WEAR AND FRACTURE PREVENTION

Proceedings of a conference held
21-22 May 1980
Peoria, Illinois

Sponsored by the
ASM Peoria Chapter
and
ASM Technical Divisions

Organized under the direction of
B. N. PRAKASH BABU
Caterpillar Tractor Company

MATERIALS/METALWORKING TECHNOLOGY SERIES

American Society for Metals
Metals Park, Ohio 44073

THE EFFECT OF INCLUSIONS ON THE PROPERTIES OF CONSTRUCTIONAL STEELS

Alexander D. Wilson
Senior Research Engineer
Lukens Steel Company
Coatesville, PA 19320

ABSTRACT

The influence of nonmetallic inclusions on the mechanical properties of two constructional heavy gage, plate steels, A633C and A514F is reported. In particular the effect of calcium treatment on the inclusions and on the tensile ductility, Charpy-V-notch and dynamic tear impact toughness, and the fatigue crack propagation behavior of these steel grades is given. Calcium treatment was found to give the most dramatic improvements to percent reduction of area and fatigue crack propagation growth rate in the through-thickness testing orientation, while the Charpy-V-notch and dynamic tear toughness were improved in all testing orientations. Also, it was noted that generally larger improvements to all mechanical properties were realized for the higher strength A514F in comparison to A633C.

INTRODUCTION

It has been widely established that indigenous nonmetallic inclusions have an adverse effect on the ductility, toughness and weldability of steels (1,2). Therefore minimization of these inclusions has been pursued using various steelmaking practices when improvements in the above properties are required. One such advanced steelmaking technique is Calcium Treatment (CaT), which leads to steels with lower inclusion and sulfur levels and inclusion shape control such as Lukens' "Fineline"[R] steels. A wide range of plate steel

---

[R] Registered trademark of Lukens Steel Company.

grades are produced using CaT and have been used in applications ranging from nuclear pressure vessels, wind turbines, to offshore oil drilling rigs. This is because steels produced using CaT have enhanced toughness and fatigue properties to improve service performance and resist "lamellar tearing" on welding during fabrication. This behavior is similarly desired for steels used in heavy construction equipment.

Specifically, CaT has been found to improve the levels of tensile ductility, particularly in the through-thickness testing orientation, Charpy-V-notch and Dynamic Tear impact and J_{Ic} fracture toughness, and the fatigue endurance limit and fatigue crack propagation properties in a number of plate steels (1-6). In many instances the properties have approached the quality of electroslag remelted (ESR) steels, which have been shown to supply a superior level of properties in plate steels (1-3,7,8).

In this paper two steel grades, A633C and A514F, that are used in the heavy equipment industry are evaluated. In both cases heavy gage plates in both the CaT and conventionally produced (CON) quality levels are examined.

TEST MATERIALS

A633C is a C-Mn-Cb, heat treated, microalloyed (0.05% maximum columbium) steel, which relies on its very fine grain size to give excellent toughness transition properties (9,10). In addition A633C has a lower carbon content than other carbon steels, 0.20% maximum versus 0.27 - 0.31% maximums for A516-70 for example, thus giving good upper shelf toughness due to decreased levels of carbides in the structure. The yield point minimums of A633C are 345 MPa (50 ksi) for plates up to 63.5 mm (2½ in.) and 317 MPa (46 ksi) for plates 63.5 - 102 mm (2½ - 4 in.). Inclusion control by CaT has been shown to be particularly helpful to A633C in improving properties (6,9,10). In this evaluation the properties of two, 102 mm (4 in.) thick normalized plates of CON and CaT quality were determined. Both plates exhibited a very fine ferritic-pearlitic microstructure. The chemistries of these two plates are given in Table 1. The effect of CaT is principally shown in the sulfur level difference of 0.006% for the CaT plate and 0.021% for the plate produced using a conventional electric furnace practice (CON).

Table 1. Test Materials.

Grade	Quality	Plate Thickness in.	(mm)	Chemistry (weight percent) C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Al	Cb
A633C	CON	4	(102)	.13	1.41	.011	.021	.24	.23	.23	.20	.057	.001	.049	.026
	CaT	4	(102)	.14	1.46	.007	.006	.17	.24	.26	.21	.081	.002	.032	.025
A514F	CON	2¼	(57)	.17	.88	.009	.014	.27	.22	.91	.57	.52	.054	.022	--
	CaT	2¼	(57)	.16	.86	.011	.006	.26	.19	.95	.63	.45	.046	.045	--

CON - Conventional Electric Furnace Heat.

CaT - Calcium Treated Electric Furnace Heat.

Heat Treatment: A633C - Normalized 1650°F (899°C) and air cooled.

A514F - 1650°F (899°C) water quenched, tempered 1150°F (621°C) water quenched, stress relieved 1100°F (593°C) air cooled. Note: It is normally not recommended that this grade of steel be stress relieved, however due to the effect of residual stresses on FCP testing, stress relieving was required for these plates.

