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(54) **Titre : ACIER DE RESISTANCE ELEVEE PRESENTANT UNE BONNE DUCTILITE ET PROCEDE DE PRODUCTION PAR UN TRAITEMENT THERMIQUE EN LIGNE EN AVAL D'UN BAIN DE ZINC FONDU**  
(54) **Title: HIGH STRENGTH STEEL EXHIBITING GOOD DUCTILITY AND METHOD OF PRODUCTION VIA IN-LINE HEAT TREATMENT DOWNSTREAM OF MOLTEN ZINC BATH**

(57) **Abrégé/Abstract:**

Steel with high strength and good formability is produced with compositions and methods for forming austenitic and martensitic microstructure in the steel. Carbon, manganese, molybdenum, nickel copper and chromium may promote the formation of room temperature stable (or meta- stable) austenite by mechanisms such as lowering transformation temperatures for non-martensitic constituents, and/or increasing the hardenability of steel. Thermal cycles utilizing a rapid cooling below a martensite start temperature followed by reheating may promote formation of room temperature stable austenite by permitting diffusion of carbon into austenite from martensite.

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(57) **Abstract:** Steel with high strength and good formability is produced with compositions and methods for forming austenitic and martensitic microstructure in the steel. Carbon, manganese, molybdenum, nickel copper and chromium may promote the formation of room temperature stable (or meta- stable) austenite by mechanisms such as lowering transformation temperatures for non-martensitic constituents, and/or increasing the hardenability of steel. Thermal cycles utilizing a rapid cooling below a martensite start temperature followed by reheating may promote formation of room temperature stable austenite by permitting diffusion of carbon into austenite from martensite.

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**High Strength Steel Exhibiting Good Ductility and Method of Production via In-Line Heat Treatment Downstream of Molten Zinc Bath**

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**[0001]**

**BACKGROUND**

**[0002]** It is desirable to produce steels with high strength and good formability characteristics. However, commercial production of steels exhibiting such characteristics has been difficult due to factors such as the desirability of relatively low alloying additions and limitations on thermal processing capabilities of industrial production lines. The present invention relates to steel compositions and processing methods for production of steel using hot-dip galvanizing/galvannealing (HDG) processes such that the resulting steel exhibits high strength and cold formability.

**SUMMARY**

**[0003]** The present steel is produced using a composition and a modified HDG process that together produces a resulting microstructure consisting of generally martensite and austenite (among other constituents). To achieve such a microstructure, the composition includes certain alloying additions and the HDG process includes certain process modification, all of which are at least partially

related to driving the transformation of austenite to martensite followed by a partial stabilization of austenite at room-temperature.

### **BRIEF DESCRIPTION OF THE FIGURES**

- [0004] The accompanying figures, which are incorporated in and constitute a part of this specification, illustrate embodiments, and together with the general description given above, and the detailed description of the embodiments given below, serve to explain the principles of the present disclosure.
- [0005] FIGURE 1 depicts a schematic view of a HDG temperature profile with a partitioning step performed after galvanizing/galvannealing.
- [0006] FIGURE 2 depicts a schematic view of a HDG temperature profile with a partitioning step performed during galvanizing/galvannealing.
- [0007] FIGURE 3 depicts a plot of one embodiment with Rockwell hardness plotted against cooling rate.
- [0008] FIGURE 4 depicts a plot of another embodiment with Rockwell hardness plotted against cooling rate.
- [0009] FIGURE 5 depicts a plot of another embodiment with Rockwell hardness plotted against cooling rate.
- [0010] FIGURE 6 depicts six photo micrographs of the embodiment of FIG. 3 taken from samples being cooled at various cooling rates.
- [0011] FIGURE 7 depicts six photo micrographs of the embodiment of FIG. 4 taken from samples being cooled at various cooling rates.
- [0012] FIGURE 8 depicts six photo micrographs of the embodiment of FIG. 5 taken from samples being cooled at various cooling rates.
- [0013] FIGURE 9 depicts a plot of tensile data as a function of austenitization temperature for several embodiments.

- [0014] FIGURE 10 depicts a plot of tensile data as a function of austenitization temperature for several embodiments.
- [0015] FIGURE 11 depicts a plot of tensile data as a function of quench temperature for several embodiments.
- [0016] FIGURE 12 depicts a plot of tensile data as a function of quench temperature for several embodiments.

## DETAILED DESCRIPTION

[0017] FIG. 1 shows a schematic representation of the thermal cycle used to achieve high strength and cold formability in a steel sheet having a certain chemical composition (described in greater detail below). In particular, FIG. 1 shows a typical hot-dip galvanizing or galvannealing thermal profile (10) with process modifications shown with dashed lines. In one embodiment the process generally involves austenitization followed by a rapid cooling to a specified quench temperature to partially transform austenite to martensite, and the holding at an elevated temperature, a partitioning temperature, to allow carbon to diffuse out of martensite and into the remaining austenite, thus, stabilizing the austenite at room temperature. In some embodiments, the thermal profile shown in FIG. 1 may be used with conventional continuous hot-dip galvanizing or galvannealing production lines, although such a production line is not required.

[0018] As can be seen in FIG. 1, the steel sheet is first heated to a peak metal temperature (12). The peak metal temperature (12) in the illustrated example is shown as being at least above the austenite transformation temperature ( $A_1$ ) (e.g., the dual phase, austenite + ferrite region). Thus, at the peak metal temperature (12), at least a portion of the steel will be transformed to austenite. Although FIG. 1 shows the peak metal temperature (12) as being solely above  $A_1$ , it should be understood that in some embodiments the peak metal temperature may also include temperatures above the temperature at which ferrite completely transforms to austenite ( $A_3$ ) (e.g., the single phase, austenite region).

[0019] Next the steel sheet undergoes rapid cooling. As the steel sheet is cooling, some embodiments may include a brief interruption in cooling for galvanizing or galvannealing. In embodiments where galvanizing is used, the steel sheet may briefly maintain a constant temperature (14) due to the heat from the molten zinc galvanizing bath. Yet in other embodiments, a galvannealing process may be used and the temperature of the steel sheet may be slightly raised to a galvannealing temperature (16) where the galvannealing process may be performed. Although,

in other embodiments, the galvanizing or galvannealing process may be omitted entirely and the steel sheet may be continuously cooled.

