Quasi-Static Spot Weld Strength of Advanced High-Strength Sheet Steels

This study highlights the spot weld strength in tension-shear and cross-tension loading modes, and HAZ strength as a function of base metal strength, in sheet steels

By H. Ghassemi-Armaki, S. Bhat, S. Kelley, and S. Sadagopan

ABSTRACT

Quasi-static spot weld strength is expected to increase with base metal tensile strength. This paper highlights the spot weld strength (evaluated in tension-shear and cross-tension loading modes) as a function of the base metal ultimate tensile strength (UTS). The studied steels included those with ferritic, dual-phase, and/or martensitic microstructures with tensile strengths ranging from ~ 300 to 1700 MPa. Tension-shear strength (TSS) increases with weld diameter. However, there was an inflection point in the trendline where the failure mode changed from interfacial fracture to plug failure. The weld diameter where inflection occurred in the trendline increased with an increase in sheet thickness and changed slightly with the base metal characteristics. Overall, the effect of sheet thickness seems more pronounced than that associated with the chemistry/microstructure in the plug failure mode. The TSS and cross-tension strength (CTS) data were normalized to offset differences in sheet thickness and weld diameter. Examination of the data shows that TSS increases linearly with base metal tensile strength up to about 800 MPa, and then deviates from linearity. In contrast, CTS appears independent of the base metal UTS. For further analysis, the influence of the heat-affected zone (HAZ) softening (the difference between the base metal hardness and minimum hardness in the subcritical HAZ) on the spot weld strength was studied. The correlation of HAZ softening and spot weld mechanical behavior shows that the TSS increases, even with increasing HAZ softening, although there is a discontinuity in the trendline with the onset of HAZ softening. However, CTS appears to be independent of HAZ softening.

KEYWORDS
• Spot Weld Strength • Tension Shear • Cross Tension • Base Metal Strength • Heat-Affected Softening

Introduction

The development of advanced high-strength steels (AHSS) has been a key enabler for meeting future environmental regulations and safety requirements in the automotive industry. Development of AHSS has been accompanied by increased ultimate tensile strength along with good ductility. Light weighting the automotive body structure can be achieved by reducing sheet thickness. However, any material intended for automotive use should be readily weldable and exhibit good weld strength. Resistance spot welding (RSW) is a preferred welding process for body-in-white automotive joining (Ref. 1).

The spot weld strength of developed steels should be examined in both static and dynamic modes if intended for application in the automotive industry. Quasi-static spot weld strength is one of the key properties for qualifying new steels, and it is usually evaluated in tension-shear and cross-tension loading modes. Quasi-static tension-shear and cross-tension strengths are two important aspects of spot welded joints, which are expected to increase with increasing base metal tensile strength. Tension shear strength (TSS) and cross tension strength (CTS) depend on the properties of the weld-affected zone, which includes the spot weld nugget and HAZ. The AHSS nugget microstructure typically consists of martensite because of the rapid cooling rate characteristic of the spot welding process. The microstructure changes gradually from martensite to the base metal microstructure with increasing distance from the nugget, depending on the peak temperature experienced during welding. These microstructural changes result in significant changes in crack propagation resistance, fracture modes, and maximum load capacity. Based on this change in fracture mode, different analytical formulas have been provided to correlate TSS with sheet thickness (Ref. 2). Also, CTS has been related to base metal properties and fracture toughness of the nugget (Refs. 3–5).

In this paper, TSS and CTS are evaluated for different fracture modes, and analytical techniques are used to normalize TSS and CTS from data available for different thicknesses and weld diameters. Then, material strength in the weld nugget and HAZs are evaluated by hardness measurements, and correlated with base metal UTS. Finally, any HAZ softening that

H. Ghassemi-Armaki (hassan.ghassemi@arcelormittal.com), S. Bhat, S. Kelley, and S. Sadagopan are with ArcelorMittal Global R&D, E. Chicago, Ind.
occurs in AHSS is correlated with base metal UTS and its quantitative relation with TSS and CTS. Note that all TSS and CTS testing during the study have been performed on homogenous welding stackups under quasi-static conditions.