A514F is a high strength, quenched and tempered, structural alloy steel. Alloying additions of Ni, Cr, Mo, V and B are used to obtain the martensitic microstructure that gives this grade its 690 MPa (100 ksi) minimum 0.2% yield strength for plates up to 63.5 mm (2½ in.) thick. Properties of this grade have also been found to improve after CaT (6). In this investigation the properties of two, 51 mm (2¼ in.) thick plates were established. The chemistries of the CON and CaT quality plates are given in Table 1. Once more the difference in sulfur level is obvious.

INCLUSIONS IN TEST MATERIALS

Indigenous inclusions precipitate as discrete phases during the solidification of molten steel; i.e. sulfides and oxides, whereas exogenous inclusions result from the entrapment of exterior materials relative to the molten steel, such as refractory of slag. The indigenous inclusions that remain in steel are primarily a result of the steelmaking practice that is used in melting and refining (1,2). Generally aluminum-killed plate steels, such as A633C and A514F, tend to have the same kinds of inclusions when produced by the same steelmaking technique (1,2). Additionally, the solidification procedures and rolling practices can influence the size, shape and distribution of these inclusions (2,11).

In general, steels produced by CaT have significantly lower levels of indigenous nonmetallic inclusions when compared to steels produced by conventional steelmaking practice (CON) (1,2,4). The predominant inclusions in CON quality steel are Type II manganese sulfide and alumina (Al_2O_3) inclusions. In CaT steels the presence of both of these inclusion types is minimized and the most prevelant inclusions are Type III MnS and duplex, calcium modified sulfide-alumina inclusions.

The Type II MnS inclusions in CON steels are associated in formations or patches and have a characteristic interdendritic pattern as shown somewhat in Figure 1, but more dramatically in the scanning electron microscopy (SEM) fractograph in Figure 2. In addition these MnS inclusions are easily deformed at hot rolling temperatures and elongate, forming stringers and elongated pancakes, as noted in Figures 1 and 2. The Al_2O_3 inclusions in CON steels also are present in groups, called galaxies and are a direct result

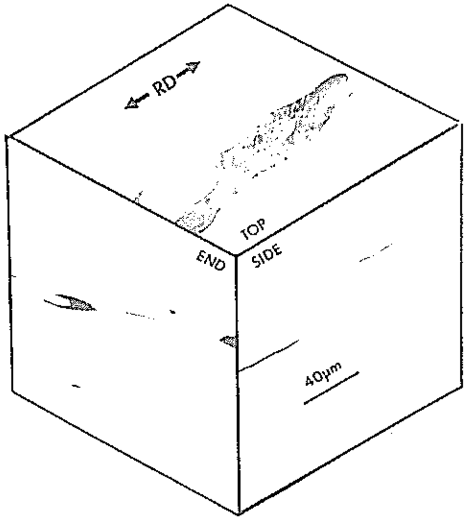

Figure 1 - Composite of light photomicrographs showing Type II MnS inclusions in CON A633C steel.

Figure 2 - SEM fractograph of through-thickness (SL) CVN fracture revealing Type II MnS inclusions in CON A633C steel.

of the aluminum addition for deoxidation of the molten steel. Although the individual Al_2O_3 inclusions do not deform on hot rolling, as a group the galaxy is spread out and elongated. This is indicated to some degree in Figures 3 and 4. Both of these inclusion types affect not only the level, but also the isotropy of certain mechanical properties in CON steels. This is due not only to the presence of the inclusions themselves, but also to their association in groups.

As mentioned previously, CaT minimizes the formation of the above inclusion types. This is done through desulfurization (0.010% maximum sulfur) and inclusion modification and shape control. Type III MnS inclusions are present in CaT steels at higher sulfur levels, while at very low sulfur contents (e.g., less than 0.003%) no MnS inclusions are found. In the CaT A633C and A514F steels investigated in this program some Type III MnS inclusions were noted. Type III MnS inclusions tend to be smaller and more uniformly distributed than Type II, although they still elongate on hot rolling. The types of calcium modified inclusions that are present in CaT steels are normally duplex in nature, being comprised of a sulfide phase and an aluminate phase. Typical Ca modified inclusions are shown in Figs. 5 and 6. The chemical make-up of a sample inclusion is shown in Figure 7. Ca modified inclusions normally have a Ca and/or Mg aluminate phase which is dark color in light and electron microscope images. The beneficial presence of Mg is due to pick-up from refractory materials. The lighter colored sulfide phase is a compound with Ca and/or Mn. These duplex inclusions tend to resist deformation on hot rolling and thus the terminology "inclusion shape control" is applicable. The above inclusion modification in CaT steels is additionally beneficial because of the minimization of the presence of the inclusion formations or groups that are commonplace in CON steels.