[0020] The rapid cooling of the steel sheet is shown to continue below the martensite start temperature ( $M_s$ ) for the steel sheet to a predetermined quench temperature (18). It should be understood that the cooling rate to  $M_s$  may be high enough to transform at least some of the austenite formed at the peak metal temperature (12) to martensite. In other words the cooling rate may be rapid enough to transform austenite to martensite instead of other non-martensitic constituents such as ferrite, pearlite, or bainite which transform at relatively lower cooling rates.

[0021] As is shown in FIG. 1, the quench temperature (18) is below  $M_s$ . The difference between the quench temperature (18) and  $M_s$  may vary depending on the individual composition of the steel sheet being used. However, in many embodiments the difference between quench temperature (18) and  $M_s$  may be sufficiently great to form an adequate amount of martensite to act as a carbon source to stabilize the austenite and avoid creating excessive “fresh” martensite upon final cooling. Additionally, quench temperature (18) may be sufficiently high to avoid consuming too much austenite during the initial quench (e.g., to avoid excessive carbon enrichment of austenite greater than that required to stabilize austenite for the given embodiment).

[0022] In many embodiments, quench temperature (18) may vary from about 191 °C to about 281 °C, although no such limitation is required. Additionally, quench temperature (18) may be calculated for a given steel composition. For such a calculation, quench temperature (18) corresponds to the retained austenite having an  $M_s$  temperature of room temperature after partitioning. Methods for calculating quench temperature (18) are known in the art and described in J. G. Speer, A. M. Streicher, D. K. Matlock, F. Rizzo, and G. Krauss, “Quenching And Partitioning : A Fundamentally New Process to Create High Strength Trip Sheet Microstructures,” *Austenite Formation and Decomposition*, pp. 505-522, 2003; and A. M. Streicher, J. G. J. Speer, D. K. Matlock, and B. C. De Cooman, “Quenching and Partitioning Response of a Si-Added TRIP Sheet Steel,” in

*Proceedings of the International Conference on Advanced High Strength Sheet Steels for Automotive Applications, 2004.*

[0023] The quench temperature (18) may be sufficiently low (with respect to  $M_s$ ) to form an adequate amount of martensite to act as a carbon source to stabilize the austenite and avoid creating excessive “fresh” martensite upon the final quench. Alternatively, the quench temperature (18) may be sufficiently high to avoid consuming too much austenite during the initial quench and creating a situation where the potential carbon enrichment of the retained austenite is greater than that required for austenite stabilization at room temperature. In some embodiments, a suitable quench temperature (18) may correspond to the retained austenite having an  $M_s$  temperature of room temperature after partitioning. Speer and Streicher *et al.* (above) have provided calculations that provide guidelines to explore processing options that may result in desirable microstructures. Such calculations assume idealized full partitioning, and may be performed by applying the Koistinen-Marburger (KM) relationship twice ( $f_m = 1 - e^{-1.1 \times 10^{-2}(\Delta T)}$ ) – first to the initial quench to quench temperature (18) and then to the final quench at room temperature (as further described below). The  $M_s$  temperature in the KM expression can be estimated using empirical formulae based on austenite chemistry (such as that of the well known in the art Andrews’ linear expression):

[0024] 
$$M_s(^{\circ}C) = 539 - 423C - 30.4Mn - 7.5Si + 30Al$$

[0025] The result of the calculations described by Speer *et al.* may indicate a quench temperature (18) which may lead to a maximum amount of retained austenite. For quench temperatures (18) above the temperature having a maximum amount of retained austenite, significant fractions of austenite are present after the initial quench; however, there is not enough martensite to act as a carbon source to stabilize this austenite. Therefore, for the higher quench temperatures, increasing amounts of fresh martensite form during the final quench. For quench temperatures below the temperature having a maximum amount of retained



austenite, an unsatisfactory amount of austenite may be consumed during the initial quench and there may be an excess amount of carbon that may partition from the martensite.

[0026] Once the quench temperature (18) is reached, the temperature of the steel sheet is either increased relative to the quench temperature or maintained at the quench temperature for a given period of time. In particular, this stage may be referred to as the partitioning stage. In such a stage, the temperature of the steel sheet is at least maintained at the quench temperature to permit carbon diffusion from martensite formed during the rapid cooling and into any remaining austenite. Such diffusion may permit the remaining austenite to be stable (or meta-stable) at room temperature, thus improving the mechanical properties of the steel sheet.

[0027] In some embodiments, the steel sheet may be heated above  $M_s$  to a relatively high partitioning temperature (20) and thereafter held at the high partitioning temperature (20). A variety of methods may be utilized to heat the steel sheet during this stage. By way of example only, the steel sheet may be heated using induction heating, torch heating, and/or the like. Alternatively, in other embodiments, the steel sheet may be heated but to a different, lower partitioning temperature (22) which is slightly below  $M_s$ . The steel sheet may then be likewise held at the lower partitioning temperature (22) for a certain period of time. In still a third alternative embodiment, another alternative partitioning temperature (24) may be used where the steel sheet is merely maintained at the quench temperature. Of course, any other suitable partitioning temperature may be used as will be apparent to those of ordinary skill in the art in view of the teachings herein.

[0028] After the steel sheet has reached the desired partitioning temperature (20, 22, 24), the steel sheet is maintained at the desired partitioning temperature (20, 22, 24) for a sufficient time to permit partitioning of carbon from martensite to austenite. The steel sheet may then be cooled to room temperature.