**Materials Studied and Experimental Procedures**

The steels in this study ranged from those with a low base metal tensile strength and a ferritic microstructure to materials possessing UTS as high as 1700 MPa. Steels with UTS between ~ 600 and 1200 MPa have a primarily dual-phase microstructure consisting of martensite in a ferrite matrix. As the UTS of materials with ferrite and martensite microstructure increases, the volume fraction of martensite increases. Steels with UTS above ~ 1200 MPa typically have a fully martensitic microstructure. Materials with the same UTS can have somewhat different microstructures depending on the strengthening mechanisms employed to achieve the desired strength.

In this study, material thickness ranged from 1 to 2.5 mm, and all sheet steels were cold rolled. Products were separated by surface condition into the following two categories: 1) bare (without coating) and electrogalvanized coating and 2) galvanized, galvannealed, and AlSi coated (for press hardening steels). The identifying codes used were as follows: a) DP = dual-phase (mainly martensite and ferrite), b) M = fully martensitic, c) IF = interstitial free, and d) HSLA = high-strength low alloy. All sheets were tested in the as-received condition, and oil cleaning was not applied for any studied sheet steel.

Spot welding practices were based on commercially available standards, mainly AWS D8.9 and General Motor’s GWS-5A (Refs. 6, 7). Welds were made using a pedestal type AC spot welding machine. Welding parameters were chosen from a standard based on the category of thickness and material strength (Refs. 6, 7). Cross-weld microhardness, tension-shear, and cross-tension tests were performed based on AWS D8.9 (Ref. 6) using an Instron tensile machine equipped with hydraulic grips at a cross-head speed of 0.4 in./min. The ultimate load was recorded for tension-shear and cross-tension tests. Weld diameters for tension-shear and cross-tension data were measured from samples after mechanical testing. The measured weld size after mechanical tests depends on fracture mode. The measured weld diameter for fully interfacial failure is close to the fusion diameter and nugget size, while its weld button is for plug failure. However, all measured weld sizes have been called weld diameter, regardless of failure mode. The interpretation of TSS and CTS results in this study, the failure modes were divided into plug failure modes (mode 1) and interfacial failure modes (modes 2–7).

Also, all welded test samples were within the safe current range and no welded sample above expulsion current was considered in this study. While the majority of tests carried out used the standard spot weld protocols (Refs. 6, 7), special temper cycles were developed to improve CTS values of AHSS. These results are described in the section titled improving CTS in AHSS by post-weld heat treatment (PWHT).

**Results and Discussions**

**Tension-Shear Strength**

**Evaluating TSS as a Function of Weld Diameter**

Figure 1 shows tension shear strength as a function of weld diameter for high-strength interstitial free sheet steel having UTS ~ 300 MPa and 1.2 mm thickness. While the TSS increases linearly with increasing weld diameter, the trend line deviates at higher weld diameters. The failure mode changes from interfacial at lower weld diameters (indicated by solid symbols) to plug failure at higher weld diameters (indicated by open symbols). So, the change in trend of TSS appears to be associated with a change in failure mode from interfacial to plug failure.
Figure 2 shows TSS as a function of weld diameter for two grades of galvannealed (GA) DP980 with different chemistries. One is a low-carbon grade (LC, ~ 0.09 wt-% C), and the other is a medium-carbon grade (MidC, ~ 0.16 wt-% C). Data was given for two different thicknesses for each grade (1.2 and 1.6 mm). Solid symbols represent interfacial failure mode, while open symbols indicate plug failure. As seen in Fig. 2, TSS increases linearly as a function of weld diameter for each chemistry/thickness combination. However, the slope of the trend line suddenly decreases at a point where the failure mode changes from interfacial fracture to plug failure. All four steels show almost similar TSS for a given weld diameter in the interfacial failure mode zone; however, the weld diameter where the deviation occurs appears to depend both on the sheet thickness and material grade (mainly carbon content). In plug failure mode, lower thickness sheets show lower TSS, while higher thickness sheets follow the same trend in interfacial fracture modes until deviation starts at a higher weld diameter. On the other hand, for a given sheet thickness, TSS is higher in the plug failure mode region for steel with lower carbon content. Therefore, the chemistry, microstructure, and sheet thickness affect TSS at higher weld diameters where the TSS trend transitions from the interfacial failure to plug failure mode.

