DEVELOPMENT OF STEEL PLATES FOR API X70 LINE PIPES IN GERDAU OURO BRANCO*

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Abstract
Since 2016 Gerdau Ouro Branco has been producing steel plates of various qualities and grades. However, it was not until 2018 that the first plates produced by accelerated cooling process were made available for external testing, in this case for large diameter UOE pipes manufacturing. Recent line pipe and OCTG specifications are showing that the oil and gas market still consumes regular API grades, such as X60, X65 and X70, however with increasing wall thicknesses, reaching values up to 1.5 inches. These specifications also demand longitudinal and transverse tensile guarantees and drop weight tear tests in temperatures as low as -40°C. Projects with these types of mechanical properties present process requirements as challenging as those necessary for higher API grades in lower thicknesses. This paper shows the steel design concepts and rolling routes for achieving the necessary properties for X70 steel plates in 28.15 mm. The microstructural features were also investigated and associated with the production process and the tensile and toughness results. Finally, challenges such as tensile anisotropy and DWTT abnormal fracture are presented.
Keywords: Steel plates, API X70, thermomechanical controlled process.

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1 INTRODUCTION

Steel is the best material to be used in the manufacture of tubes for economical transportation of oil and gas from remote regions to areas of high population density, where these fluids will be used for the generation of energy.

There are several technical challenges associated with the manufacture of steels for these types of pipes, including the need for homogeneous microstructure and properties, weldability, low yield to tensile ratio value, consistent with the safety design, and an adequate level of toughness to curb high speed crack propagation. In addition, the steels must resist property modifications due to cold work during the conformation of the tubes. In fact, the quality requirements currently required are much more stringent, given the difficulty of exploration in high-depth environments, uneven terrain and subzero temperatures. These and other requirements necessary to ensure integrity during use are well known and understood to be incorporated in the fabrication of steel.

More recent specifications have incorporated the need to guarantee tensile properties in the transverse and longitudinal directions. This need has added yet another challenge in the production of steel, since the control of the anisotropy often causes adverse reactions in the other properties of the material, such as the drop weight tear test (DWTT).

All these requirements raise the need to obtain an optimized microstructure, where both strength and toughness will have to be maximized. To achieve this, the microstructure must have the right proportion of soft polygonal ferrite, hard bainite and tough acicular ferrite. The control of the amount of each microconstituents will depend on chemical composition, level of deformation austenite, rolling and cooling temperatures and cooling rate.

Steels having such high performance requirements for toughness exhibit a phenomena known as inverse fracture or abnormal fracture during the drop weight tear test. Inverse fracture means that ductile fracture initiates at the notch side and turns into the brittle fracture while normally the brittle fracture initiates at the notch tip then the brittle fracture arrests and turns into the shear fracture depending on materials property and/or test temperatures [1]. The abnormal fracture makes the DWTT technique difficult to employ and some approaches have been made to prevent it from occurring. However, no satisfactory solution has been proposed yet [2]. According to the API RP 5L3, DWTT specimen which shows inverse fracture is judged as invalid specimen. As shown in figure 1, inverse fracture usually observed shear area fraction between 40 - 95 %. Therefore, it is difficult to obtain SATT 85 % to evaluate the brittle crack arrestability of the linepipe materials.

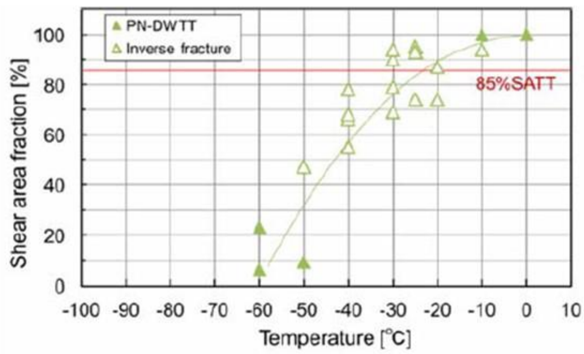

Figure 1: Comparison of shear area transition curve between PN-DWTT and pipe burst test [1].

2 MATERIAL AND METHODS

The samples used for this paper were taken from 28.15 mm thick plates for API X70 PSL2 pipes using two distinct chemical compositions, as shown on table 1.