- [0029] FIG. 2 shows an alternative embodiment of the thermal cycle described above with respect to FIG. 1 (with a typical galvanizing/galvannealing thermal cycle shown with a solid line (40) and departures from typical shown with a dashed line). In particular, like with the process of FIG. 1, the steel sheet is first heated to a peak metal temperature (42). The peak metal temperature (42) in the illustrated embodiment is shown as being at least above  $A_1$ . Thus, at the peak metal temperature (42), at least a portion of the steel sheet will be transformed to austenite. Of course, like the process of FIG. 1, the present embodiment may also include a peak metal temperature in excess of  $A_3$ .
- [0030] Next, the steel sheet may be rapidly quenched (44). It should be understood that the quench (44) may be rapid enough to initiate transformation of some of the austenite formed at the peak metal temperature (42) into martensite, thus avoiding excessive transformation to non-martensitic constituents such as ferrite, pearlite, bainite, and/or the like.
- [0031] The quench (44) may be then ceased at a quench temperature (46). Like the process of FIG. 1, quench temperature (46) is below  $M_s$ . Of course, the amount below  $M_s$  may vary depending upon the material used. However, as described above, in many embodiments the difference between quench temperature (46) and  $M_s$  may be sufficiently great to form an adequate amount of martensite yet be sufficiently low to avoid consuming too much austenite.
- [0032] The steel sheet is then subsequently reheated (48) to a partitioning temperature (50, 52). Unlike the process of FIG. 1, the partitioning temperature (50, 52) in the present embodiment may be characterized by the galvanizing or galvannealing zinc bath temperature (if galvanizing or galvannealing is so used). For instance, in embodiments where galvanizing is used, the steel sheet may be re-heated to the galvanizing bath temperature (50) and subsequently held there for the duration of the galvanizing process. During the galvanizing process, partitioning may occur similar to the partitioning described above. Thus, the galvanizing bath temperature (50) may also function as the partitioning temperature (50). Likewise,

in embodiments where galvannealing is used, the process may be substantially the same with the exception of a higher bath/partitioning temperature (52).

- [0033] Finally, the steel sheet is permitted to cool (54) to room temperature where at least some austenite may be stable (or meta-stable) from the partitioning step described above.
- [0034] In some embodiments the steel sheet may include certain alloying additions to improve the propensity of the steel sheet to form a primarily austenitic and martensitic microstructure and/or to improve the mechanical properties of the steel sheet. Suitable compositions of the steel sheet may include one or more of the following, by weight percent: 0.15-0.4% carbon, 1.5-4% manganese, 0-2% silicon or aluminum or some combination thereof, 0-0.5% molybdenum, 0-0.05% niobium, other incidental elements, and the balance being iron.
- [0035] In addition, in other embodiments suitable compositions of the steel sheet may include one or more of the following, by weight percent: 0.15-0.5% carbon, 1-3% manganese, 0-2% silicon or aluminum or some combination thereof, 0-0.5% molybdenum, 0-0.05% niobium, other incidental elements, and the balance being iron. Additionally, other embodiments may include additions of vanadium and/or titanium in addition to, or in lieu of niobium, although such additions are entirely optional.
- [0036] In some embodiments carbon may be used to stabilize austenite. For instance, increasing carbon may lower the Ms temperature, lower transformation temperatures for other non-martensitic constituents (e.g., bainite, ferrite, pearlite), and increase the time required for non-martensitic products to form. Additionally, carbon additions may improve the hardenability of the material thus retaining formation of non-martensitic constituents near the core of the material where cooling rates may be locally depressed. However, it should be understood that carbon additions may be limited as significant carbon additions may lead to detrimental effects on weldability.

- [0037] In some embodiments manganese may provide additional stabilization of austenite by lowering transformation temperatures of other non-martensitic constituents, as described above. Manganese may further improve the propensity of the steel sheet to form a primarily austenitic and martensitic microstructure by increasing hardenability.
- [0038] In other embodiments molybdenum may be used to increase hardenability.
- [0039] In other embodiments silicon and/or aluminum may be provided to reduce the formation of carbides. It should be understood that a reduction in carbide formation may be desirable in some embodiments because the presence of carbides may decrease the levels of carbon available for diffusion into austenite. Thus, silicon and/or aluminum additions may be used to further stabilize austenite at room temperature.
- [0040] In some embodiments, nickel, copper, and chromium may be used to stabilize austenite. For instance, such elements may lead to a reduction in the  $M_s$  temperature. Additionally, nickel, copper, and chromium may further increase the hardenability of the steel sheet.
- [0041] In some embodiments niobium (or other micro-alloying elements, such as titanium, vanadium, and/or the like) may be used to increase the mechanical properties of the steel sheet. For instance, niobium may increase the strength of the steel sheet through grain boundary pinning resulting from carbide formation.
- [0042] In other embodiments, variations in the concentrations of elements and the particular elements selected may be made. Of course, where such variations are made, it should be understood that such variations may have a desirable or undesirable effect on the steel sheet microstructure and/or mechanical properties in accordance with the properties described above for each given alloying addition.

**EXAMPLE 1**

- [0043] Embodiments of the steel sheet were made with the compositions set forth in Table 1 below.
- [0044] The materials were processed on laboratory equipment according to the following parameters. Each sample was subjected to Gleeble 1500 treatments using copper cooled wedge grips and the pocket jaw fixture. Samples were austenitized at 1100 °C and then cooled to room temperature at various cooling rates between 1-100 °C/s.

Table 1 Chemical compositions in weight %.

ID	Description	Al	C	Co	Cr	Cu	Mn	Mo	Nb	Ni	P	Si	Sn	Ti	V	W
V4037	Lab Material	1.41	0.19	-	0.01	<0.003	1.54	<0.003	<0.003	<0.003	<0.003	0.11	<0.003	0.01	<0.003	-
V4038	Lab Material	1.29	0.22	-	0.20	<0.003	1.68	<0.003	0.02	<0.003	0.02	0.01	<0.003	0.01	<0.003	-
V4039	Lab Material	<0.003	0.20	<0.002	0.01	<0.002	2.94	<0.002	0.00	<0.002	0.00	1.57	<0.002	0.01	<0.002	0.00

**EXAMPLE 2**

[0045] The Rockwell hardness of each of the steel compositions described in Example 1 and Table 1 above was taken on the surface of each sample. The results of the tests are plotted in FIGS. 3-5 with Rockwell hardness plotted as a function of cooling rate. The average of at least seven measurements is shown for each data point. The compositions V4037, V4038 and V4039 correspond to FIGS. 3, 4, and 5, respectively.