Overall, the effect of sheet thickness seems more pronounced than that associated with the chemistry/microstructure in the plug failure mode. Interfacial failure happens as long as the weld nugget strength is higher than the HAZ or base material strength. However, weld nugget strength increases linearly with an increase in weld diameter, and plug failure takes place when the weld nugget strength goes above the HAZ or base material strength.

The behavior of TSS as a function of weld diameter was also evaluated for other grades having different combinations of microstructure and chemistry resulting in a range of base metal ultimate tensile strengths. Figure 3A–C show TSS for the following: 1) HSLA, 2) steels having nominal 590 MPa UTS, and 3) fully martensitic grades (M1500 and M1700) with differing thicknesses. Figure 3 shows the same TSS vs. weld diameter trend (and dependence on failure mode) previously observed in Figs. 1 and 2 for other steel grades. Therefore, these results suggest that the TSS behavior is independent of the steel grade, UTS, microstructure, chemistry, thickness, and surface condition (uncoated and coated steels).

As seen in Fig. 3B, three steels with minimum nominal UTS of 590 MPa show the same TSS at a given weld diameter in the interfacial failure mode. The weld diameter where inflection occurs increases with an increasing sheet thickness from 1.4 to 1.6 mm.

Figure 3C shows the TSS for M1500 and M1700 martensitic steels, and TSS is higher for M1700 steel in the interfacial failure region. However, the weld diameter at which inflection happens, as well as the slope of the regression line in the plug failure mode, is approximately similar for both M1500 and M1700 steels with 1.0 mm thickness. The inflection point and slope of the regression analyses in the plug failure mode change mostly with sheet thickness, as it was apparent for M1500 from 1 to 1.2 and 1.5 mm.
TSS as a Function of Base Metal UTS

Figure 4A and B show TSS as a function of weld diameter for 1.2-mm-thick ferritic steels having an UTS less than 440 MPa and steels containing martensite and UTS above 440 MPa for the following: A — Interfacial and B — plug failure modes.

Figure 5 shows $\alpha_{pf}$ as a function of base metal UTS studied steels for $6\sqrt{t}$ and $7\sqrt{t}$ weld diameters. Here, UTS was experimentally determined rather than nominal minimum values. As seen in Fig. 5, $\alpha_{pf}$ increases with increasing base metal UTS.
UTS in the range from 300 to ~800 MPa, and then there was unknown behavior from 800 to 1200 MPa UTS, but it increased again linearly from 1200 MPa up to maximum studied steel, which was M1700CR. The regression analysis in Fig. 5 presents $\alpha_{PF}$ as the following:

$$\alpha_{PF} \propto (UTS - \xi)$$

(3)

where $\xi = 0$ for UTS < 800 MPa

$\xi = 600$ for UTS > 1200 MPa

Unknown for 800 < UTS < 1200 MPa

This analytical equation presents $\alpha_{PF}$ in Equation 2 and depends on base material UTS. However, the significant effect of UTS on TSS decreases for steels showing HAZ softening, as indicated in Fig. 5. As shown in Fig. 5, TSS increases linearly with base metal tensile strength for the strength ranges of 0 to 800 MPa and beyond 1200 MPa. However, in the range of 800 to 1200 MPa, the TSS behavior was uncertain. Data for dual-phase (DP980) and fully martensitic steels (M900) show that this uncertainty was independent of the microstructure. However, further investigation is necessary for the range of 800 to 1200 MPa to correlate $\alpha_{PF}$ with the base metal UTS.

**Cross-Tension Strength**

Figure 6 shows the CTS of two DP980 GA low-carbon materials with thicknesses of 1.2 and 1.6 mm. Not only does the CTS increase linearly with increasing weld diameter, but also with increasing thickness. A similar trend was observed for other steel grades, and CTS can therefore be modeled by the following equation (Ref. 8):

$$CTS = \beta dt$$

(4)

where $d$ is the weld diameter, $t$ is the sheet thickness, and $\beta$ is a coefficient characteristic of each steel but independent of the sheet thickness and weld diameter. The trend lines in Fig. 6 are modeled based on a value for $\beta$ specifically determined for the studied DP980 GA steel.