Table 1: Chemical compositions used for X70 plates

Alloy	%C	%Mn	%(S+P)	%(Nb+V+Ti)	%(Cu+Ni)	%(Cr+Mo)	N ppm
1	0,06	1,55	0,023	0,10	0,10	0,30	<60
2	0,05	1,55	0,023	0,07	0,20	0,25	<60

For the adjustment of the production process 3 rolling trials were performed for alloy 1 and 2 rolling trials for alloy 2. On each trial between 4 and 9 slabs were rolled from an initial 250 mm thickness down to 28.15 mm. The reheating temperature was chosen based on Irvine´s equation for NbCN solubilization [3].

The rolling and accelerated cooling parameters were determined using the Ar3 temperature as a reference. The Ar3 temperature was calculated by the Ouchi equation [4]. Table 2 shows a summary of the rolling conditions, A-C for alloy 1 and D-E for alloy 2. As a measure to assure high DWTT toughness at -20°C, the transfer thickness was always at least 4 times the final plate thickness.

Table 2: Rolling and accelerated cooling parameters as a function of the Ar3 temperature.

Alloy	Condition	RHT	TRANSF	FRT	SCT
1	Trial 1	1100°C	120 mm	Ar3+110°C	Ar3+50°C
	Trial 2	1100°C	120 mm	Ar3+100°C	Ar3+40°C
	Trial 3	1100°C	120 mm	Ar3+50°C	Ar3+10°C
2	Trial 4	1100°C	120 mm	Ar3+80°C	Ar3+10°C
	Trial 5	1150°C	130 mm	Ar3+90°C	Ar3+25°C

Where:
RHT = reheating temperature.
TRANSF = thickness at beginning of the second stage of rolling.
FRT = final rolling temperature.
SCT = start cooling temperature.

After the rolling process the samples were taken as presented on figure 2. Tensile tests were performed using full thickness test pieces with 50.8 mm gauge machined on the transverse and longitudinal directions. Toughness was evaluated through Charpy test at -20°C and DWTT at -20°C, according to API 5L3 standard.

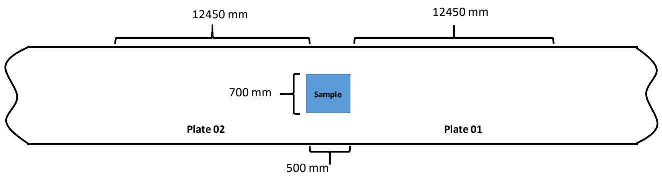

Figure 2: Sketch showing the sample location within the rolled unit.

Samples were also evaluated by optical microscopy with the objective of correlating the obtained mechanical properties with the microstructures. Samples for optical microscopy were taken at ¼ thickness of the plate and etched with nital 2%.

3 RESULTS AND DISCUSSION

Table 3 shows a summary of the mean values found for mechanical properties of the tested conditions.

Table 3: Mechanical properties of the tested X70 plates

Alloy	Condition	YS (Mpa)	TS (Mpa)	EL (%)	E (J)	SA (%)
1	Trial 1	488	618	52	433	60
	Trial 2	535	638	48	457	78
	Trial 3	525	613	53	458	97
2	Trial 4	549	608	55	431	95
	Trial 5	556	626	57	459	97

Where:
YS = Yield strength
TS = Tensile strength
EL = Elongation
E = Impact energy
SA = DWTT shear area

In general, alloy 2 had better performance in terms of YS, EL, DWTT and about the same level of TS and energy as alloy 1.

Figures 3 to 6 show the materials tensile properties as a function of the rolling temperatures (FRT) for each trial and alloy design.

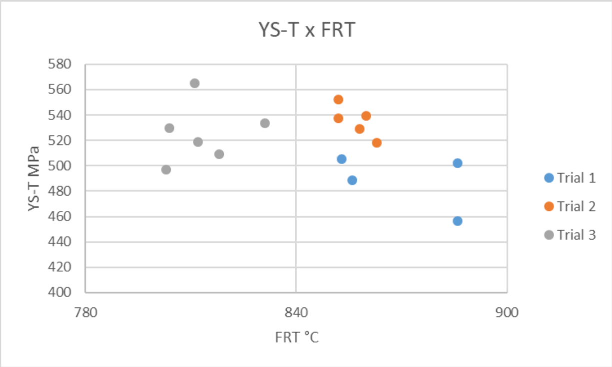

Figure 3: Transverse yield strength variation as a function of the FRT – Alloy 1.

