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(54) **Title:** ABRASION RESISTANT STEEL, METHOD OF MANUFACTURING AN ABRASION RESISTANT STEEL AND ARTICLES MADE THEREFROM

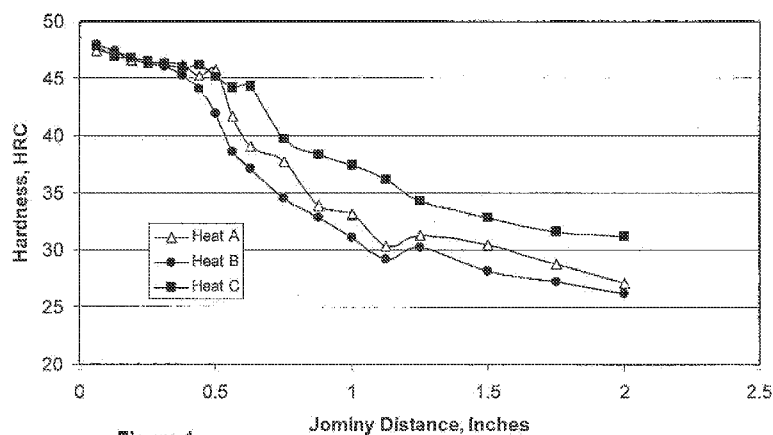


Figure 1

(57) **Abstract:** An abrasion resistant steel consisting essentially of, in weight %: 0.20-0.30% carbon, 0.40-1.25% manganese, 0.05% maximum phosphorous, 0.01% maximum sulfur, 0.20-0.60% silicon, 0.50-1.70% chromium, 0.20-2.00% nickel, 0.07-0.60% molybdenum, 0.022-0.10% titanium, 0.001-0.10% boron, 0.027-0.10% aluminum, balance iron, and incidental impurities. The steel may be melted and cast into a steel ingot or slab, hot rolled to a desired plate thickness; austenitized at 1650-1700°F; water quenched; and tempered at 350-450 °F. The resulting steel plate may have a surface hardness of at least 440 HBW, a mid-thickness hardness of at least 90% of the surface hardness, and toughness in the transverse direction at -60°F of at least 20 ft-lbs and at room temperature of at least 40 ft-lbs.

ABRASION RESISTANT STEEL, METHOD OF MANUFACTURING AN ABRASION RESISTANT STEEL AND ARTICLES MADE THEREFROM

BACKGROUND OF THE INVENTION

Field of the Invention

[0001] The present invention relates to an abrasion resistant steel and, more specifically, to an abrasion resistant steel having good hardenability, good weldability, and high toughness, and a method of manufacturing same.

Description of Related Art

[0002] Steels used to manufacture tools used for extraction, movement, and processing of abrasive materials such as liners for haul truck beds, bulldozers, chutes, and other material handling equipment for the mining (coal, hardrock, gold, silver, and others), timber and paper, biomass, quarrying, and other similar industries must have high abrasion and wear resistance as well as high toughness to avoid fracture. Generally, abrasion resistance and wear resistance increase as hardness and hardenability increase while toughness often decreases with increased hardness and hardenability. Therefore, it is desired that steels for these applications possess a combination of high hardness and hardenability and good toughness.

[0003] Such steels generally include significant amounts of alloying elements such as Cr, Ni, Si, and Al to achieve the high hardness and hardenability in combination with good toughness which can make them expensive and difficult to weld.

SUMMARY OF THE INVENTION

[0004] The present invention is directed to an abrasion resistant steel, a method for making an abrasion resistant steel plate, and articles made therefrom. The steel of the present invention consists essentially of in weight %: 0.20-0.30% carbon, 0.40-1.25% manganese, 0.05% maximum phosphorous, 0.01% maximum sulfur, 0.20-0.60% silicon, 0.50-1.70% chromium, 0.20-2.00% nickel, 0.07-0.60% molybdenum, 0.022-0.10% titanium, 0.001-0.10% boron, 0.027-0.10% aluminum, balance iron, and incidental impurities. The inventive steel plate may have a microstructure of tempered martensite, a surface hardness of at least 440 HBW, a mid-thickness hardness that is at least 90% of the surface hardness, and a toughness in the transverse direction at -60°F of at least 20 ft-lbs and at room temperature of at least 40 ft-lbs.