**EXAMPLE 3**

[0046] Light optical micrographs were taken in the longitudinal through thickness direction near the center of each sample for each of the compositions of Example 1. The results of these tests are shown in FIGS. 6-8. The compositions V4037, V4038, and V4039 correspond to FIGS. 6, 7, and 8, respectively. Additionally, FIGS. 6-8 each contain six micrographs for each composition with each micrograph representing a sample subjected to a different cooling rate.

**EXAMPLE 4**

[0047] A critical cooling rate for each of the compositions of Example 1 was estimated using the data of Examples 2 and 3 in accordance with the procedure described herein. The critical cooling rate herein refers to the cooling rate required to form martensite and minimize the formation of non-martensitic transformation products. The results of these tests are as follows:

[0048] V4037: 70 °C/s

[0049] V4038: 75 °C/s

[0050] V4039: 7 °C/s

**EXAMPLE 5**

- [0051] Embodiments of the steel sheet were made with the compositions set forth in Table 2 below.
- [0052] The materials were processed by melting, hot rolling, and cold rolling. The materials were then subjected to testing described in greater detail below in Examples 6-7. All of the compositions listed in Table 2 were intended for use with the process described above with respect to FIG. 2 with the exception of V4039 which was intended for use with the process described above with respect to FIG. 1. Heat V4039 had a composition intended to provide higher hardenability as required by the thermal profile described above with respect to FIG. 1. As a result V4039 was subjected to annealing at 600 °C for 2 hours in 100% H<sub>2</sub> atmosphere after hot rolling, but prior to cold rolling. All materials were reduced during cold rolling about 75% to 1mm. Results for some of the material compositions set forth in Table 2 after hot rolling and cold rolling are shown in Tables 3 and 4, respectively.



Table 2 Chemical compositions in weight %.

Heat	Description	C	Mn	Si	Al	Mo	Cr	Nb	B
V4037	Lab Material	0.19	1.54	0.11	1.41	0	0.009	0	0.0007
V1307	Lab Material	0.19	1.53	1.48	0.041	0	0	0	0.0005
V4053	Lab Material	0.19	1.6	0.11	1.34	0	0.003	0	0.0007
V4038	Lab Material	0.22	1.68	0.007	1.29	0	0.2	0.021	0.0008
V4039	Lab Material	0.2	2.94	1.57	<0.030	<0.002	0.005	0.002	N/R
V1305	Lab Material	0.2	2.94	1.57	0	0	0	0	0.0006
V4107	Lab Material	0.18	4.03	1.63	0.005	0	0	0	0.0008
V4108	Lab Material	0.18	5.06	1.56	0.004	0	0	0	0.0009
V4050	Lab Material	0.4	1.2	1.97	0.003	0	0.19	0.007	0.0005
V4051	Lab Material	0.41	1.2	0.98	0.003	0	0.003	0	0.0004
V4052	Lab Material	0.39	1.18	0.012	1.16	0	0.003	0	0.0007
V4078-1	Lab Material	0.2	1.67	0.1	1.41	0.28	0.003	<0.003	0.0007
V4078-2	Lab Material	0.2	1.67	0.1	1.41	0.27	<0.003	0.051	0.0007
V4079-1	Lab Material	0.19	1.94	0.088	1.43	<0.003	<0.003	<0.003	0.0007
V4079-2	Lab Material	0.19	1.96	0.089	1.41	<0.003	<0.003	0.051	0.0007

Table 3 – Tensile Data, Post Hot Rolling

Heat	YPE (%)	Upper YS		Lower YS		Yield Strength 0.2% Offset		UTS		Total Elongation (2")	Uniform Elongation %	Hardness HRA
		MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi			
V4063	0	N/A	N/A	N/A	N/A	375	54	652	95	26	15	53
V4039*	0	N/A	N/A	N/A	N/A	380	55	648	94	26	15	53
V4039* (annealed)	0	N/A	N/A	N/A	N/A	640	93	1085	157	14	9	67
V4060	0.6	645	94	637	92	633	92	883	128	20	10	61
V4061	0.5	610	89	605	88	611	89	876	127	20	11	63
V4062	0	N/A	N/A	N/A	0	496	72	790	115	22	12	61
V4078-1	1.1	507	74	501	73	506	73	712	103	20	11	60
V4078-2	0.7	505	73	502	73	502	73	713	103	24	12	60
V4079-1	0.8	427	62	416	60	425	62	594	86	32	18	57
V4079-2	0.6	525	76	519	75	525	76	685	99	21	15	51
V4078-1	1.8	364	53	361	52	361	52	544	79	30	17	55
V4078-2	1.2	497	72	481	70	489	71	639	93	24	13	48

\*Tensile test performed in transverse direction for V4039

Table 4 – Tensile Data, Post Cold Rolling

Heat	Yield Strength 0.2% Offset		UTS		Total Elongation (2") %	Uniform Elongation %	Hardness HRA
	MPa	ksi	MPa	ksi			
V4037	927	134	971	141	4.8	1.4	64
V4063	1046	152	1101	160	2.4	1.3	65
V4038	1001	145	1054	153	5.5	1.6	65
V4039	1149	167	1216	176	4.4	1.5	68
V4060	1266	184	1393	202	5.4	1.9	69
V4061	1187	172	1279	186	4.3	1.7	68
V4062	1111	161	1185	172	4.3	1.7	68
V4078-1	1047	152	1105	160	3.6	1.4	65
V4078-2	1154	167	1209	175	4.2	1.4	66
V4079-1	932	135	975	141	4.6	1.4	64
V4079-2	1034	150	1078	156	3.9	1.3	66

**EXAMPLE 7**

[0053] The compositions of Example 5 were subjected to Gleeble dilatometry. Gleeble dilatometry was performed in vacuum using a 101.6x25.4x1 mm samples with a c-strain gauge measuring dilation in the 25.4 mm direction. Plots were generated of the resulting dilation vs. temperature. Line segments were fit to the dilatometric data and the point at which the dilatometric data deviated from linear behavior was taken as the transformation temperature of interest (e.g.,  $A_1$ ,  $A_3$ ,  $M_s$ ). The resulting transformation temperatures are tabulated in Table 5.