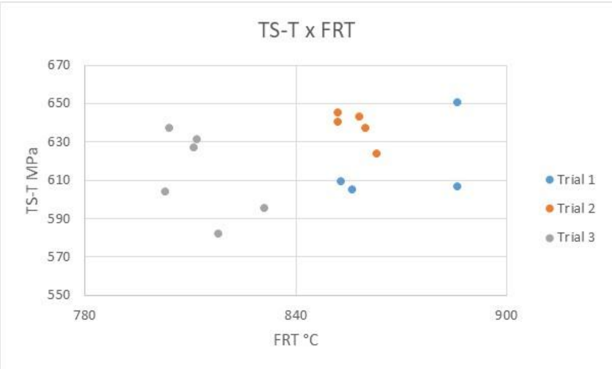

Figure 4: Transverse tensile strength variation as a function of the FRT – Alloy 1.

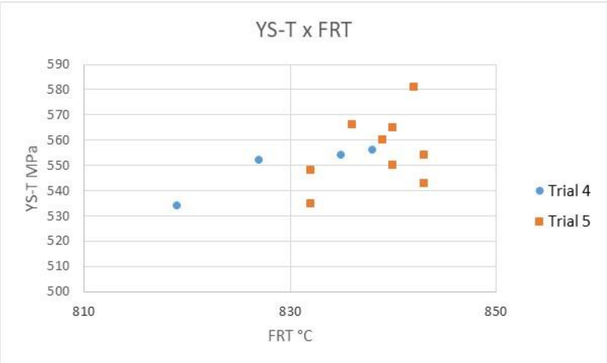

Figure 5: Transverse yield strength variation as a function of the FRT – Alloy 2.

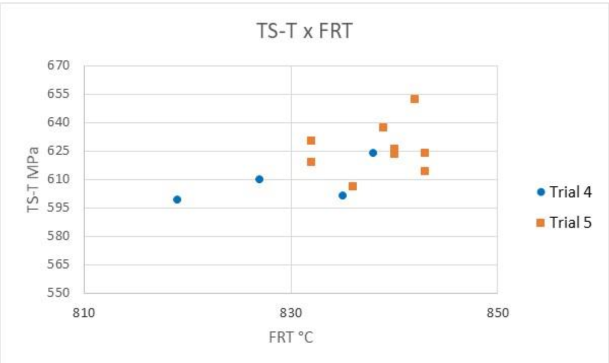

Figure 6: Transverse tensile strength variation as a function of the FRT – Alloy 2.

From the above figures it is noticeable that alloy 1 and alloy 2 have different trends for the YS as a function of the FRT. While alloy 1 exhibits an increase of YS as FRT decreases, alloy 2 shows the opposite behavior. Both alloys had the predominant contribution from grain refinement for the increase in YS, however, alloy 1 was affected by the lower rolling temperatures in trial 3, whereas alloy 2 was affected by the higher transfer thickness in trial 5.

Both materials showed higher TS as the FRT increased, which can be explained by the higher amount of phase transformation to bainite. For alloy 2 there was also the contribution of the higher RHT for trial 5, providing more microalloy carbon-nitrides in solution for precipitation.

For an assessment of the yield strength anisotropy, the difference between longitudinal and transverse YS as a function of the YS/TS ratio was determined, as shown on figures 7 and 8.

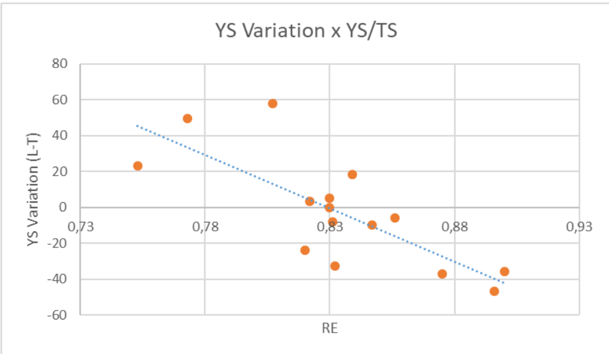

Figure 7: Yield strength anisotropy variation as a function of the YS/TS ratio for alloy 1.