[0005] The inventive method of making the abrasion resistant steel plate of the invention comprises melting and casting a steel ingot or slab of the composition detailed above, hot rolling the ingot or slab to a plate of the desired thickness, austenitizing the plate at 1650-1700°F, water quenching the plate, and tempering the plate at 350-450 °F.

BRIEF DESCRIPTION OF THE DRAWING(S)

[0006] Fig. 1 shows Jominy hardenability curves for laboratory melted heats of abrasion, resistant steel and a prior art steel;

[0007] Fig. 2A shows Charpy impact energies for longitudinal samples from laboratory produced plates of abrasion resistant steel; and

[0008] Fig. 2B shows Charpy impact energies for transverse samples from laboratory produced plates of abrasion resistant steel.

DESCRIPTION OF THE PREFERRED EMBODIMENT(S)

[0009] The abrasion resistant steel of the present invention consists essentially of, in weight %: 0.20-0.30% carbon, 0.40-1.25% manganese, 0.05% maximum phosphorous, 0.01% maximum sulfur, 0.20-0.60% silicon, 0.50-1.70% chromium, 0.20-2.00% nickel, 0.07-0.60% molybdenum, 0.022-0.10% titanium, 0.001-0.10% boron, 0.027-0.10% aluminum, balance iron, and incidental impurities. It may more narrowly consist essentially of, in weight %: 0.22-0.26% carbon, 0.70-0.90% manganese, 0.025% maximum phosphorous, 0.003% maximum sulfur, 0.20-0.40% silicon, 0.80-1.00% chromium, 0.40-0.60% nickel, 0.07-0.15% molybdenum, 0.022-0.04% titanium, 0.001-0.003% boron, 0.027-0.06% aluminum, balance iron, and incidental impurities. And nominally, the composition may consist essentially of, in weight %: 0.24% carbon, 0.80% manganese, 0.010% maximum phosphorous, 0.003% maximum sulfur, 0.25% silicon, 0.90% chromium, 0.50% nickel, 0.10% molybdenum, 0.03% titanium, 0.0015% boron, 0.035% aluminum, balance iron, and incidental impurities.

[0010] The ranges for each alloying element have been chosen to achieve the necessary hardness and hardenability while maintaining good weldability. The lower limit for each alloying element is necessary to achieve the desired hardness and the upper limit is necessary to assure good weldability. In addition, Cr + Mn + Mo may equal 1.4% minimum and/or Ni + Si + Cr may equal 1.4% minimum, and/or Cr + Si may equal 1% minimum in order to assure that the necessary hardness and hardenability are achieved to provide good wear resistance.

[0011] The steel may be melted and cast into ingots or slabs. During the melting and casting, the steel may be killed, desulfurized, vacuum degassed, and treated for sulfide shape control according to common methods known in the art. Desulfurization and/or sulfide shape control may be used to reduce the amount of large sulfide inclusions that can contribute to a reduction in toughness by acting as crack nucleation sites.

[0012] The steel may then be hot rolled into plate of 1 inch or less in thickness. Cross-rolling may be utilized to improve toughness in the transverse direction. The steel plate may be held for a minimum of 24 hours prior to heat treating to allow any hydrogen from the melting and/or hot rolling processes to outgas from the steel plate.

[0013] The steel plate may be austenitized at 1650-1700°F for a minimum of 30 minutes per inch of thickness, water quenched, and then tempered at 350-450 °F for a minimum of 1 hour per inch of thickness to form a microstructure of tempered martensite. Austenitizing for times exceeding 1 hour per inch of thickness may lead to grain growth and/or loss of impact strength and tempering times exceeding 2 hours per inch of thickness may lead to detrimental surface oxidation.

[0014] The resulting steel plate may have surface hardness of at least 440 HBW, a mid-thickness hardness that is at least 90% of the surface hardness, longitudinal yield strength of 1200 MPa or greater, longitudinal tensile strength of 1450 MPa or greater, and toughness in the transverse direction at -60°F of at least 20 ft-lbs and at room temperature of at least 40 ft-lbs. The steel may further have surface hardness of 440-514 HBW.