[0054] Gleeble methods were also used to measure a critical cooling rate for each of the compositions of Example 5. The first method utilized Gleeble dilatometry, as described above. The second method utilized measurements of Rockwell hardness. In particular, after samples were subjected to Gleeble testing at range of cooling rates, Rockwell hardness measurements were taken. Thus, Rockwell hardness measurements were taken for each material composition with a measurement of hardness for a range of cooling rates. A comparison was then made between the Rockwell hardness measurements of a given composition at each cooling rate. Rockwell hardness deviations of 2 points HRA were considered significant. The critical cooling rate to avoid non-martensitic transformation product was taken as the highest cooling rate for which the hardness was lower than 2 point HRA than the maximum hardness. The resulting critical cooling rates are also tabulated in Table 5 for some of the compositions listed in Example 5.

Table 5 – Transformation Temperatures and Critical Cooling Rate from Gleeble Dilatometry

Heat	$A_1$ (°C)	$A_3$ (°C)	$M_s$ (°C)	Critical Cooling Rate (°C/s)	
				Gleeble Dilatometry	Gleeble/Hardness
V4037	737	970	469	Inconclusive	65
V4063	720	975	425	70	-
V4038	791	980	441	-	65
V4039	750	874	394	<10	6
V4060	725	975	325	30	-
V4061	675	900	325	40	55

V4062	700	975	375	30	-
V4078-1	750	925	450	40	55
V4078-2	790	980	425	40	-
V4079-1	800	1000	430	40	-
V4079-2	750	990	425	40	-

### EXAMPLE 8

[0055] The compositions of Example 5 were used to calculate quench temperature and a theoretical maximum of retained austenite. The calculations were performed using the methods of *Speer et al.*, described above. The results of the calculations are tabulated below in Table 6 for some of the compositions listed in Example 5.

Table 6 – Quench Temperature and Theoretical Maximum of Retained Austenite

Heat	QT (°C)	f( $\gamma$ ) Theoretical Maximum
V4037	281	0.15
V4063	278	0.15
V4038	270	0.18
V4039	203	0.2
V4060	191	0.35
V4061	196	0.36
V4062	237	0.31
V4078-1	276	0.16
V4078-2	276	0.16
V4079-1	273	0.16
V4079-2	272	0.16

### EXAMPLE 9

[0056] The samples of the compositions of Example 5 were subjected to the thermal profiles shown in FIGS. 1 and 2 with peak metal temperature and quench temperature varied between samples of a given composition. As described above, only composition V4039 was subjected to the thermal profile shown in FIG. 1, while all other compositions were subjected to the thermal cycle shown in FIG. 2. For each sample, tensile strength measurements were taken. The resulting tensile measurements are

plotted in FIGS. 9-12. In particular, FIGS. 9-10 show tensile strength data plotted against austenitization temperature and FIGS. 11-12 show tensile strength data plotted against quench temperature. Additionally, where the thermal cycles were performed using Gleeble methods, such data points are denoted with “Gleeble.” Similarly, where thermal cycles were performed using a salt bath, such data points are denoted with “salt.”

[0057] Additionally, similar tensile measurements for each composition listed in Example 5 (where available) are tabulated in Table 7, shown below. Partitioning times and temperatures are shown for example only, in other embodiments the mechanisms (such as carbon partitioning and/or phase transformations) occur during non-isothermal heating and cooling to or from the stated partitioning temperature which may also contribute to final material properties.

Table 7 – Tensile Data, Post Partitioning

Heat	Peak Metal Temp (°C)	Quench Temp (°C)	Partitioning Temp (°C)	Partitioning Time (s)	0.2% Yield Strength	Ultimate Tensile Strength	Total Elongation (%)	TE x UTS (Mpa x %)
V1307	800	250	466	30	419	818	27	22,424
	800	250	466	30	416	807	28	22,345
	850	250	466	30	553	862	25	21,805
	850	250	466	30	535	847	25	21,336
	900	250	466	30	548	854	24	20,144
	800	250	400	30	445	898	22	19,675
	900	250	466	30	566	856	23	19,594
V4060	800	250	400	30	432	889	22	19,478
	800	160	466	15	746	1317	23	29,630
	800	200	466	15	716	1332	19	25,309
	800	250	466	15	718	1403	18	25,115
	800	200	466	15	632	1309	19	24,746
	800	250	466	15	701	1379	18	24,407
	800	160	466	15	845	1311	18	23,986
V4037	850	250	466	15	891	1291	18	23,749
	850	250	466	15	735	1223	19	23,729
	850	300	466	15	443	657	32	20,763
	921	200	466	30	325	612	34	20,633
	850	250	466	15	405	696	30	20,543
	921	300	466	30	380	591	34	20,090
	921	356	466	30	386	592	34	20,078
	921	400	466	30	388	588	34	19,937
	940	200	466	30	362	598	33	19,906
	850	200	466	15	427	687	28	19,022
	940	200	466	30	353	592	32	18,989
	980	200	466	30	341	612	31	18,897
	900	300	466	15	493	727	26	18,767
	850	200	466	15	447	702	27	18,600
	850	300	466	15	404	678	27	18,435
	980	200	466	30	347	611	30	18,387
V4038	940	200	466	30	330	548	33	18,253
	980	200	466	30	345	612	29	17,939
	850	300	466	15	481	754	26	19,536
	918	400	466	30	377	681	27	18,461
	918	286	466	30	357	695	26	18,348
	918	200	466	30	363	697	26	18,193
	918	300	466	30	354	696	26	17,949
V4039	850	300	466	15	457	773	23	17,777
	800	250	400	60	821	1299	15	19,225
	800	250	400	60	821	1298	15	18,945
	900	250	400	60	923	1273	15	18,593
	850	250	400	60	874	1278	14	18,142
V4060	900	250	400	60	913	1258	14	17,984
	800	160	466	15	746	1317	23	29,630
	800	200	466	15	716	1332	19	25,309
	800	250	466	15	718	1403	18	25,115
	800	200	466	15	632	1309	19	24,746
	800	250	466	15	701	1379	18	24,407
	800	160	466	15	845	1311	18	23,986
	850	250	466	15	891	1291	18	23,749
	850	250	466	15	735	1223	19	23,729
V4061	800	200	466	30	942	1319	17	22,422
	850	200	466	15	695	1222	16	19,070
	750	250	466	15	553	985	20	19,902
V4062	750	250	466	15	581	918	21	18,996
	750	200	466	15	478	813	23	18,778
	750	250	466	15	480	816	22	17,944
V4107	750	200	466	15	536	790	23	17,936
	850	250	400	60	776	1382	13	17,824
V4108	900	250	400	60	923	1642	11	17,401
	850	250	400	60	952	1620	11	17,337