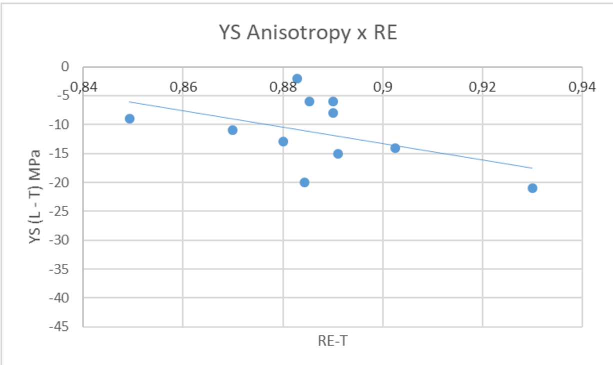

Figure 8: Yield strength anisotropy variation as a function of the YS/TS ratio for alloy 2.

The figures show that as the YS/TS ratio increases, the anisotropy tends to increase [5]. Additionally, figure 7 shows some data for alloy 1 where the longitudinal YS was higher than the transverse YS (data that exhibit positive YS variation values). This behavior was not expected, since the longitudinal YS should be lower due to texture interference. So further analysis involving texture determination by EBSD and/or X-Ray diffraction will be needed.

In order to control the anisotropy of yield strength, it was necessary to stablish a correlation with some process parameter. Figures 9 and 10 show the relation between YS/TS ratio and SCT.

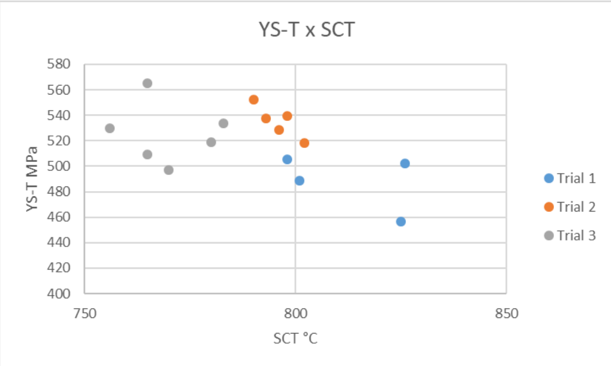

Figure 9: YS/TS ratio variation as a function of SCT for alloy 1.

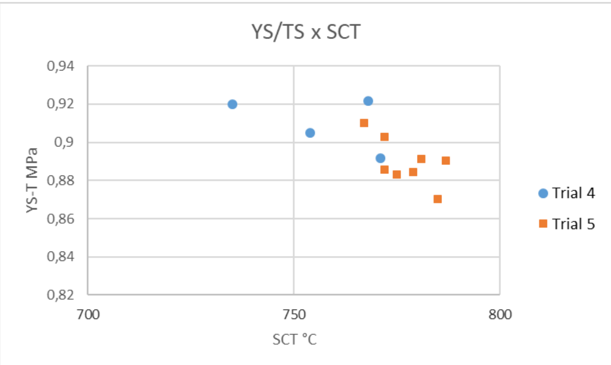

Figure 10: YS/TS ratio variation as a function of SCT for alloy 2.

Results for both alloys show that as the start cooling temperature decreases the YS/TS ratio increases. This happens because in lower temperatures more deformation is retained in austenite and as a result there is greater grain refinement that can promote higher YS/TS ratio values [6].

The microstructures for alloy 1 can be seen in figures 11 to 13.

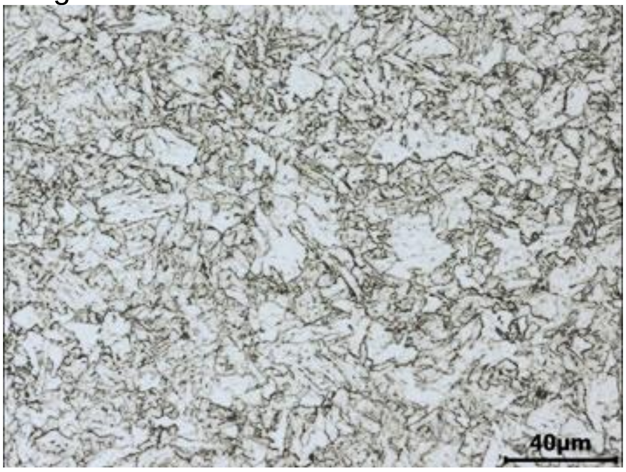

Figure 11: Microstructure for alloy 1 trial 1.