In the A514F steels there is an additional inclusion type present, namely titanium nitrides. These are present in both CON and CaT steels and appear to be unaffected by CaT. They are present because of the use of titanium to lower the nitrogen in solution in steel to allow for efficient use of the Boron addition to this steel grade.

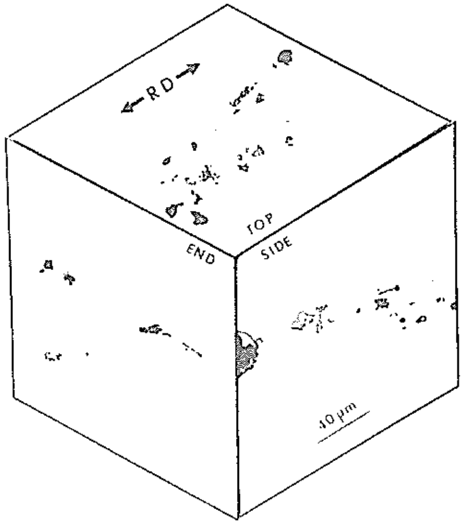

Figure 3 - Composite of light photomicrographs showing Al_2O_3 inclusion galaxies in CON A633C steel.

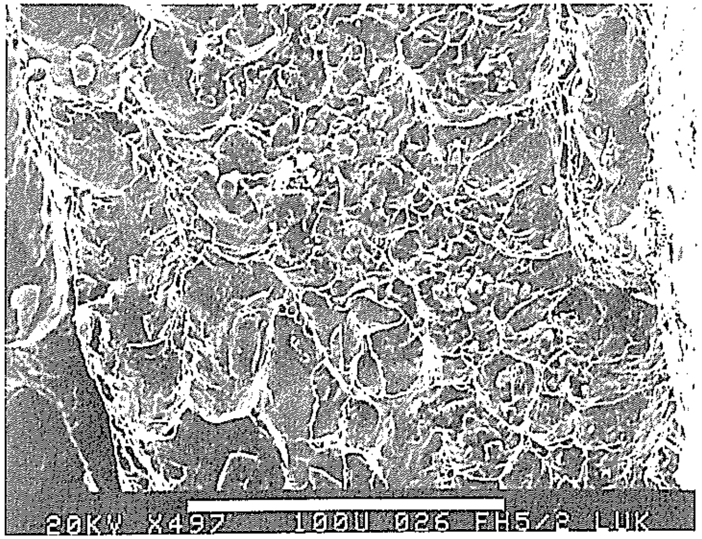

Figure 4 - SEM fractograph of through-thickness (SL) CVN fracture revealing Al_2O_3 inclusion galaxies in CON A633C steel.

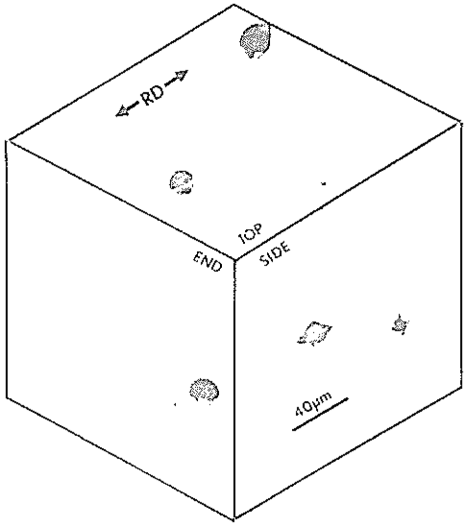

Figure 5 - Composite of light photomicrographs showing calcium modified inclusions in CaT A633C steel.

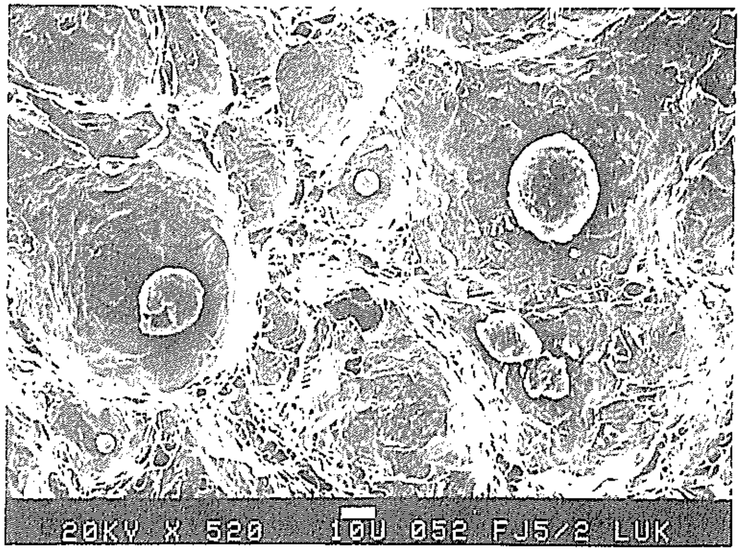

Figure 6 - SEM fractograph of through-thickness (SL) CVN fracture revealing calcium modified inclusions in CaT A633C steel.