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V4078-1	850	300	466	15	448	783	24	19,016
	850	300	466	15	492	761	24	17,888
V4078-2	900	250	466	30	713	843	21	17,946
	850	300	466	15	689	859	20	17,525
	850	300	466	15	671	871	20	17,503

[0058] It will be understood various modifications may be made to this invention without departing from the scope of it. Therefore, the limits of this invention should be determined from the appended claims.



## CLAIMS

1. A method for processing a steel sheet, the steel sheet comprising the following elements by weight percent:  
0.15-0.4% carbon;  
1.5-4% manganese;  
2% or less silicon, aluminum, or some combination thereof;  
0.5% or less molybdenum;  
0.05% or less niobium; and  
the balance being iron and other incidental impurities;  
the method comprising:
  - (a) heating the steel sheet to a first temperature (T1), wherein T1 is at least above the temperature at which the steel sheet transforms to austenite and ferrite;
  - (b) cooling the steel sheet to a second temperature (T2) by cooling at a cooling rate, wherein T2 is below the martensite start temperature ( $M_s$ ), wherein the cooling rate is sufficiently rapid to transform austenite to martensite;
  - (c) subjecting the steel sheet to hot dip galvanizing or galvannealing while cooling the steel sheet to T2;
  - (d) re-heating the steel sheet to a partitioning temperature, wherein the partitioning temperature is sufficient to permit diffusion of carbon within the structure of the steel sheet;
  - (e) stabilizing austenite by holding the steel sheet at the partitioning temperature for a holding time, wherein the holding time is of a period of time sufficient to permit diffusion of carbon from martensite to austenite; and
  - (f) cooling the steel sheet to room temperature.
2. The method of claim 1, wherein the hot dip galvanizing or galvannealing occurs above  $M_s$ .
3. The method of claim 1, wherein the partitioning temperature is above  $M_s$ .

4. The method of claim 1, wherein the partitioning temperature is below  $M_s$ .
5. A method for processing a steel sheet of a selected composition, the steel sheet comprising the following elements by weight percent:
  - 0.15-0.4% carbon;
  - 1.5-4% manganese;
  - 2% or less silicon, aluminum, or some combination thereof;
  - 0.5% or less molybdenum;
  - 0.05% or less niobium; and
  - the balance being iron and other incidental impurities;the method comprising:
  - (a) heating the steel sheet to a first temperature ( $T_1$ ), wherein  $T_1$  is at least above the temperature at which the steel sheet transforms to austenite and ferrite;
  - (b) cooling the steel sheet to a second temperature ( $T_2$ ) by cooling at a cooling rate, wherein  $T_2$  is below the martensite start temperature ( $M_s$ ), wherein the cooling rate is sufficiently rapid to transform austenite to martensite, wherein the cooling rate is defined for the selected composition of the steel sheet by a critical cooling rate that results in a room temperature hardness of the steel sheet that is no lower than 2 HRA below a maximum room temperature hardness of the steel sheet, to avoid the formation of non-martensitic transformation products;
  - (c) subjecting the steel sheet to hot dip galvanizing or galvannealing while cooling the steel sheet to  $T_2$ ;
  - (d) re-heating the steel sheet to a partitioning temperature, wherein the partitioning temperature is sufficient to permit diffusion of carbon within the structure of the steel sheet;
  - (e) stabilizing austenite by holding the steel sheet at the partitioning temperature for a holding time, wherein the holding time is of a period of time sufficient to permit diffusion of carbon from martensite to austenite; and
  - (f) cooling the steel sheet to room temperature.

6. The method of claim 5, wherein the hot dip galvanizing or galvannealing occurs above  $M_s$ .
7. The method of claim 5, wherein the partitioning temperature is above  $M_s$ .
8. The method of claim 5, wherein the partitioning temperature is below  $M_s$ .