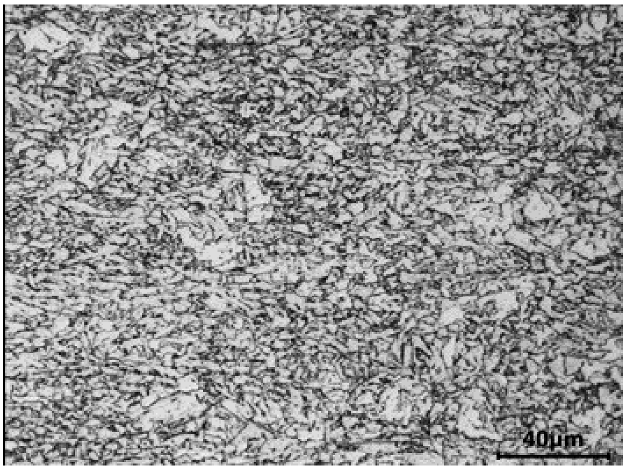

Figure 12: Microstructure for alloy 1 trial 2.

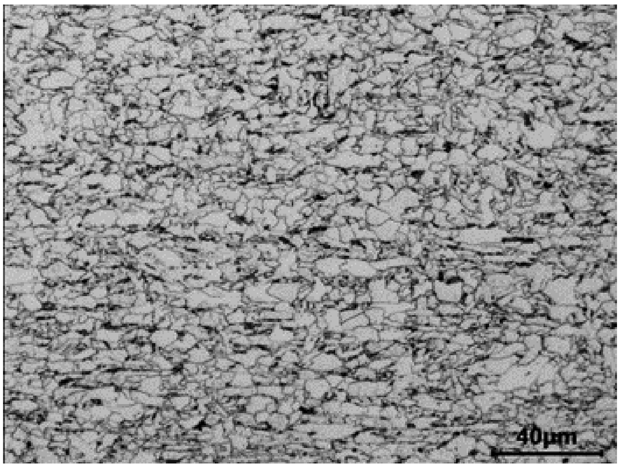

Figure 13: Microstructure for alloy 1 trial 3.

The microstructure obtained for trial 1 was composed of coarse bainite due to higher rolling temperatures. Trial 2, where the rolling temperatures were lower, the microstructure was mainly fine bainite. For trial 3 there was transformation to ferrite and carbides during the transportation of the plate from the rolling mill to the accelerated equipment.

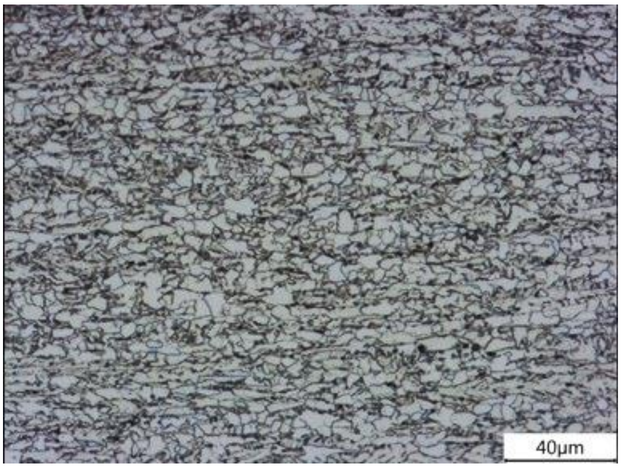

Figure 14: Microstructure for alloy 2 trial 4.

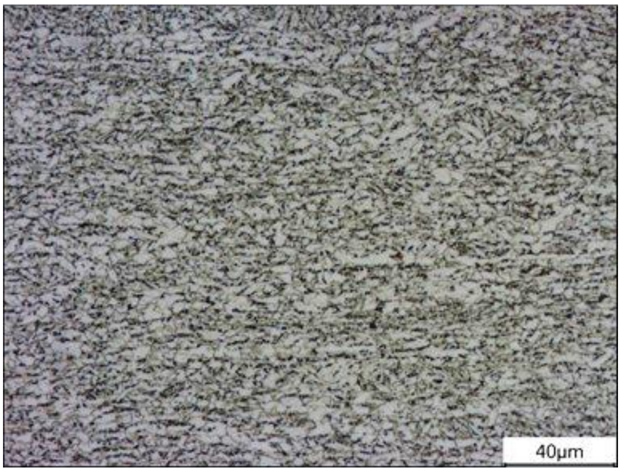

Figure 15: Microstructure for alloy 2 trial 5.