[0015] Three heats (A, B, C) of steel were melted in a 45-kg (100-lb) vacuum induction furnace. Each heat was top cast into iron molds to produce one ingot per heat measuring approximately 125 by 125 by 360 mm (5 x 5 x 14-inches). The three heats of steel had compositions as shown in Table 1 with heat C representing the inventive steel.

Table 1

Heat	C	Mn	P	S	Cu	Ni	Cr	Mo	Si	Ti	Al	B	N
A	0.23	0.79	0.009	0.004	0.10	0.50	0.89	0.10	0.26	0.021	0.024	0.0006	0.0062
B	0.23	0.71	0.008	0.004	0.10	0.51	0.90	0.10	0.25	0.020	0.012	0.0008	0.0055
C	0.24	0.79	0.007	0.004	0.11	0.51	0.90	0.10	0.26	0.022	0.027	0.0015	0.0078
Prior Art	0.22	0.90				0.65	1.65	0.23	0.25	0.025	0.025	0.0015	0.0080

[0016] A 1-1/2-inch (37 mm) thick slice was sawcut from the bottom of each ingot to provide material for as-cast Jominy hardenability specimens. The slices were normalized at 1650 °F (900 °C) and one standard ASTM A255 Jominy specimen was machined from each slice. The Jominy specimens were austenitized at 1650 °F (900 °C) and end-quenched. The Jominy hardenability curves for the three laboratory heats are presented in Fig. 1. Compared to prior art abrasion resistant steel, the inventive steel has higher initial hardness and less hardenability as intended. It can be seen that the three laboratory heats exhibit different degrees of hardenability. This is because heats A and B contain only 0.0006 and 0.0008 %B, respectively, as compared to heat C which has 0.0015 %B.

[0017] The balance of the ingots were conditioned, then reheated at 2250 °F (1230 °C) in an electric furnace with a protective nitrogen atmosphere. The ingots from heats A and B were rolled to 3/8 inch (9.6 mm) thick plates and the ingot from heat C was rolled to a 3/4 inch (19mm) thick plate.

[0018] The plates were then heat treated to simulate mill processing. They were austenitized at a temperature of 1650 °F (900 °C) for 30 minutes/inch of thickness followed by water quenching by agitating in cold water. The plates were then tempered at 400 °F (205 °C) for 30 minutes/inch of thickness and air cooled.

[0019] Brinell hardness (HBW) measurements were made on both surfaces of the three plates. Round 0.350-inch (9 mm) tensile specimens were machined from plate C in both the longitudinal and the transverse directions. Flat tensile specimens were machined from plates A and B and tested in the longitudinal direction. All tests were performed in duplicate.

[0020] Charpy V-notch specimens were machined in both the longitudinal and transverse directions. For plates A and B, the thickness of the Charpy specimens was 7.5 mm, while full size 10.0 mm specimens were machined from plate C. The Charpy transition curves were measured by testing triplicate specimens at -60, -40, 0, 40, 72, and 212°F (-51, -40, -18, 4, 22, and 100 °C).

[0021] The hardness of the three plates is presented in Table 2. Hardness values on opposite surfaces of each plate were the same. Plates A and B failed to achieve the targeted 440 HBW minimum hardness. However, plate C, having the inventive composition, achieved an average hardness of 460 HBW, which is well above the desired value of 440 HBW minimum.

Table 2

	Plate Thickness (mm)	Plate Thickness (in.)	HBW Values	Average HBW
Plate A	9.6	3/8	440, 440, 442	441
Plate B	9.6	3/8	428, 435, 438	434
Plate C	19	3/4	456, 460, 460, 460, 461, 462	460

[0022] The tensile properties of the three plates are presented in Table 3. Plates A and B exhibited essentially the same tensile properties. The longitudinal yield strength of plate C is the same as the thinner plates at about 1210 MPa (176 ksi). However, consistent with the higher hardness of plate C, its tensile strength is about 100 MPa (15 ksi) higher. The yield strength of plate C is higher in the transverse orientation than the longitudinal orientation while the tensile strength in both directions is approximately the same. Although plates A and B have higher elongations than plate C which is expected based on their lower hardness, the reduction of area value of plate C is higher than plates A and B, indicating reasonable tensile ductility for the inventive steel.

