness reading equipment can also be used to measure the hardness of the edge. However, when grinding is used on the edge there is a concern that this would

influence the hardness results. Furthermore, the amount of grinding that is performed may have an influence on hardness results as well. Forty-one cuts from the previous AISI study were chosen for this evaluation. On each sample, a hardness evaluation was performed of the as-cut edge using the seven point readings at the centerline as done in the AISI study. On another half of the sample, the TCE was lightly ground to remove the cutting grooves using a hand sander with an abrasive sanding disc with 100 grit finish. The thickness of the sample was measured prior to grinding the sample that had been cut from the thermal cut edge. After grinding, it was measured again and the amount of metal removed determined. The hardness was then taken using seven points at the centerline on the ground surface of the TCE. The results of hardness testing in the as-cut and in the ground conditions were then compared.

Some comparisons of this limited data base are useful in understanding the variability of properties in TCEs.

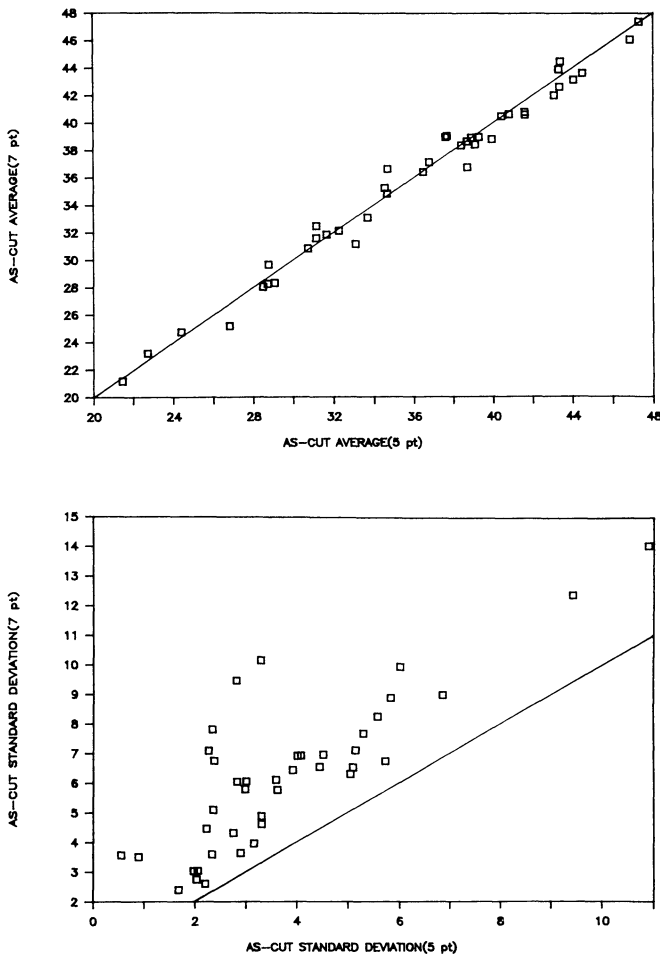


Fig. 7. Comparison plots of as-cut hardness data using 7-point versus 5-point calculation of a) average, b) standard deviation. Line of equivalence shown in each graph.