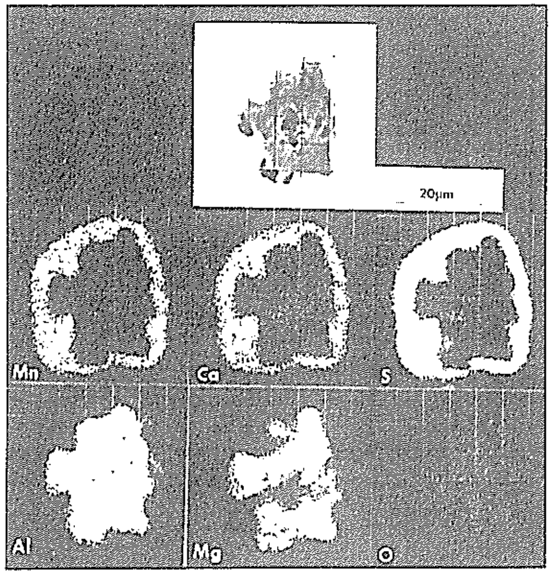

Figure 7 - Electron microprobe X-ray images of calcium modified inclusion in a CaT steel.

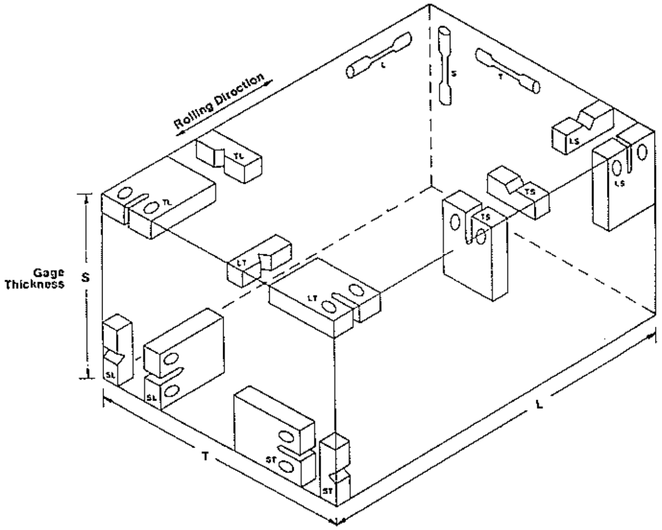

Figure 8 - Testing orientations used in this investigation, according to ASTM E399 (12).

MECHANICAL PROPERTIES

The mechanical property tests used in this investigation were performed following the applicable ASTM test methods (12). Specimens for all 4 test plates were taken at center-gage. Testing orientations and designations that were used in this study are shown in Figure 8. Tensile, Charpy-V-notch impact (CVN), dynamic tear (DT) and fatigue crack propagation (FCP) tests were used to characterize each plate. Certain parameters representative of each of the tests will be discussed below. Other mechanical property information that is not given in the following discussion is provided in Table 2.

Tensile Percent Reduction of Area

Tensile tests were performed in the 3 major testing orientations for all 4 plates. The strength levels for the A633C plates ranged from 324-379 MPa (47-55 ksi) in 0.2% yield strength and 510-552 MPa (74-80 ksi) in ultimate tensile strength, while the results for the A514F plates were 745-800 MPa (108-116 ksi) and 758-855 MPa (110-124 ksi) respectively. A comparison of the tensile percent reduction of area is given in Figure 9. In both steel grades the primary improvement by CaT is found in the through-thickness (S) testing orientation. Furthermore, a more dramatic improvement of CaT over the CON steel was shown in the A514F steel than was present for the A633C steels.

The percent reduction of area is commonly used as a quality control parameter to assure a steel is resistant to "lamellar tearing" (13). Therefore, improvements demonstrated in this parameter by CaT indicate that the CaT quality plates would be expected to be generally more resistant to "lamellar tearing" for these two steel grades.

Impact Toughness

The impact toughness properties of steels are used to establish guidelines for the resistance of a steel to fracture in the presence of notches or cracks. Both the CVN and DT impact toughness properties of the 4 plates were determined. Six testing orientations were used in CVN testing and two in DT testing. The comparison of the upper shelf energies (USE) in 3 of the major testing orientations for CVN and two orientations for DT are given in Figures 10 and 11.

Table 2. Summary of Other Mechanical Properties.

