MICHIGAN DEPARTMENT OF TRANSPORTATION
M•DOT

EFFECT OF ELEVATED TEMPERATURE ON FRACTURE CRITICAL STEEL MEMBERS

Roger D. Till, P.E.

Research and Technology Section
Materials and Technology Division
Research Project 90 TI-1517
Research Report No. R-1344

Lansing, July 1996

ACKNOWLEDGMENTS

This study was a cooperative effort between Design, Materials and Technology, and Maintenance Divisions over the years this project existed. As people moved around in the Department, their roles changed concurrently. The requestor is now the author, and the investigators have since moved to jobs affected by the results. The efforts of the following people make this worthwhile: Sonny Jadun and Bard Lower for project direction, Ron McCrum for metallurgical consultation, Larry Pearson for project testing, Dave Kowalski and the Statewide Bridge Crew, along with LaVerne Lass and the Machine Shop.

INTRODUCTION

The Statewide Bridge Crew of the Maintenance Division follows the recommendations of the Design Division when repairing damaged steel members in the field. A majority of these damaged members have been struck by over height vehicles.

In the past, the Department has utilized heat straightening methods during repair. In Michigan this type of repair is limited to non-fracture critical members. The Materials and Technology Division was requested to examine the effects of elevated temperature on the notch toughness of treated steel before adopting this method for use in Michigan on fracture critical members (FCM). To investigate these effects, a 406 mm x 203 mm x 25 mm (16 by 8 by 1-inch) steel plate was obtained by the Structural Research Unit from the center portion of the web from a W36x300 fracture critical uplift beam of the bascule bridge on LaFayette Street in Bay City (B01 of 09032). See Figure 1. This steel was salvaged from the initial W36x300 uplift beam damaged from a construction accident during rehabilitation in 1989. The portion of steel selected for testing had sustained limited damage from the accident. The W36x300 was specified as ASTM A-36 steel and was produced to a killed, fine grain practice according to the mill certification.

TEST PROCEDURES

Specimen Preparation and Heating:

The 406 mm x 203 mm x 25 mm (16 by 8 by 1-inch) steel piece was subdivided and cut into nine specimens, as shown in Figure 2, prior to heating (the 203 mm (8-inch) dimension was in the direction of rolling). All specimens, except the control specimen (specimen A), were heated to a specific elevated temperature, held at that temperature for one minute, and then cooled. Holding the specimen at the elevated temperature for one minute was chosen to replicate field practice. The specimens were cooled to room temperature by one of the following three methods:

Method 1. Allow to cool under room conditions.
Method 2. Helped to cool by compressed air at 689 kPa (100 psi).
Method 3. Allow to cool to 316 °C (600 F) under room conditions then cooled to room temperature by a water mist.

To duplicate the field heat straightening process in the laboratory, the Statewide Bridge Crew was asked to heat the specimens. In the majority of instances in the field, a Vee heat pattern is employed when straightening a steel member bent about its major axis, whereas a spot heating pattern is used for a member bent about its minor axis. (The name Vee heat derives from the way the heat is applied to a member. The heating pattern looks like a "v".) The size of our specimens was small when compared with the size of the flame, so a spot heat pattern was used. All the specimens were heated from the top with the original rolled surface horizontal.

During the heating process, close monitoring on the temperature of the specimen was done. The amount of time that each specimen was held at a particular temperature was also closely monitored. The temperature of each specimen was determined by a digital thermocouple, with an accuracy of ±0.25 percent, attached to the heated surface of the specimen. During the heat measurement process it was assumed that the whole specimen was uniformly heated. There may have been a slight temperature gradient between the top, the interior, and the bottom surfaces of the specimen, but since the specimen was small this difference was considered insignificant.

Each specimen was subjected to the following specific treatment.

Specimen A:

Specimen A was a control specimen, and it was not subjected to any heat treatment.

Specimen B:

There were three B specimens, B1, B2, and B3. All three specimens were heated to the same elevated temperature of approximately 593 °C (1100 F) for one minute and then cooled.

Specimen B1:

The specimen was heated to 607°C (1124 F). Before one minute had elapsed, the temperature dropped to 592°C (1097 F). The specimen was reheated raising the temperature to 608 °C (1127 F). After one minute elapsed from the initial heating to 593 °C (1100 F), the specimen was allowed to cool to room temperature on its own (Method 1).