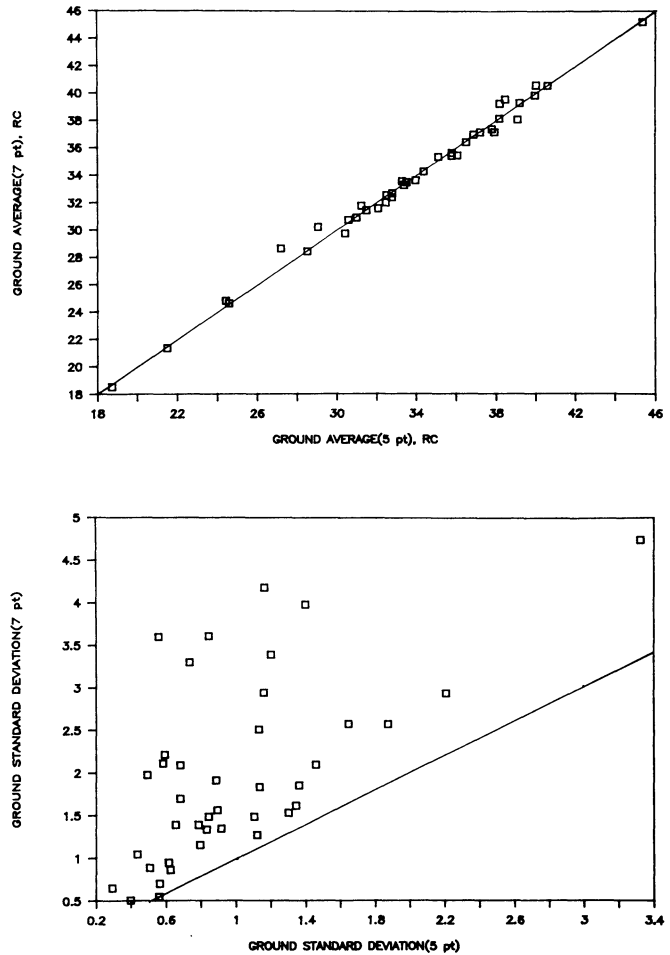


Fig. 8. Comparison plots of ground hardness data using 7-point versus 5-point calculation of a) average, and b) standard deviation. Line of equivalence shown in each graph.

Figure 7 shows the results of the hardness testing of the as-cut edges comparing averages using all seven hardness test results, with those using the five point method with the high and low results removed. Whereas the average results are very close whether using the seven or the five point method. The standard deviation is significantly lower using the five point calculation. In Fig. 8 the results for the ground surfaces are compared using either seven or five point calculation. Once more, the average results are nearly identical whether calculated from seven or five points. In this case, the standard deviations are not nearly as large for either calculation method. The five point calculation of the ground edge gives the lowest standard deviation.

Figure 9 compares the averages and standard deviations of the as-cut versus the ground results. The average results are not significantly different as shown in Fig. 9(a) whereas the standard deviations are significantly different as shown in Fig. 9(b). The numerical difference in hardness between the as-cut and the ground edge is shown in Fig. 10. This fig-

ure shows that there is a slight decrease due to grinding. Additionally in this figure, the difference between the averages or standard deviations does not appear to change with increasing hardness. In other words, the influence of grinding does not change with the general hardness level of the edge. Furthermore, the correlation between average bend rating and average hardness measurement, as presented originally in Fig. 4, was found to be nearly identical whether using the as-cut or ground hardness determinations.

Figure 11 demonstrates that there is no significant influence of the amount of thickness removed on the hardness level. The maximum amount of thickness removed was 0.010 in. It might generally be hypothesized that increased grinding would lead to lower hardness levels. However, when the amount removed was less than 0.010 in., there was no consistent effect of grinding on the hardness measurement. Table 3 summarizes the comparison for all of the 41 cases evalu-

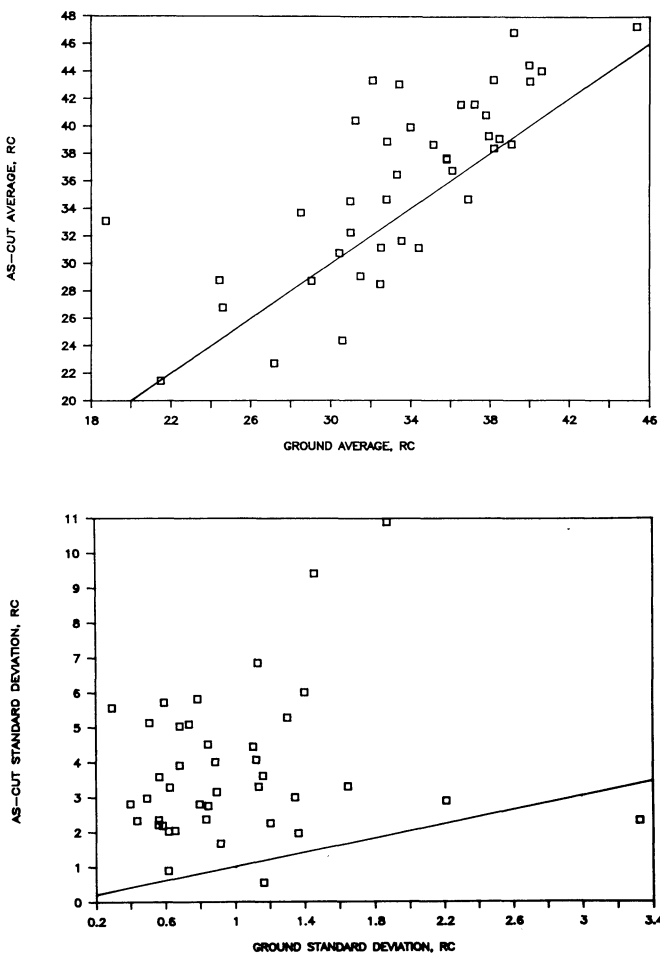


Fig. 9. Comparison plots of as-cut and ground hardness data using 5-point calculation of a) average, and b) standard deviation. Line of equivalence shown in each graph.