<u>A633C 102 mm (4 in.) Plates</u>

	% El.	CVN USE	NDT	n
CON	23/26	290/61 J	-54°C	3.1/3.6
		214/45 ft-lbs	-65°F	
CaT	29/33	302/134 J	-62°C	2.9/3.1
		223/99 ft-lbs	-80°F	

<u>A514F 57 mm (2¼ in.) Plates</u>

	% El.	CVN USE	NDT	n
CON	2/21	129/16 J	-90°C	2.6/5.1
		95/12 ft-lbs	-130°F	
CaT	14/19	152/46 J	-79°C	2.7/3.5
		112/34 ft-lbs	-110°F	

% El. - Range of Tensile Percent elongations, L, T, S orientations.

CVN USE - Range of CVN upper shelf energies, 6 orientations.

NDT - Nil-ductility temperature, TS orientation.

n - Range of Exponents in FCP equation {1}, 6 orientations.

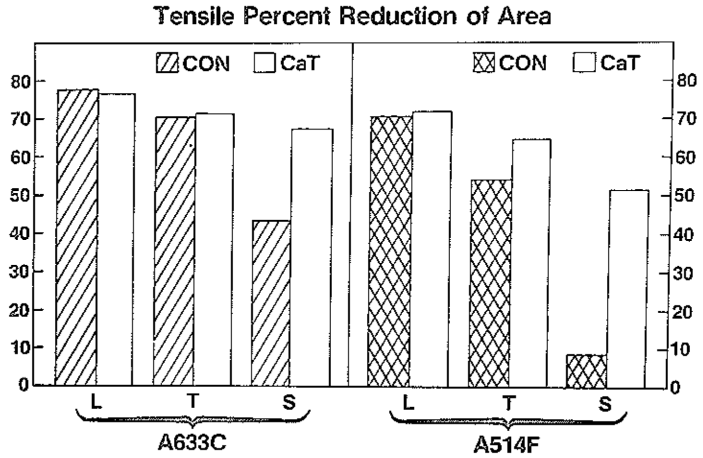

Figure 9 - Comparison of average tensile percent reduction of area results for A633C and A514F plates.

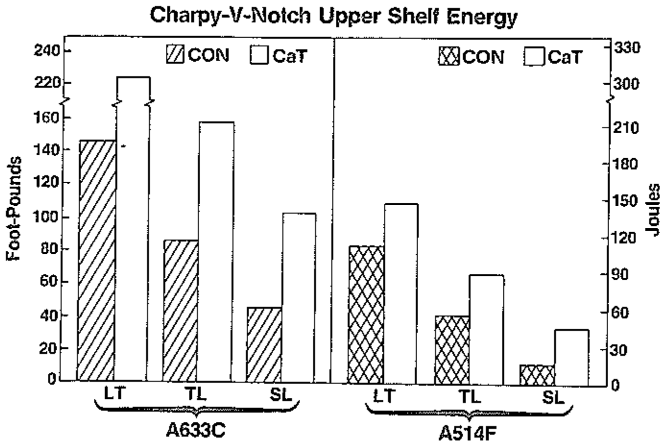

Figure 10 - Comparison of Charpy-V-notch upper shelf energies for A633C and A514F plates.

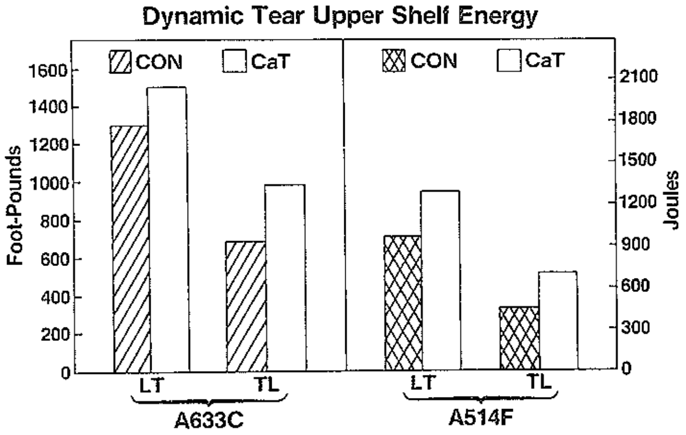

Figure 11 - Comparison of dynamic tear upper shelf energies for A633C and A514F plates.

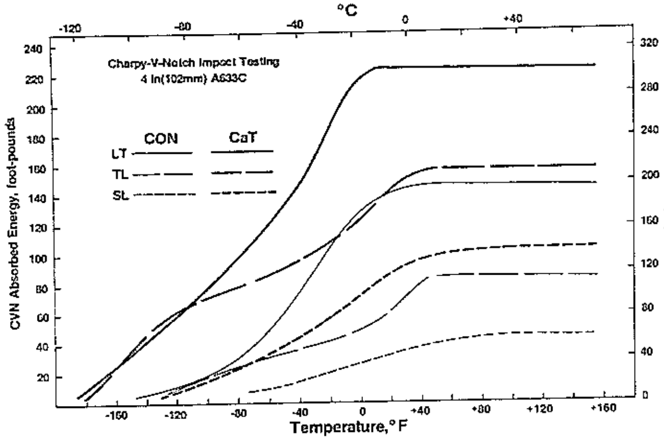

Figure 12 - Charpy-V-notch transition curves in 3 testing orientations for both A633C plates.