Table 3

	Direction	Yield Strength		Tensile Strength		Elongation	RA
		MPa	ksi	MPa	ksi	%	%
Plate A	L	1223	177.6	1496	217.2	15.7	43.0
Plate B	L	1214	176.2	1488	216.0	16.3	41.3
Plate C	L	1210	175.7	1584	229.9	8.7	45.0
Plate C	T	1330	193.1	1600	232.2	9.3	54.3

[0023] The Charpy impact test results are presented in Table 4 and in Figs. 2A and 2B. To compare the thinner plate, A and B, values to the values for plate C, the "Full-size Equivalent" absorbed energy values were calculated as recommended by ASTM A370 by dividing the measured energies from the 7.5 mm thick specimens by 0.75. Both the raw data and the "Full-size Equivalent" values are presented in Figure 2. Consistent with the high hardness of the steels, the Charpy specimens exhibit low percent shear at all test temperatures. The full-size equivalent data for the three plates have essentially the same values in the longitudinal

orientation as well as in the transverse orientation, although the transverse absorbed energies are, as expected, somewhat lower than the longitudinal.

[0024] Although the invention has been described in detail for the purpose of illustration based on what is currently considered to be the most practical and preferred embodiments, it is to be understood that such detail is solely for that purpose and that the invention is not limited to the disclosed embodiments, but, on the contrary, is intended to cover modifications and equivalent arrangements that are within the spirit and scope of the appended claims.

Table 4

	Temp. (°F)	L/T	Energy (ft.-lbs)				Lat. Expansion (inches)				% Shear
			1	2	3	Avg.	1.000	2.000	3.000	Avg.	
A	-60	L	19	21	21	20	0.015	0.015	0.015	0.015	20
		T	17	18	19	18	0.013	0.014	0.015	0.014	20
	-40	L	22	24	26	24	0.016	0.017	0.012	0.015	20
		T	12	18	20	17	0.012	0.013	0.014	0.013	20
	0	L	19	22	21	21	0.016	0.017	0.018	0.017	20
		T	18	19	19	19	0.014	0.015	0.015	0.015	20
	40	L	26	27	28	27	0.014	0.016	0.017	0.016	20
		T	20	21	22	21	0.015	0.016	0.018	0.016	20
	72	L	27	30	31	29	0.025	0.032	0.033	0.030	20
		T	20	22	22	21	0.017	0.020	0.020	0.019	20
B	-60	L	20	23	23	22	0.016	0.016	0.017	0.016	20
		T	16	16	16	16	0.014	0.014	0.015	0.014	10
	-40	L	24	26	27	26	0.016	0.017	0.017	0.017	20
		T	17	18	19	18	0.009	0.013	0.015	0.012	20
	0	L	28	29	30	29	0.018	0.019	0.019	0.019	20
		T	20	20	21	20	0.014	0.015	0.015	0.015	20
	40	L	31	32	32	32	0.018	0.020	0.020	0.019	30
		T	20	21	21	21	0.013	0.014	0.016	0.014	20
	72	L	32	32	34	33	0.022	0.022	0.026	0.023	20
		T	22	22	23	22	0.022	0.023	0.023	0.023	20
C	-60	L	29	31	31	30	0.018	0.019	0.021	0.019	30
		T	20	21	22	21	0.014	0.015	0.017	0.015	20
	-40	L	30	32	32	31	0.016	0.017	0.018	0.017	30
		T	22	23	23	23	0.011	0.015	0.016	0.014	20
	0	L	33	35	35	34	0.014	0.016	0.018	0.016	20
		T	24	25	26	25	0.014	0.014	0.016	0.015	20
	40	L	37	37	37	37	0.016	0.016	0.013	0.015	30
		T	25	26	26	26	0.015	0.016	0.020	0.017	20
	72	L	36	38	40	38	0.017	0.020	0.022	0.020	20
		T	25	26	27	26	0.017	0.017	0.020	0.018	20
	212	L	42	42	43	42	0.016	0.016	0.018	0.017	
		T	27	28	29	28	0.012	0.014	0.014	0.013	

THE INVENTION CLAIMED IS

1. An abrasion resistant steel consisting essentially of, in weight %: 0.20-0.30% carbon, 0.40-1.25% manganese, 0.05% maximum phosphorous, 0.01% maximum sulfur, 0.20-0.60% silicon, 0.50-1.70% chromium, 0.20-2.00% nickel, 0.07-0.60% molybdenum, 0.022-0.10% titanium, 0.001-0.10% boron, 0.027-0.10% aluminum, balance iron, and incidental impurities.