Specimen B2:

The specimen was heated to 597 °C (1107 F). Before one minute had elapsed, the temperature dropped to 592 °C (1097 F). The specimen was reheated raising the temperature to 613 °C (1135 F). After one minute elapsed from the initial heating, the specimen was cooled to room temperature using compressed air (Method 2).

Specimen B3:

The specimen was heated to 606 °C (1123 F). Before one minute had elapsed, the temperature dropped to 592 °C (1097 F). The specimen was reheated raising the temperature to 635 °C (1175 F). After one minute from the initial heating, the specimen was mistakenly cooled to room temperature by water mist. In the original proposal it was to be cooled to 316 °C (600 F) on its own and then cooled to room temperature by water mist (Method 3 modified).

Specimen C:

There were three C specimens, C1, C2, and C3. All three specimens were heated to the same elevated temperature of approximately 704 °C (1300 F) for one minute and then cooled.

Specimen C1:

The specimen was heated to 725 °C (1337 F). Before one minute had elapsed, the temperature dropped to 703 °C (1297 F). The specimen was reheated raising the temperature to 736 °C (1357 F). After one minute elapsed from the initial heating, the specimen was allowed to cool to room temperature on its own (Method 1).

Specimen C2:

The specimen was heated to 732 °C (1350 F). The temperature was maintained above 704 °C (1300 F) for one minute. After one minute elapsed from the initial heating, the specimen was cooled to room temperature using compressed air (Method 2).

Specimen C3:

The specimen was heated to 727 °C (1340 F). At the end of one minute, the temperature dropped to 704 °C (1300 F) and the specimen was not reheated. The specimen was allowed to cool to 316 °C (600 F) on its own. A water mist was then applied to cool it to room temperature (Method 3).

Specimen D:

The specimen was heated to 760 °C (1400 F). Before one minute had elapsed, the temperature dropped to 747 °C (1377 F). The specimen was reheated raising the temperature to 771 °C (1420 F). After one minute elapsed from the initial heating, the specimen was allowed to cool to room temperature on its own (Method 1).

Specimen E:

The specimen was heated to 843 °C (1550 F). The temperature stayed above 816 °C (1500 F) for one minute. After one minute, the specimen was allowed to cool to room temperature on its own (Method 1).

Specimen Testing:

The factors that affect the notch toughness of steel may be broadly classified into two categories.

1. Chemical composition.
2. Physical factors.

Chemical composition effects on toughness are influenced by carbon content, alloying elements, gas content, and impurities in the steel.

Some physical factors that may affect the notch toughness are hot and cold working, heat treatment, method of manufacturing (deoxidation practice), section size, specimen orientation in relation to working direction, surface condition (carbonized or decarbonized), microstructure, and grain size.

To determine how the above factors vary in the individual test specimens and whether these variations have any effect on the test results, the following tests were performed on all specimens A through E.

1. Metallographic investigation of all specimens, which included microscopic and macroscopic inspection. All heated specimens were inspected after heat treatment.
2. Chemical composition analysis.
3 Rockwell hardness tests before and after heat treatment.
4. Charpy V-notch tests.

Metallographic Inspection:

The microstructure (grain size, shape, and orientation) of steel does affect the Charpy V-notch toughness and other mechanical properties of steel. Grain size is significantly affected by the heat treatment and the rate of cooling of the steel specimens. Therefore, for better understanding of the steel behavior, it was decided to inspect the microstructure under an optical microscope according to ASTM E-112.

The cut specimens were polished to a smooth and mirror-like finish. The microstructure was revealed by etching the surface with 5 percent Nital (nitric acid+alcohol).

Chemical Composition Analysis:

The chemical composition of steel also affects the microstructure, hardenability, strength, ductility and toughness of steel. Increasing the weight percent of carbon causes an increase in strength, hardness, and hardenability of steel. The addition of several other alloys or elements can result in an increase or decrease in hardenability and ductility.

According to the mill certification, the steel used in this test was obtained from Bethlehem Steel Corporation, heat number 171N736, and had the following chemical composition (weight percent).

C	Mn	P	S	Si	Al
0.11	0.98	0.009	0.028	0.21	0.019

Chemistry of each specimen was obtained to check uniformity of composition.

Hardness Testing:

Hardness and yield strength measure material resistance to plastic deformation. For some metals, such as steel, there is a direct relationship between the hardness number and the tensile/yield strength of the material.