Alternatively, using Equation 4, the value of $\beta$ can be determined for dif-
This approach results in 

\[ \frac{t_1}{t_2} \]

to sheet thickness, given here as 

\[ \sqrt[6]{t} \]

three different weld diameters, related 

to the base metal UTS for 

different stackups. Figure 7 shows 

and brittle microstructures (marten-

tial carbon. This enriched chemistry 

amounts of alloying elements, espe-

rentially a part of a welding schedule spec-

plored in-situ PWHT, which tempers 

crease obtained through the applica-

and HAZ, and temper the martensite. 

temperature, an appropriate current pulse 

recovery was associated with sufficient 

reformation of hard, untempered martensite 

during tempering, allowing the forma-

Figure 8A illustrates the CTS in-

terface. As a result, 

in the nugget and results in improving 

increase in CTS.

Figure 8B depicts the changes in 

the weld hardness profile resulting 

from the application of the temper 
pulses referred to in Fig. 8A. Note that 

the 80% WC and 87.5% WC pulses 

produce a hardness reduction with the 

greatest decrease corresponding to the 

87.5% WC condition. In contrast, the 

hardness peak evident in the 95% WC 

pulse hardness profile indicates hard-

ness recovery in the weld center. This 

recovery was associated with sufficient 

heating to reaustenitize the weld area 
during tempering, allowing the forma-

The properties of most ultrahigh 

strength sheet steels (UHSS) are 

achieved through adding significant 

amounts of alloying elements, espe-

ially carbon. This enriched chemistry 

increases the material’s hardenability 

and promotes the formation of hard 

and brittle microstructures (marten-

site) during spot welding. As a result, 

CTS was reduced, despite the en-

hanced strength of the unwelded prod-

uct (Ref. 11).

In the simplest spot welding 

process, a pulse of welding current was 

applied to the stackup to be joined. 

The sheets were fused together by a 

nugget of melted and resolidified ma-

terial produced at the faying interface. 

If the weldment was kept clamped be-

tween the water-cooled electrodes sub-

sequent to the welding pulse, the weld 

cooling is accelerated. Given sufficient 

time for the weld/HAZ temperature to 

fall below the martensite finish tem-

perature, an appropriate current pulse 

can then be applied to reheat the weld 

and HAZ, and temper the martensite. 

Figure 8A illustrates the CTS in-

crease obtained through the applica-

tion of temper pulsing to 1.2 mm 

M1500 EG. The data shown was for 

welds made for three conditions with-

in the welding current range: a) \( I_{\text{MIN}} \) 

— current to produce the minimum 

weld size, b) \( I_{\text{M50}} \) — current from the 

middle of the current range, and c) \( I_{\text{EXP}} \) 

— the minimum current to produce 

expulsion. Four temper current con-

ditions are included: a) no temper (as 

welded), b) 80% WC — 80% of the 

welding current, c) 87.5% WC — 

87.5% of the welding current, and d) 

95% WC — 95% of the welding 

current.

In Fig. 8A, any CTS improvement is 

signified by the vertical separation be-

tween the as-welded data points (solid 

blue) and the symbols corresponding 

to the varying temper pulse condi-

tions. Note that the 87.5% WC data 

(solid black) falls most consistently at 

the high end of the CTS range for \( I_{\text{M50}} \) 

and \( I_{\text{EXP}} \), signifying that the 87.5% WC 

condition provides the greatest in-

crease in CTS.

Figure 8B depicts the changes in 

the weld hardness profile resulting 

from the application of the temper 
pulses referred to in Fig. 8A. Note that 

the 80% WC and 87.5% WC pulses 

produce a hardness reduction with the 

greatest decrease corresponding to the 

87.5% WC condition. In contrast, the 

hardness peak evident in the 95% WC 

pulse hardness profile indicates hard-

ness recovery in the weld center. This 

recovery was associated with sufficient 

heating to reaustenitize the weld area 
during tempering, allowing the forma-

of hard, untempered martensite 
during post-temper cooling. There-

fore, the improvement of CTS as seen 

in Fig. 8A was contributed to temper-

ing of the martensitic microstructure 
in the nugget and results in improving 

the nugget fracture toughness.