For alloy 2 the chemical composition was optimized in order to reduce the grain size and this resulted in a finer microstructure and better results for DWTT. Figure 14 shows the microstructure for alloy 2 trial 4, exhibiting a mix of fine polygonal ferrite, bainite, acicular ferrite and carbides. Figure 15 represents the microstructure for alloy 2 trial 5, having microconstituents of the same nature as trial 4, but much finer.

As mentioned, the DWTT results improved from alloy 1 to 2, as demonstrated on figures 16 and 17. The graphs represent the shear area variation with the final rolling temperature. As expected as FRT decreased, the DWTT results improved for alloy 1. For alloy 2 the shear area percentage maintained a constant performance.

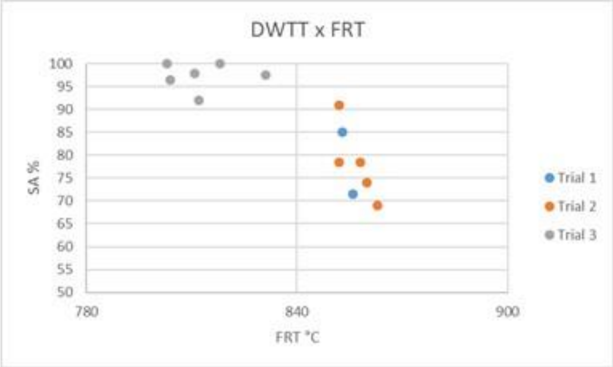

Figure 16: DWTT results for alloy 1.

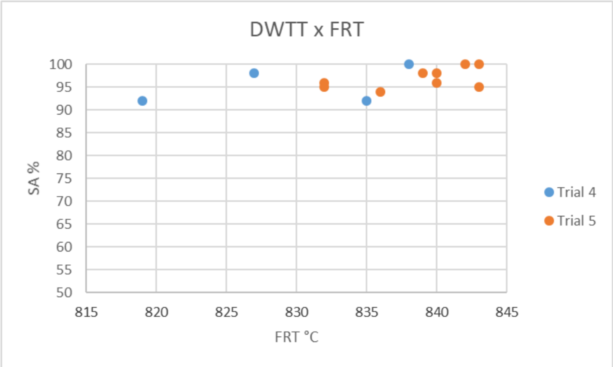

Figure 17: DWTT results for alloy 2.

Although trial 3 for alloy 1 showed good percentage of shear area, alloy 2 had much better stability.

One of the challenges of the DWTT for materials with high toughness is the occurrence of abnormal fracture or inverse fracture. The X70 produced by Gerdau presented this kind of phenomena, as shown on figure 18.

Figure 18: DWTT test piece surface showing inverse fracture.

As a measure to minimize the occurrence of inverse fracture, a reduced specimen was used as allowed by API RP 5L3, where a reduction on the test temperature is necessary to compensate the smaller cross section of the test piece. Figures 19 and 20 show a comparison between the full size DWTT specimen and the reduced specimen.

Figure 19: DWTT full size specimen.

Figure 20: DWTT reduced specimen.

The figures show that the reduced specimen is capable of minimizing the inverse fracture [7], in a level that is possible to discard the affected region during the shear area measurement.

4 CONCLUSION

This paper showed the results of the development of 28.15 mm thick plates for X70 API pipes, and the correlations between process and product properties were stablished. Differences in microstructure and DWTT performance were compared using 2 alloy designs. The results showed that an optimized chemical composition and rolling parameters can achieve better microstructure and overall mechanical properties.

Anisotropy is an important issue to be addressed in recent specifications, where strict control of the rolling parameters become critical. Moreover, to better understand the phenomena it is necessary to obtain data on the textures produced during rolling, using advanced techniques such as EBSD.

Inverse fracture is another issue that materials having high level of toughness exhibit. This kind of result invalidates the DWTT, making it impractical for routine testing. This issue was partially mitigated using reduced specimens, however, further research is necessary to completely eliminate the problem.

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