A Rockwell hardness tester was used to measure the hardness of each specimen according to ASTM A-370. The tester measures the depth of surface indentation by a hardened probe under controlled loading conditions, which in turn is related to a hardness number. The larger the hardness number, the harder the material and vice versa. Rockwell Scale B was used to measured hardness (1.6 mm diameter steel sphere indenter with 10 Kg minor and 100 Kg major load). Rockwell hardness values (indicated by RHB for B scale) for specimens A, B, C, D, and E were measured before and after heat treatment. Fifteen readings were taken at various locations on each specimen, before and after heat treatment.

Charpy V-notch Testing:

From each large specimen, six Charpy V-notch specimens were cut and numbered as shown in Figure 2. For comparison of notch toughness, Charpy specimens 1, 3, and 4 were cut from the surface, while specimens 2, 5, and 6 were cut from the mid thickness of the plate thickness as shown in Figure 3. The notch toughness was determined according to ASTM A-370. A longitudinal Charpy test was performed on all the specimens with the notch cut perpendicular to the rolled surface. Each Charpy specimen was cooled for 24 hours at -26 °C (-15 F), which is the lowest anticipated service temperature (LAST) for southern Michigan, before determining the notch toughness. The lowest anticipated service temperature was used for this testing temperature since it was the Department's specification requirement at the time of testing. Since that time the FHWA has rescinded its Technical Advisory 5140.9 requiring testing at the LAST. This is in recognition of the consensus reached between American Association of State Highway and Transportation Officials and American Welding Society in the Bridge Welding Code. Current MDOT specifications require testing at 4°C (40 F), which follows the Bridge Welding Code.

TEST RESULTS

Metallographic Inspection

The average grain size of each specimen was determined by using the standard comparison chart as described in ASTM E112. The grain sizes were measured at 100X for each specimen and are shown in Table 1.

An increase in grain size number (7 to 10) indicates an increase in number of grains per square inch and thus a decrease in the diameter of the grains.

The results of metallographic investigation indicate that the diameter of the grains decreased with an increase in temperature up to 816 °C (1500 F). Any metal plastically deformed (cold worked) at low temperature undergoes a change in grain size (grains become elongated) and becomes strain hardened. This results in a stronger, but more brittle material. An increase in temperature, if high enough, will restore the material to its original state prior to cold working. The increase in temperature causes the recrystalization of the grains and if the material is at this temperature long enough, growth of recrystalized grains will occur. Even though the tested steel was hot worked during most of the rolling process, it was still subjected to some amount of strain hardening.

Our metallographic inspection of the heated specimens indicated that at 593 °C (1100 F) and 704 °C (1300 F) recrystalization had initiated at the grain boundaries. It appears that at 760 °C (1400 F) recrystalization of grains was completed. At 816 °C (1500 F) an increase in grain size as compared to the 760 °C (1400 F) grain size indicates occurrence of grain growth after recrystalization. Any difference in microstructure is attributable to the difference in temperature to which each specimen was subjected and the rate of cooling. Prior cold work will affect the microstructure, but these specimens had not experienced cold working.

Chemical Composition Analysis:

The laboratory-tested specimens had the chemical compositions (weight percent) as shown in Table 2. The chemical compositions of all the specimens are nearly identical, with slight differences in chemistry being attributed to random variations in the product and the accuracy of the analysis.

Hardness Testing:

The Rockwell Hardness (RHB) values for each specimen, before and after heat treatment, are shown in Table 3.

The heating of steel does have an effect on the hardness of the steel. Heating to 593 °C (1100 F) and 704 °C (1300 F) decreased the average hardness of the heat treated steel. The decrease in hardness can be attributed to the recrystallization of grains, making the material less hard but more ductile. The average hardness of the specimens heated to 760 °C (1400 F) and 816 °C (1500 F) is less than the average hardness of the control, but greater than those heated to 593 °C (1100 F) and 704 °C (1300 F). Variations in hardness are likely related to the cooling rate of the specimens.

A two-sided t-Test was used to analyze the statistical significance of the difference in the average hardness within each heat treatment process. All of the t-Tests were performed at the 95 percent confidence level.