HAZ Softening and Spot Weld 

Strength

Effect of Base Metal UTS on the 

Hardness of Welding Zones and 

HAZ Softening

Figure 9A shows typical cross weld 

microhardness profiles for DP590CR 

and M1700CR steels. As seen for 

DP590CR, while the hardness increas-

es as one moves from the base metal, 

through the HAZ and into the weld 

nugget, there is no HAZ softening. In 

contrast, the M1700CR microhardness 
drops rapidly from a high base metal 

value to a minimum in the HAZ, and 

then increases quickly to a maximum 

value in the nugget. The sharp hard-

ness drop in the HAZ, quantified by 

subtracting the minimum HAZ hard-

ness from the average base metal 

hardness, was due to martensite tem-

pering (Ref. 12). Because the 

M1700CR microhardness profile is 

fully martensitic, the tempering effect 

in response to the welding-induced ther-

mal cycle is maximized. In contrast, 

the volume fraction of martensite in 

the DP590CR is very low, providing lit-
tle martensite to be softened and minimizing the HAZ softening effect. Also, the difference of HAZ softening between these two steels can be correlated to the kinetics of martensite tempering, which was higher in M1700CR because of higher carbon content (Refs. 5, 11, and 12).

To better understand the correlation between the hardness drop in the M1700 CR and the time/temperature distribution associated with the welding process, SORPAS software was used to simulate the corresponding welding condition. Figure 9B shows the maximum temperature distribution from a cross-section view. Boundary lines signifying the Ac1 as well as the melting temperature were drawn, and the center of the Fig. was the weld nugget. Figure 9C shows an etched cross-section metallography of the same relative weld location as that in Fig. 9B. A comparison of Fig. 9A corresponds to material exposed to a maximum temperature near the Ac1. The thermal history of an existing finite element node close to the line marked as Ac1 in Fig. 9B (but a little bit far from the line and closer to the base material) was plotted in Fig. 9D. As shown, the maximum temperature reached ~ 680°C, which is close to Ac1 for M1700 CR (~ 730°C).

Base metal hardness, minimum HAZ hardness, and weld nugget hardness were plotted as a function of the base metal UTS in Fig. 10 for the studied steels. The hardness of these three zones can be formulated by linear regression analysis as a function of base metal UTS:

\[ H_v = A(BM_{UTS}) + B \]  

where \( BM_{UTS} \) is the ultimate tensile strength of the base metal, and \( A \) and \( B \) are coefficients (Table 1).

The comparison of \( A \) coefficients regarding the slope of regression analysis shows that the slope of the nugget hardness curve was lower than that for the base metal hardness (0.28 vs. 0.15). Nugget hardness has been tied to the Yurioka carbon equivalent (CEY) (Ref. 4). Figure 10 shows that the trend lines for the nugget hardness and the minimum value at HAZ were approximately parallel, exhibiting a constant hardness difference independent of the base metal tensile strength. In contrast, the nugget hardness and base metal hardness trend lines converge as the UTS increases. Higher strength steels (UTS above ~ 1300 MP) in this study have fully martensitic microstructures, so solidified nugget and base metal will consist of martensite, resulting in almost similar hardness. Minimum hardness in the HAZ (\( H_v_{MHAZ} \)) increases with base metal UTS, but at a slower rate due to HAZ softening during welding (Ref. 13). HAZ softening is attributed to martensite tempering that is associated with thermal history experienced during welding (Refs. 5, 12, and 13).

The difference in hardness between the base metal and minimum hardness at the HAZ, which was expressed as maximum HAZ softening (\( HAZ_{MAX} \)), has been plotted as a function of base metal UTS in Fig. 11. As shown, \( HAZ_{MAX} \) increases with an increasing base metal UTS, regardless of the surface condition of the product (coated and uncoated). \( HAZ_{MAX} \) can be expressed in terms of base metal UTS (\( BM_{UTS} \)) with the following equation:

\[ H_v = C(BM_{UTS}) - D \]  

where \( BM_{UTS} \) was the ultimate tensile strength of the base metal, and \( C \) and \( D \) were coefficients that have been reported for bare/EG and GA/GI/AlSi surface conditions, respectively (Table 2).