2. The abrasion resistant steel according to claim 1, wherein the surface hardness is at least 440 HBW and the mid-thickness hardness is at least 90% of the surface hardness.

3. The abrasion resistant steel according to claim 1, wherein the microstructure is tempered martensite.

4. The abrasion resistant steel according to claim 1, wherein the toughness in the transverse direction at -60°F is at least 20 ft-lbs and at room temperature is at least 40 ft-lbs.

5. The abrasion resistant steel according to claim 1, wherein the surface hardness is at least 440 HBW.

6. The abrasion resistant steel according to claim 5, wherein the surface hardness is between 440-514 HBW.

7. The abrasion resistant steel according to claim 1, consisting essentially of, in weight %: 0.22-0.26% carbon, 0.70-0.90% manganese, 0.025% maximum phosphorous, 0.003% maximum sulfur, 0.20-0.40% silicon, 0.80-1.00% chromium, 0.40-0.60% nickel, 0.07-0.15% molybdenum, 0.022-0.04% , 0.001-0.003% boron, 0.027-0.06% aluminum, balance iron, and incidental impurities.

8. The abrasion resistant steel according to claim 1, consisting essentially of, in weight %: 0.24% carbon, 0.80% manganese, 0.010% maximum phosphorous, 0.003% maximum sulfur, 0.25% silicon, 0.90% chromium, 0.50% nickel, 0.10% molybdenum, 0.03% titanium, 0.0015% boron, 0.035% aluminum, balance iron, and incidental impurities.

9. The abrasion resistant steel according to claim 1, wherein the steel has been austenitized at 1650-1700°F, water quenched, and tempered 350-450 °F.

10. The abrasion resistant steel according to claim 1, wherein Cr + Mn + Mo is 1.4% minimum.

11. The abrasion resistant steel according to claim 1, wherein Ni + Si + Cr is 1.4% minimum

12. The abrasion resistant steel according to claim 1, wherein Cr + Si is 1% minimum.

13. A method for producing an abrasion resistant steel plate comprising:

a. melting and casting a steel ingot or slab consisting essentially of, in weight %: 0.20-0.30% carbon, 0.40-1.25% manganese, 0.05% maximum phosphorous, 0.01% maximum sulfur, 0.20-0.60% silicon, 0.50-1.70% chromium, 0.20-2.00% nickel, 0.07-0.60% molybdenum, 0.022-0.10% titanium, 0.001-0.10% boron, 0.027-0.10% aluminum, balance iron, and incidental impurities;

b. hot rolling the ingot or slab to the desired thickness;