Results of the statistical analysis indicate that when the hardness of heat treated specimens are compared with the hardness of the same specimens prior to heating, only group E specimens had a higher hardness after heating that was significant, with a probability of error less than 5 percent. Specimen groups B1, B2, B3 and C3 had lower hardness values after heating, which were significant at the same confidence level.

Charpy V-notch Testing:

The notch toughness of each Charpy specimen, as indicated by the standard Charpy V-notch test method is given in Table 4 and Figure 4. Toughness values of Charpy specimens taken from the surface and mid thickness for each cooling procedure have been separated and also shown in Table 4.

During the impact testing, six of the Charpy specimens failed at comparatively low fracture toughness. Five out of these six specimens were B specimens, which were heated to 593 °C (1100 F). For evaluation purposes, it was decided to examine the microstructure of some Charpy specimens. Microscopic examination revealed the following grain structure sizes.

CHARPY SPECIMEN	CHARPY VALUE N·m (ft-lb)	GRAIN SIZE NO.
B3-1	271.2 (200)	8
B3-4	47.5 (35)	8
E5	51.5 (38)	9

A metallographic inspection did not reveal significant differences in grain size between normal B and E specimens and those with the lower Charpy values. Impurities at the notch may have initiated brittle failure.

The notch toughness of most of the heat treated specimens was greater than the control specimens, which were not heated. The main reason for this was that the heat treatment caused recrystallization of grains, which leads to a refinement of the grain size. This leads to an increase in notch toughness.

The specimens that were heated to the same temperature, but were cooled to room temperature by different procedures experienced different notch toughness values. The highest notch toughness values were obtained for specimens that were cooled to room temperature by compressed air. Of the specimens that were heated to different temperatures, but were cooled to room temperature by the same procedure, notch toughness tended to increase with an increase in temperature.

A two-sided t-Test was used to analyze the statistical significance of the difference between the average toughness of the control specimens and the average toughness of each heat treated specimen group. A two-sided t-Test was also used to analyze the significance of the difference in the average toughness of the steel surface between the control specimens and each heat treated specimen group; and the average toughness of the steel mid thickness between the control specimens and each heat treated specimen group.

Results of the statistical analysis of groups C and D when compared with the control group A indicate there were no groups that were significantly lower than the control group. In fact, specimen groups C2, C3, and D were found to have higher toughness values than control group A, with a probability of error less than 5 percent. The same results occurred when the surface specimens of groups C and D were compared with the surface specimens of the control group A. Comparing the mid-thickness specimens of groups C and D to the mid-thickness specimens of the control group A showed no significant difference.

After reviewing the result of the t-Test analysis of groups B and E compared with the control group A, it was decided to do additional statistical tests on these groups because of the comparatively low toughness values (values less than 54 N·m (40 ft-lb)) occurring in groups B and E. An outlier test according to ASTM E178, Practice for Dealing with Outlying Observations, and an f-Test was performed. In recognition of the apparent lack of normal distribution of values in groups B and E and the small sample size of groups A, B, and E, it was concluded that these statistical analyses were not reliable. It should be noted that for groups B and E the coefficient of variation increased dramatically when compared with the other groups and that negative toughness values (which are not physically possible) are implied if a normal distribution is assumed.

DISCUSSION

For any heat treatment process, the rate of transformation of austenite grains play an important role in the development of the microstructure and thus the mechanical properties of the materials. Transformation is time and temperature dependent and is accompanied by two processes, i.e., nucleation and growth of the grains. The time-temperature dependence on transformation for a continuous cooling process is indicated by a Continuous Cooling Diagram (CCT). The shape of the CCT diagram is affected by change in carbon content and alloy composition. This diagram was unavailable for the carbon and alloy composition of our steel. It became extremely difficult to determine if any transformation was taking place and the effect different cooling rates had on the phase transformation process. Microscopic inspection of the specimens revealed the equilibrium phase at room temperature. For all the specimens, the equilibrium microconstituents were ferrite and pearlite. All heated specimens inspected at room temperature under an optical microscope showed evidence that recrystallization had initiated and had reduced the size of the pearlite and ferrite grains.