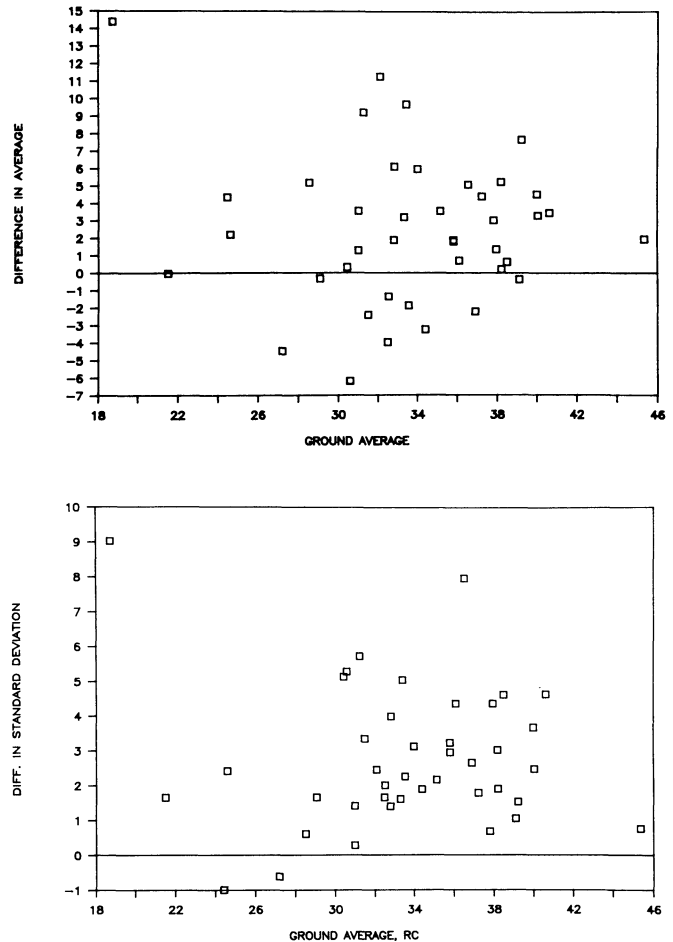


Fig. 10. The difference between as-cut and ground hardness [as-cut(ground)] results plotted versus average ground hardness for a) average hardness, and b) standard deviation. No statistically significant correlations found.

ated and demonstrates that if a small reduction in the average hardness from 36.1 to 33.6 H_{Rc} in using grinding can be tolerated there is a significant reduction in standard deviation of from 3.8 to 1.0 H_{Rc} . This indicates a test technique, which is more reproducible, thus being more applicable as a quality control test method.

Cross-sections of as-cut and ground samples are shown in Fig. 12. In this figure, it is demonstrated that the grinding used in this program removes only the sawtooth appearance of the edge, which is only a small part of the overall heat affected zone of the TCE. The remaining microstructure of the HAZ still shows the martensitic microstructure near the edge. This is the microstructure that is sampled by the hardness testing of the TCE. If a predominantly martensitic microstructure is a concern on TCEs, then Fig. 6 indicates that a maximum hardness of 35 Rockwell C is appropriate as a quality control guideline for these bridge steels.