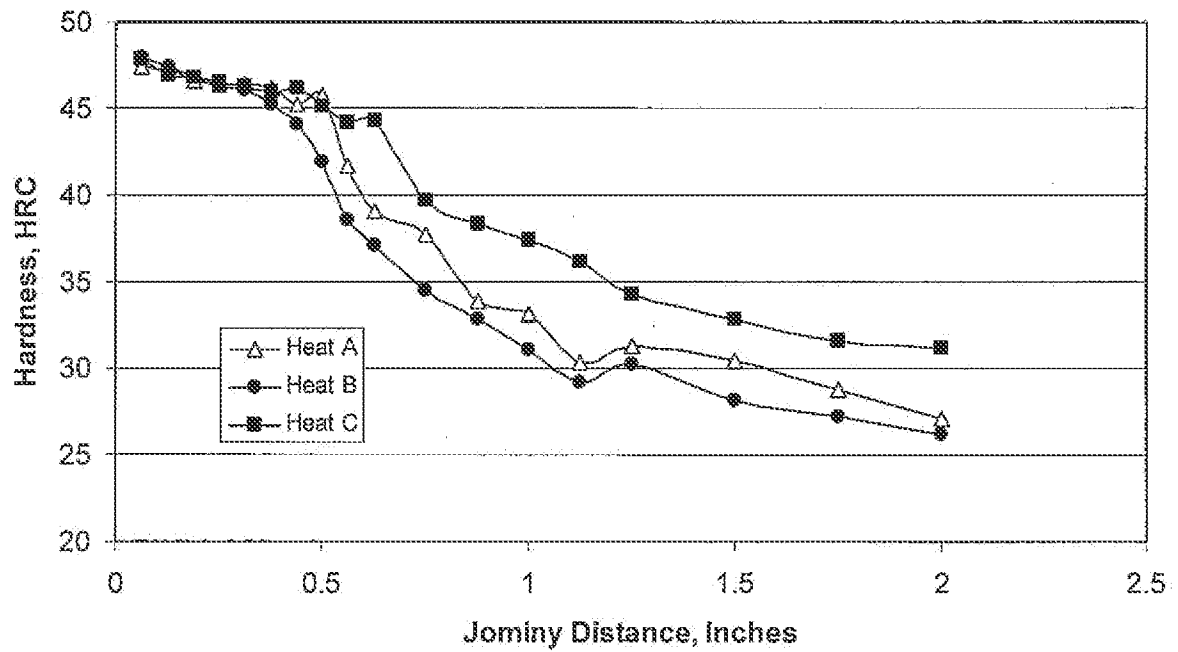
c. austenitizing the plate at 1650-1700°F;

d. water quenching the plate; and

e. tempering the plate at 350-450 °F.

14. The method according to claim 13, wherein during the melting and casting step the steel is killed, desulfurized, vacuum degassed, treated for sulfide shape control, or a combination thereof.

15. The method according to claim 13, wherein cross rolling is used during the hot rolling step.
16. The method according to claim 13, wherein the microstructure is tempered martensite.
17. The method according to claim 13, wherein the toughness in the transverse direction at -60°F is at least 20 ft-lbs and at room temperature is at least 40 ft-lbs.
18. The method according to claim 13, wherein the surface hardness is at least 440 HBW and the mid-thickness hardness is at least 90% of the surface hardness.
19. The method according to claim 13, wherein the steel consisting essentially of, in weight %: 0.22-0.26% carbon, 0.70-0.90% manganese, 0.025% maximum phosphorous, 0.003% maximum sulfur, 0.20-0.40% silicon, 0.80-1.00% chromium, 0.40-0.60% nickel, 0.07-0.15% molybdenum, 0.022-0.04% titanium, 0.001-0.003% boron, 0.027-0.06% aluminum, balance iron, and incidental impurities.
20. The method according to claim 13, wherein the steel consisting essentially of, in weight %: 0.24% carbon, 0.80% manganese, 0.010% maximum phosphorous, 0.003% maximum sulfur, 0.25% silicon, 0.90% chromium, 0.50% nickel, 0.10% molybdenum, 0.03% titanium, 0.0015% boron, 0.035% aluminum, balance iron, and incidental impurities.
21. An abrasion resistant article made from the abrasion resistant steel of claim 1.
22. The abrasion resistant article according to claim 21, wherein the microstructure is tempered martensite and the surface hardness is at least 440 HBW.