The temperature at which recrystallization is initiated is affected by the amount of alloy addition and prior cold work present in the steel. The larger the amount of cold work, the lower the recrystallization temperature. For a constant time and temperature heat treatment, an increase in the amount of cold work can increase grain size. Any bridge steel damaged due to a vehicle impact has an extensive amount of cold work present due to distortion and bending of the steel member caused by the impact. Absence of this additional extensive cold working in our tested specimens may have provided less representative results. However, the effect of prior cold work on our tested specimens would have been minimized by the presence of the silicon and aluminum, which helps keep the grain size relatively small. During the heat straightening process done in the field, the distorted and bent steel is subjected to several heating and cooling cycles. In this testing, each specimen was subjected to one heating cycle. The effect of repetitive heating and cooling cycles on the grain size and fracture toughness was not determined. The effect of cold bending from vehicle impact was not determined because of the variation naturally occurring in this type of event. One possible mitigation for cold bent steel is to limit the permissible live load stress range experienced at these areas, which decreases the likelihood of crack initiation.

For fracture critical members, Department special provisions specify a minimum notch toughness at a given temperature. The manufacturer then decides whether the steel should have fine austenite grain size or should be killed, semi-killed, rimmed, or capped (various practices used by the steel industry to deoxidize steel). The microstructure of steel and the amount of impurities present in the steel are affected by the different methods used to manufacture the steel. The specimens tested in this investigation were rolled from steel meeting ASTM A-36. The steel had been killed and had fine prior austenitic grain size before being placed in service. This mill practice results in a steel that has uniform microstructure (limited blow holes and piping) and uniform mechanical properties. The mill certification indicated that the steel provided had an average Charpy toughness value of 319.4 N·m (235.6 ft-lb) at a temperature lower than -26 °C (-15 F) (according to mill certification the specimens were tested at an unspecified lower temperature to avoid exceeding their machine capacity), whereas the Department specified a Charpy fracture toughness of 33.9 N·m (25 ft-lb) when tested at the lowest anticipated service temperature of -26 °C (-15 F). Such a wide margin in notch toughness may permit a deoxidation practice that results in a non-uniform structure, but still meets the specification requirements. Steel currently used for fracture critical members will not likely exhibit such a wide variation in toughness, but past practice in steel production and bridge design may allow its occurrence. The Department changed the Charpy V-notch test temperature requirement to 4 °C (40 F) for fracture critical members in 1992, which actually decreased the required steel toughness.

Test results indicate there were six Charpy specimens that had a comparatively low toughness value (See Table 1). Five of these six failures were from the B specimen group, which were heated to 593 °C (1100 F). This may be due to temper embrittlement of the steel. Past research has indicated that some steels may have a reduction in toughness when tempered above 577 °C (1070 F), and then cooled slowly. The diffusion of impurities to the grain boundaries is attributed to this phenomenon. During testing, the specimens heated to 593 °C (1100 F) were held at that temperature for one minute. This would limit the time for diffusion of impurities to the grain boundaries. In any case, these lower toughness values could be indicative of the consequences of heating the steel during the straightening process. Even though lowered toughness values may occur only at an isolated location, the global action of the member may be controlled by the lowered toughness value.

The cooling rates of steel depend upon the geometry, size, and shape of the specimens. If the same surface area is heated both on a full-scale beam and on a small laboratory specimen, the full-scale beam will cool much more quickly. Heat is lost on the full-scale beam due to conduction, radiation, and air convection, whereas in the small laboratory specimen heat is lost only due to radiation and air convection. This may produce a slower cooling rate of the laboratory specimens than the cooling rate actually expected in the field.

Weld procedure tests for fracture critical members require Charpy V-notch toughness testing on the weld metal, but toughness testing on the heat affected zone (HAZ) is not required. The temperature in the HAZ steel can reach 816 °C (1500 F) for a short period of time according to temperature contours shown in numerous welding handbooks. The time the steel is at this elevated temperature affects the changes occurring in the HAZ, but in most cases it is assumed that the toughness of the base metal in the HAZ is not lowered. Slower heating of a Vee heat may result in a larger area being heated for a longer period of time than occurs during welding, but the steel temperature, adjacent to the Vee heat will be less than the maximum vee-heat temperature. These differences in time the steel is at an elevated temperature affects how the steel toughness responds to heating.