Inclusion effects are most prominantly displayed on the upper shelf for all toughness tests because the fracture mode is totally ductile fracture (dimpled rupture). However, the benefits of inclusion control by CaT are also found at lower temperatures in the toughness transition area. This is shown for the A633C plates in Figure 12. In this figure it can be noted that although the single largest improvement is at temperatures on the upper shelf, there still are benefits to CaT shown down to temperatures as low as -60°C (-76°F).

The impact toughness of both steel grades is significantly improved in all testing orientations in both CVN and DT testing. It would also be expected that the fracture toughness of A633C and A514F steels would show an improvement by CaT. Previous work has also shown the enhancement of the J_{Ic} (initiation value of the J-Integral, a measure of fracture toughness) by CaT in steels with a wide range of strength levels (4,5). The higher levels of CVN USE and DT USE for CaT steels in general in the transverse (TL) testing orientation for a number of plate steel grades over a wide range of strength levels is shown in Figures 13 and 14.

Fatigue Crack Propagation

FCP tests were performed in 6 specimen orientations as noted in Figure 8 for all 4 test plates. The FCP results were analyzed by fitting the data to the Paris FCP equation (14):

$$da/dN = C_o \Delta K^n \qquad \{1\}$$

Where da/dN is the fatigue crack growth rate, ΔK is the range of stress intensity factor and C_o and n are material constants. Plots of the best fit lines for the A514F plates are shown in Figure 15. The increased isotropy in the CaT over the CON steels is evident with the through thickness (ST,SL) orientation having the fastest growth rate in the CON steel and showing the greatest improvement by CaT. Figures 16 and 17 show the FCP data summarized in the form of scatterbands encompassing all of the data results for each plate. In these presentations the generally faster FCP growth rates for the CON steels at higher ΔK levels is displayed, as well as the improved isotropy of the CaT steels. A further

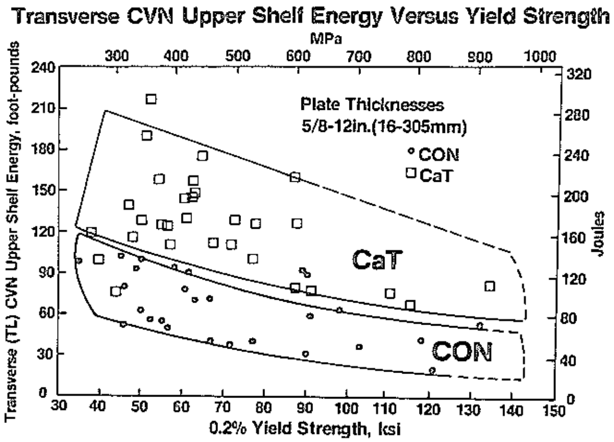

Figure 13 - Summary of Charpy-V-notch upper shelf energy data in transverse (TL) orientation versus 0.2% yield strength for data presented in this paper and from other sources.

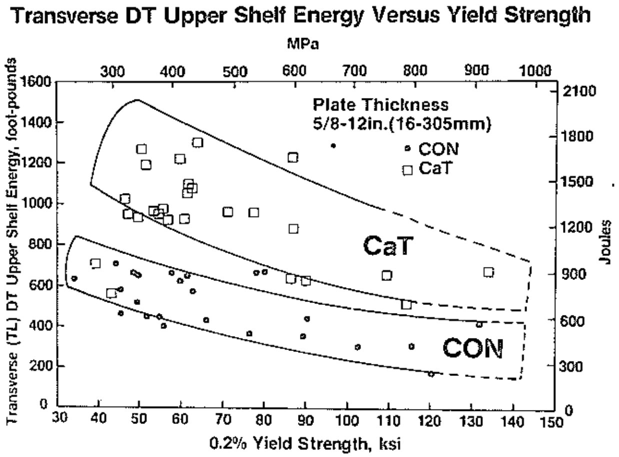

Figure 14 - Summary of dynamic tear upper shelf energy data in transverse (TL) orientation versus 0.2% yield strength for data presented in this paper and from other sources.

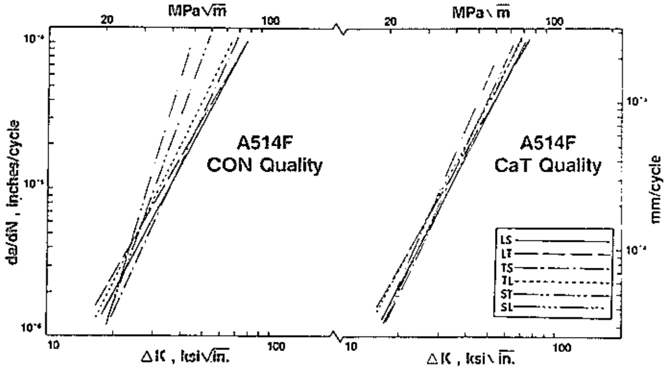

Figure 15 - Plots of fatigue crack growth rate versus range of stress intensity factor (best fit lines) for A514F plates.