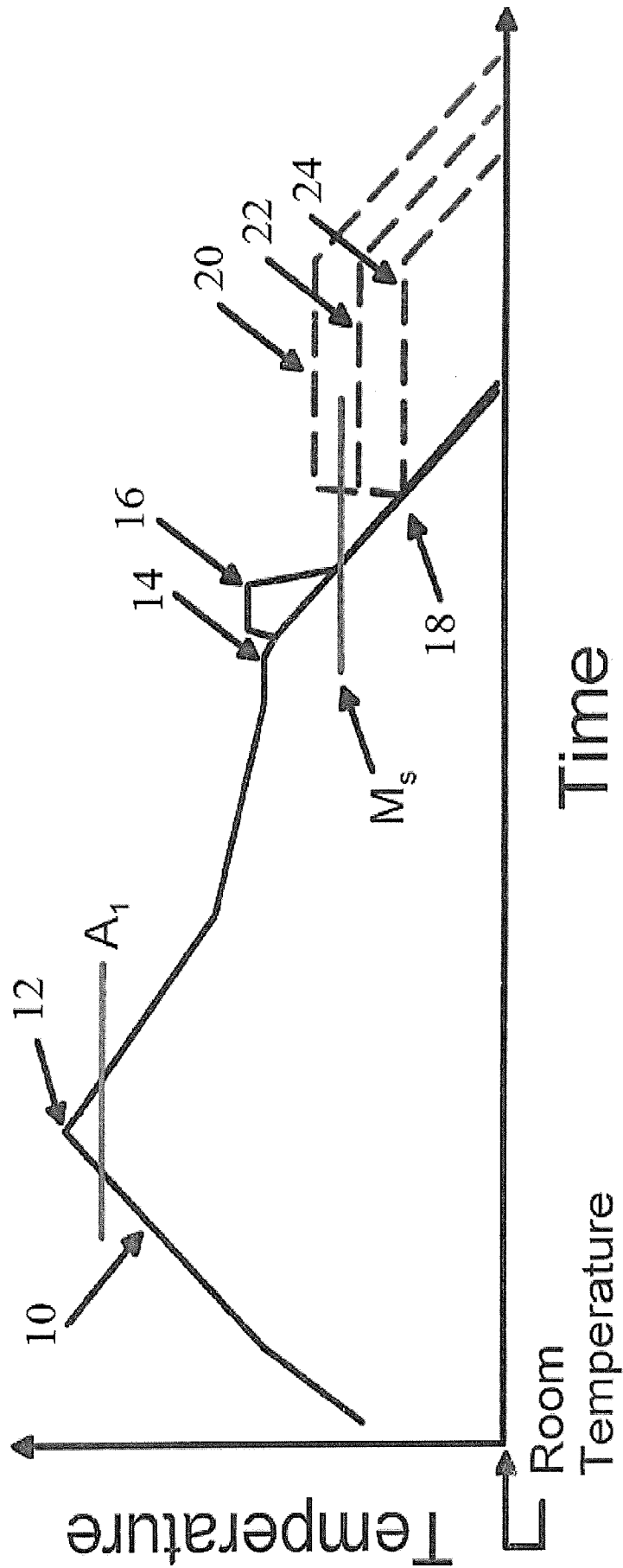


FIG. 1

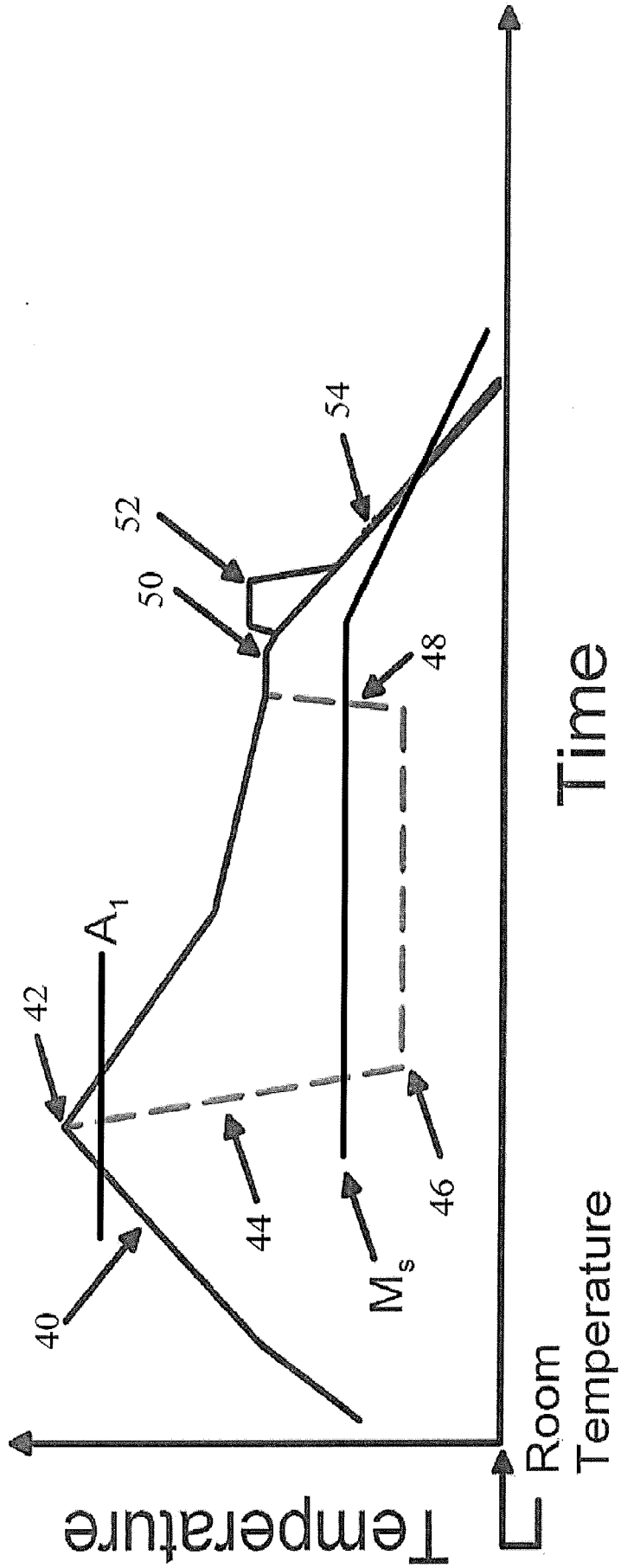


FIG. 2

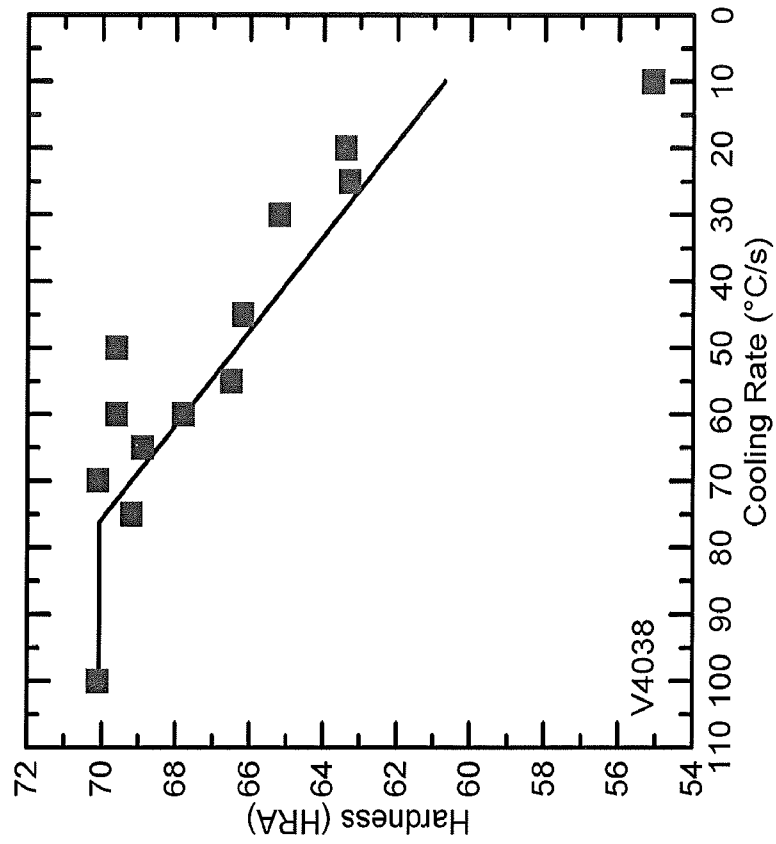