Figure 1

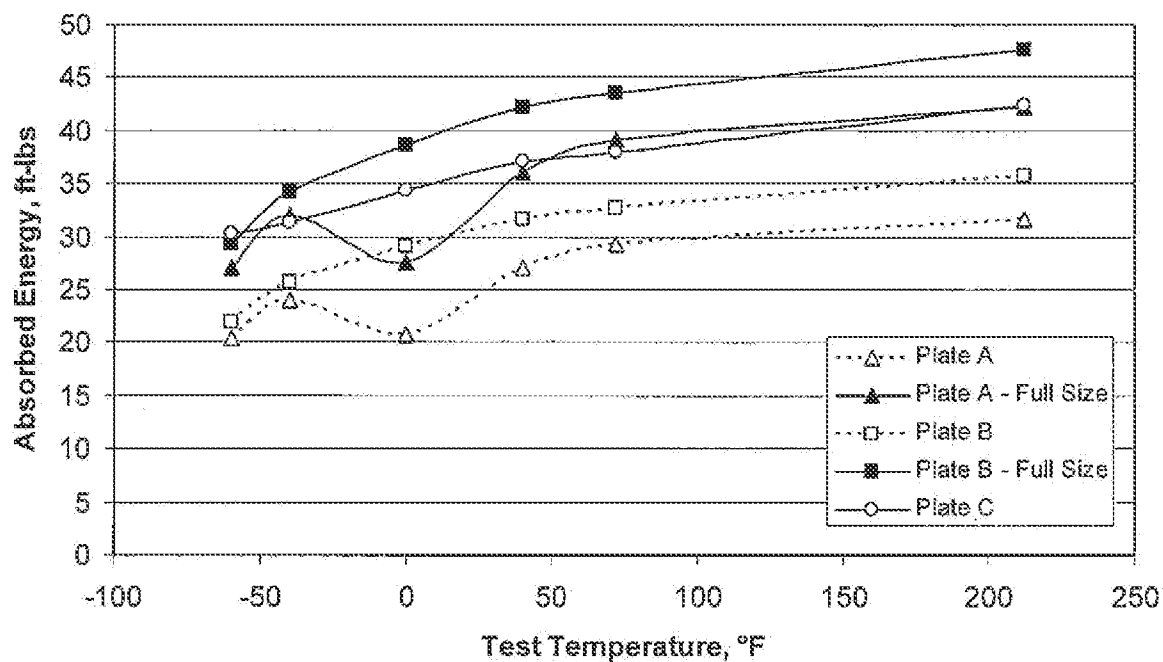


Figure 2A – Longitudinal Toughness

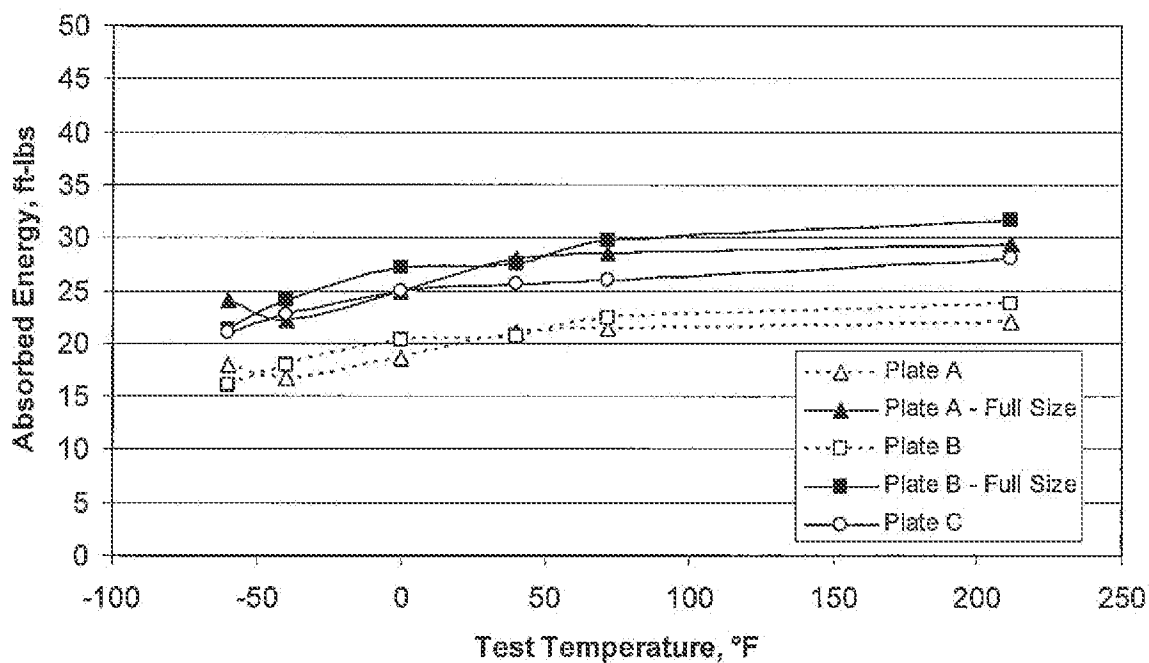


Figure 2B – Transverse Toughness