SUMMARY

Heating the test specimens did not adversely affect the grain size of any specimen group when compared with the control specimen group A. Only group E specimens had a statistically significant higher hardness after heating compared to the hardness before heating, with a probability of error less than 5 percent. These are encouraging results with respect to heat straightening this particular fracture critical member. Along this line, weld procedure testing for fracture critical members apparently assumes that significant changes do not occur in the heat affected zone of the base metal. Unfortunately, the time at temperature and cooling rates of these steel specimens may not be similar to those encountered during the field work of heat straightening. In combination with this, there were some comparatively low toughness values of the heat treated specimens, but the sample size was too small to determine statistical significance. If similar reductions occur in the field during heat straightening, global action of the member may be controlled by the lowered toughness value. **In all cases, heat straightening fracture critical members must be approached with extreme caution and care**.

RECOMMENDATIONS

Heat straightening fracture critical members may be performed after investigating the steel member as follows:

1. Determine the extent of damage to the member, including bends, tears, and cracks in the steel.
2. Determine the chemistry and grain size of the steel and its suitability for heating to an elevated temperature without adverse effects. In conjunction with this, determine if the member is made from killed, semi-killed, rimmed or capped steel.
3. Compare Charpy V-notch toughness values of the existing steel (control) and heat treated existing steel. A minimum of 48 specimens may be needed from the member as near as practical to the location where the heat straightening will occur. A minimum of 24 specimens must be tested, which includes a minimum of 6 for the control specimens and minimum of three sets of 6 from heat treated specimens. Heating of 6 specimens must be to the temperature that will be used in the field for heat straightening and maintained for a duration as expected in the field, along with heating 6 specimens 50 ºC (90 F) higher than the field temperature and heating 6 specimens between 232ºC and 371ºC (450 F and 700 F), for a total 18 heat treated specimens. Heating 6 specimens between 232ºC and 371ºC (450 F and 700 F) is intended to test for temper brittleness, blue brittleness or strain age embrittlement depending on the type of steel. The actual temperature must be established after the type of steel (low carbon or alloy) is known. A second set of 6 specimens must be prepared and replicate tested if low toughness values occur in the initial testing of the set, which may require four

sets of 6 additional specimens. Charpy toughness testing must be done at the lowest anticipated service temperature for the bridge site.

4. Determine the live load stress range experienced by the member at areas where cold bending has occurred.

This investigation requires samples from the steel member to be obtained, which may not always be possible.

Heat straightening a fracture critical member would be acceptable if:

1. The steel member is not torn or cracked.
2. Chemistry and grain size of the steel is suitable for heating to the proposed field temperature without adverse effects. Members made from killed (preferably aluminum killed) or semi-killed steel are better candidates for heat straightening than those made from rimmed or capped steels.
3. Statistical analysis of the Charpy V-notch toughness values using a t-Test indicates the heat treated specimens are not lower than the control specimens when analyzed at the 95 percent confidence level. An intraclass correlation may be done using the replicate specimen sets tested and the control specimens to confirm the low toughness values (an intraclass correlation coefficient greater than about 0.70 would confirm low values.) No single specimen value (control or heat treated) may be below the Charpy V-notch toughness value required by the current specification in force at the time of heat straightening.
4. The live load stress range occurring at the cold bent areas is below the current specification level for fatigue Category E at greater than 2,000,000 cycles.
5. Extreme caution and care are used during heat straightening. Magnetic particle inspection on the steel must show a crack free environment after straightening is completed.

SPECIMEN NUMBER	**GRAIN SIZE NUMBER**	**SPECIMEN NUMBER**	**GRAIN SIZE NUMBER**
A	7	C1	9
B1	8	C2	Between 8 & 9
B2	8	C3	Between 8 & 9
B3	8	D	10
		E	9

TABLE 1 - METALLOGRAPHIC INSPECTION

	C	Mn	P	S	Si	Al
Specimen A	0.11	1.00	0.011	0.029	0.22	0.02
Specimen B1	0.11	1.01	0.010	0.029	0.22	0.02
Specimen B2	0.11	1.01	0.010	0.029	0.22	0.02
Specimen B3	0.11	0.99	0.010	0.026	0.22	0.02
Specimen C1	0.11	1.01	0.010	0.030	0.22	0.02
Specimen C2	0.11	1.01	0.010	0.030	0.22	0.02
Specimen C3	0.11	1.00	0.010	0.027	0.22	0.02
Specimen D	0.11	1.03	0.010	0.031	0.22	0.02
Specimen E	0.11	1.01	0.010	0.029	0.22	0.02
Mill Cert.	0.11	0.98	0.009	0.028	0.21	0.019

TABLE 2 - CHEMICAL COMPOSITION