The increase in HAZ softening at higher strength steels can be attributed to a richer chemistry (mainly carbon content) of the steels. The effect

<table>
<thead>
<tr>
<th>Hardness of Different Zones</th>
<th>A</th>
<th>B</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H_v ) Base metal</td>
<td>0.28</td>
<td>31</td>
<td>0.98</td>
</tr>
<tr>
<td>( H_v ) Nugget</td>
<td>0.15</td>
<td>265</td>
<td>0.98</td>
</tr>
<tr>
<td>( H_v ) Minimum hardness in HAZ</td>
<td>0.12</td>
<td>131</td>
<td>0.89</td>
</tr>
</tbody>
</table>
of alloying elements on the kinetics of HAZ softening was explained in Refs. 12 and 13. Equations 5 and 6 for bare/EG surface conditions can be combined to produce:

$$HAZ_{Max} = 0.6 \cdot Hv_{Base\,Metal} - 155 \quad (7)$$

Equation 7 shows that maximum HAZ softening in the Vickers hardness increases by 60% of the base metal hardness. This relationship holds for materials with ferritic, dual-phase, and/or fully martensitic microstructures.

Effect of HAZ Softening on TSS and CTS

Concerns have been voiced in the automotive industry regarding the potential effect of HAZ softening on spot weld strength as measured via TSS and CTS. To address this issue, the influence of maximum HAZ softening (HAZ$_{Max}$) was studied. Normalized TSS and CTS have been plotted as a function of maximum HAZ softening (HAZ$_{Max}$) in Fig. 12A and B, respectively. In normalized form, TSS and CTS were expressed in terms of $\alpha$ (for TSS) and $\beta$ (for CTS) coefficients as shown in Equations 2 and 4. Data in both plots were presented for weld diameters of $6\sqrt{t}$ and $7\sqrt{t}$ with all studied steels showing plug failure. The trend line in Fig. 12A shows that TSS increases regardless of the appurtenance of HAZ softening, although there is a trendline inflection point where HAZ softening appears.

In contrast, Fig. 12B shows that CTS becomes relatively independent of HAZ softening as HAZ$_{Max}$ increases. As seen, maximum HAZ softening for M1700 CR is much higher than DP590 CR, but CTS was similar for both steels. This observation suggests that CTS depends on other factors, e.g., crack propagation resistance from the notch formed by the intersection of the fusion line and the faying interfaces, which may be attributed to the fracture toughness of the weld nugget (Refs. 3, 11, and 14).

Conclusions

Tension-shear strength (TSS), cross-tension strength (CTS), and heat-affected zone (HAZ) hardnesses were investigated for a wide range of sheet steels having ultimate tensile strengths in the range of ~ 300 to 1700 MPa. The results of this study can be summarized as follows:

1) TSS increases with weld diameter, but there was an inflection point in the trendline where the failure mode changed from interfacial fracture to plug failure. The weld diameter at which inflection occurs in the trendline increases with an increase in sheet thickness and changes with base metal characteristics. But, overall, the effect of sheet thickness seems more pronounced than that associated with the chemistry/microstructure in the plug failure mode. However, despite the presence of the inflection point, TSS continues to increase until the expulsion current is reached.

2) TSS increases linearly with base metal tensile strength up to about 800 MPa as well as beyond 1200 MPa, while the trend line is not well defined for TSS in the UTS range of 800–1200 MPa. However, CTS appears to be relatively independent of the base metal UTS.

3) The as-welded CTS of steels exhibiting martensitic weld nuggets can be improved through the application of an appropriate PWHT, which tempers the martensite, increasing the nugget toughness and improving the CTS.

4) The nugget hardness, minimum HAZ hardness, and base metal hardness have been correlated with base metal UTS. The results show that the minimum hardness in the HAZ, which refers to the location of HAZ exposed to the $Ac_1$ temperature, doesn’t increase as the base metal or nugget hardness increase. This deviation results in a difference of base metal strength and HAZ strength, called HAZ softening. HAZ softening increases with the increasing base metal UTS for steels having dual-phase and martensitic steels. Maximum HAZ softening (HAZ$_{Max}$) increases with almost 60% increase in base metal hardness.

5) The shape of the TSS trendline is

<table>
<thead>
<tr>
<th>Material</th>
<th>C</th>
<th>D</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bare/EG</td>
<td>0.17</td>
<td>136</td>
<td>0.95</td>
</tr>
<tr>
<td>GA/GI/AlSi</td>
<td>0.165</td>
<td>107</td>
<td>0.92</td>
</tr>
</tbody>
</table>
affected by the presence of HAZ softening. However, TSS continues to increase despite escalating HAZ softening, whereas HAZ softening does not seem to affect CTS.

Acknowledgments

The writers acknowledge ArcelorMittal Global R&D management for encouragement and support to complete this paper.

References