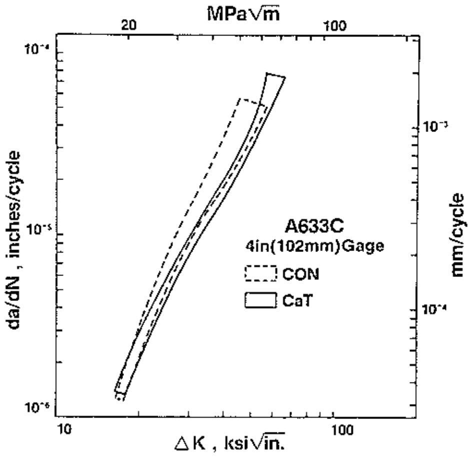

Figure 16 - Summary scatterbands of fatigue crack growth rate versus range of stress intensity factor encompassing all data points in 6 orientation testing comparing CON and CaT quality A633C plates.

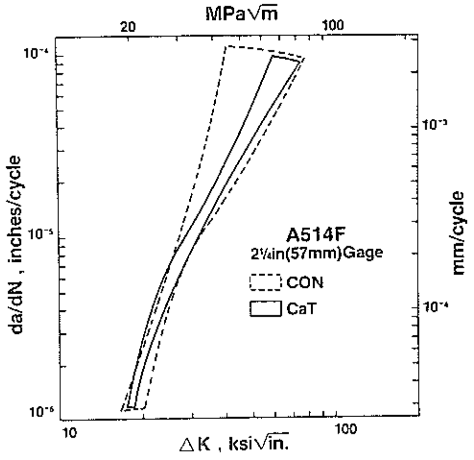

Figure 17 - Summary scatterbands of fatigue crack growth rate versus range of stress intensity factor encompassing all data points in 6 orientation testing comparing CON and CaT quality A514F plates.

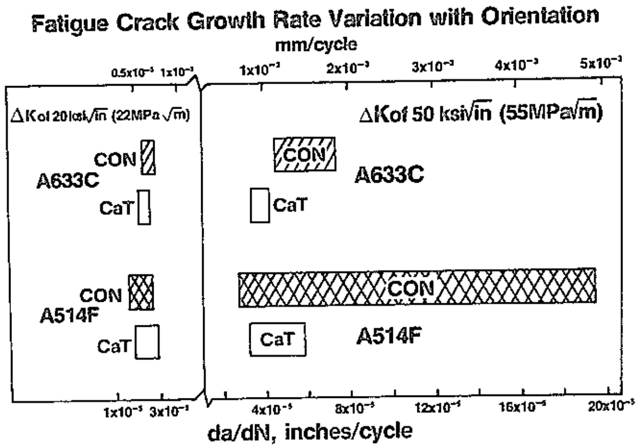

Figure 18 - Comparison of fatigue crack growth rate variation with orientation for A633C and A514F plates at two ΔK levels.

comparison is given in Figure 18, which shows that the CaT improvement in FCP growth rate takes place only at higher ΔK levels. Additionally, this figure indicates that there is a more substantial enhancement in FCP behavior for A514F. Also there generally appears to be more anisotropy in the A514F steels of both quality levels. It has previously been shown that higher strength level steels tend to be more adversely affected by inclusions associated in groups, such as present in CON steels (15).

DISCUSSION

The preceding results indicate that there is a varying degree of improvement by CaT for these A633C and A514F plates depending on the type of mechanical test being used. Although the tensile ductility is slightly improved in the transverse orientation (T), the primary benefit by CaT is found in the through-thickness (S) testing orientation, particularly for the higher strength A514F. However, in CVN and DT, impact testing there is a significant increase demonstrated in all testing orientations for both steel grades. The FCP properties of both steel grades were found to be principally improved in the through-thickness (ST, SL) testing orientations. Overall, however, the largest benefit to FCP properties for CaT was exhibited in the higher strength A514F steel. The reasons for the above differences relates to the effective plastic zone acting in the particular test and the strength level effect on the interaction of a crack front and the inclusion formations in the CON steels (4,15).