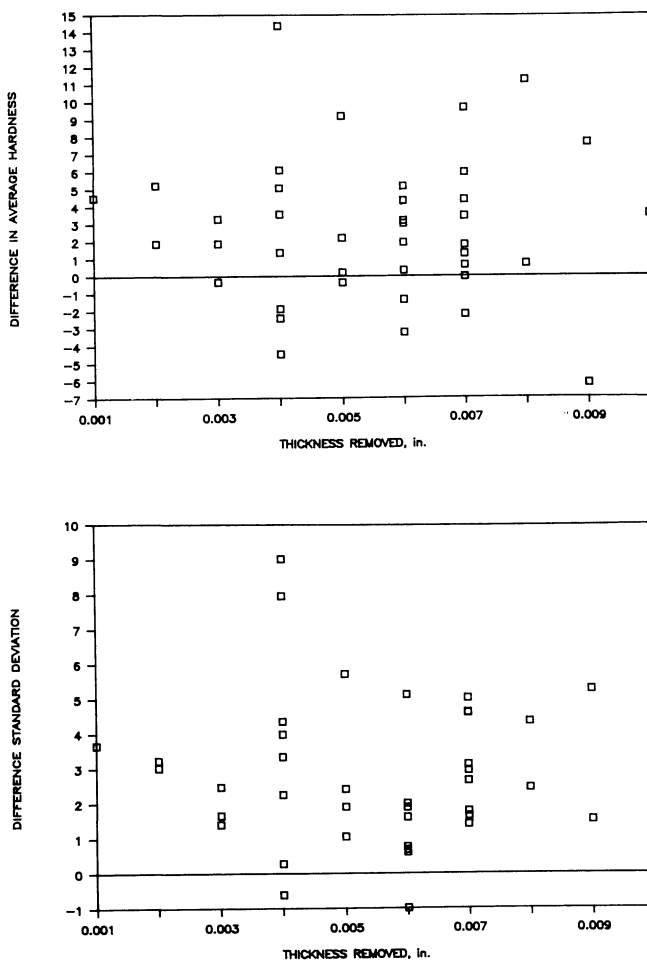


Fig. 11. The difference between as-cut and ground hardness results plotted versus amount of thickness removed during grinding for a) average hardness, b) standard deviation. No statistically significant correlations were found.

The foregoing figures have shown the significant reduction in variability in hardness measurement when grinding less than 0.010 in. is used. The smoother surface of the edge where the hardness is taken leads to a more reliable hardness measurement. Furthermore, the removal of the localized area of variable carbon content reduces the additional influence on the variability. Although there is a small reduction in the average hardness level on the ground surface, the improvement in the variability makes it justifiable. More importantly, because a smooth surface is provided for hardness testing, new portable hardness measurement devices can be reliably used.

SUGGESTED TECHNIQUE

As a result of the above evaluation, the following method is suggested for performing hardness testing of thermal cut edges.

1. Establish a location along the plate edge where hardness reading is to be taken.
 - a. The edge for testing should be perpendicular to the plate surface with a fairly uniform flatness.
 - b. The as-cut surface finish should be better than 1000 microinch.
2. Lightly grind the area for hardness testing with a hand sander/grinder with abrasive sanding disc with a 100 grit or smoother finish.
 - a. After grinding, the remaining test edge should have no remnants of the grooves caused by the thermal cutting process. This should normally be accomplished with the removal of less than 0.010 in. of metal.
 - b. The edge can be additionally lightly polished to meet requirements of various portable hardness testing equipment.
3. Hardness determination should be made at the center-line of the plate using appropriate portable testing equipment.

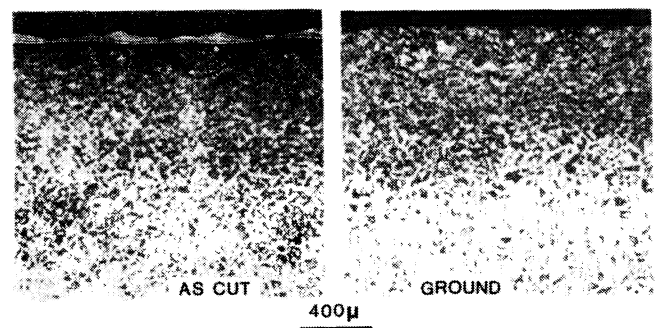


Fig. 12. Optical metallographic cross-section of as-cut and ground thermal cut edges. Grinding removes surface grooves, but full extent of heat affected zone remains. 50X magnification.

- a. Seven hardness readings should be taken.
- b. After removing the high and low readings, the average of the remaining five tests will be used to obtain an overall average hardness for this location.

CONCLUSIONS

The results of the previous AISI project have been reviewed in which variables influencing the quality of thermal cut edges have been identified. TCE hardness was found to be one variable of importance and a new suggested technique for hardness testing of thermal cut edges established. This technique involves local grinding of the thermal cut edge to allow a

smoother surface from which a hardness reading can be made. A significant reduction in the variability of hardness results with only a small reduction in the average hardnesses is obtained when using this method.

REFERENCES

1. Wilson, A. D., "Thermal Cutting of HSLA Bridge Steels," August 1987, available from the American Iron and Steel Institute, 1133 15th Street, NW, Washington, DC 20005-2701.
2. American Society for Metals, *Metals Handbook*, 9th Edition, Volume 1, Metals Park, Ohio, 1978, p. 472.