The inclusion formations in CON steels tend to act as local planes of weakness in the through-thickness direction and this tends to cause the greatest drop-off in all properties in this orientation, but particularly so in tensile ductility and FCP testing. In the transverse oriented tests the elongated individual or groups of inclusions act as sites for crack nucleation and propagation and this leads to some decrease in property levels in this orientation, primarily for impact toughness testing. Previous work (1,2,4) has developed correlations between these mechanical properties and actual inclusion structure measurements. The tensile ductility and FCP properties were found to correlate best with a measure of inclusion area on the plane of fracture, while toughness properties relate best to a measure of inclusion length. However, in both situations the inclusion shape control benefits of CaT are important in that both flattened, pancaked inclusions and elongated inclusions are minimized. Furthermore, the presence of inclusion groups is limited as well.

CONCLUSIONS

The ductility, toughness and fatigue properties of these heavy gage A633C and A514F plates were found to be improved by CaT. These improvements were shown to be most dramatic for the through-thickness testing orientations in percent reduction of area and fatigue crack propagation behavior and in all testing orientations in Charpy-V-notch and dynamic tear testing. Additionally, it was noted that CaT appeared to give larger improvements in the higher strength A514F steel.

In general it has now been shown that CaT can improve the properties of a wide range of aluminum-killed steel grades, whether the steel is a carbon or alloy steel, in the heat treated or as-rolled condition or is a light or heavy gage plate. Our future studies will continue to investigate this area of the interaction of inclusions and mechanical properties of a wide range of plate steels.

ACKNOWLEDGEMENTS

The author wishes to particularly acknowledge the efforts of L. P. Kerr in performing the mechanical tests in this study. The assistance of J. R. Lohr and D. R. Metzgar in the metallographic studies is also noted. The comments and review of the manuscript by J. A. Gulya is also appreciatively acknowledged.

DISCLAIMER

REFERENCES

(1) Wilson, A. D., "The Effect of Advanced Steelmaking Techniques on the Inclusions and Mechanical Properties of Plate Steels," in Toughness Characterizations and Specifications for HSLA and Structural Steels, ed. P. L. Manganon, Jr., The Metallurgical Society of AIME, 1979.

(2) Wilson, A. D., "The Influence of Thickness and Rolling Ratio on the Inclusion Behavior in Plate Steels," Metallography, Vol. 12, 1979, pp. 233-255.

(3) Wilson, A. D., "Fatigue Crack Propagation in A533B Steels", ASME Journal of Pressure Vessel Technology, Vol. 99, No. 3, Aug. 1977, pp. 459-469.

(4) Wilson, A. D., "The Influence of Inclusions on the Fatigue and Toughness Properties of A516-70 Steel", ASME Journal of Engineering Materials and Technology, Vol. 101, No. 3, July 1979, pp. 265-274.

(5) Wilson, A. D., "The Characterization of Plate Steel Quality Using Various Toughness Measurement Techniques", in Elastic-Plastic Fracture, ASTM STP 668, ASTM, 1979, pp. 469-492.

(6) Wilson, A. D., "Calcium Treatment of Plate Steels and Its Effect on Fatigue and Toughness Properties", proceedings of the 11th Annual Offshore Technology Conference, OTC3465, April 30 - May 3, 1979, pp. 939-948.

(7) Swift, R. A., "Advantages of Electroslag Remelted Steels", Offshore Technology Conference, May 2-5, 1977, OTC2799, Vol. 1, pp. 553-564.

(8) Gulya, J. A. and Swift, R. A., "Improved 2¼ Cr-1 Mo Pressure Vessel Steel Through Electroslag Remelting", Trans. ASME Journal of Pressure Vessel Technology, 98, Nov. 1976, pp. 298-308.

(9) Entrekin, Jr., C. H., Roper, Jr., C. R., Wilson, A. D., "Heat Treated Columbium Steel Plate for Low Temperature Applications", in Toughness Characterizations and Specifications for HSLA and Structural Steels, ed. P. L. Manganon, Jr., The Metallurgical Society of AIME, 1979.

(10) Wilson, A. D., "The Fatigue and Toughness Properties of a C-Mn-Cb Plate Steel", accepted for publication Trans. ASME Journal of Engineering Materials and Technology.

(11) Wilson, A. D., "The Effect of Plate-Rolling on Inclusion Morphology", Mechanical Work and Steel Processing XVII, Iron and Steel Society of AIME, 1979, pp. 19-32.

(12) 1979 Annual Book of ASTM Standards, Part 10, ASTM, Philadelphia.

(13) Farrar, J. C. M., Charles, J. A., and Dolby, R. E., Metallurgical Aspects of Lamellar Tearing", in Effect of Second-Phase Particles on the Mechanical Properties of Steel, The Iron and Steel Institute, London, 1971, p. 171.

(14) Paris, P. C., "The Fracture Mechanics Approach to Fatigue", Fatigue, An Interdisciplinary Approach, Syracuse University Press, 1964, pp. 107-132.

(15) Wilson, A. D., "Fractographic Characterization of the Effect of Inclusions on Fatigue Crack Propagation", presented ASTM Symposium on Fractography and Materials Science, November 1979, Williamsburg, Va., to be published.