FIG. 4

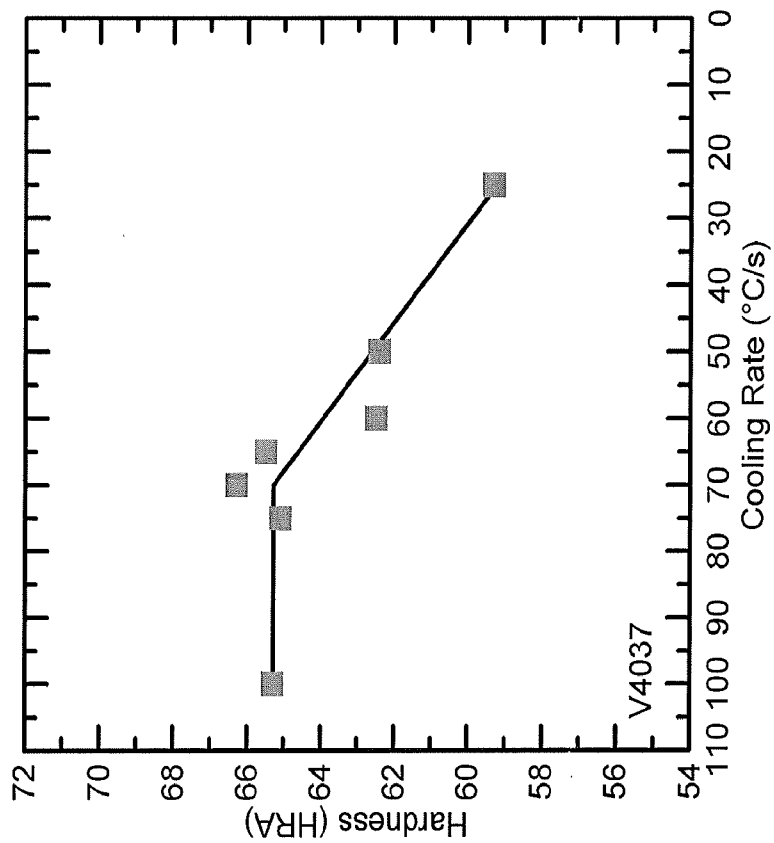


FIG. 3

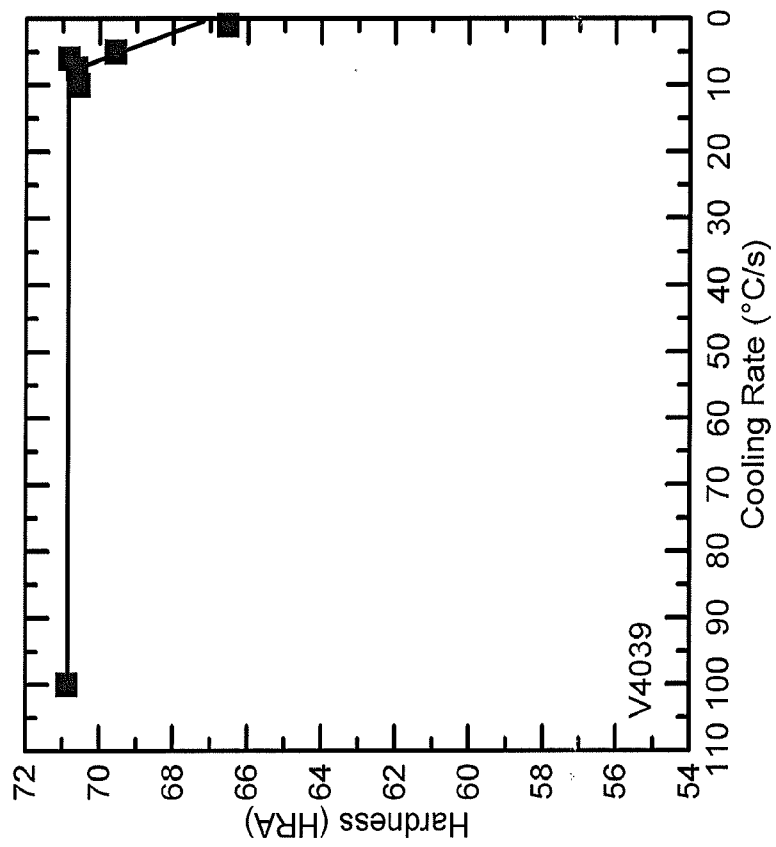


FIG. 5

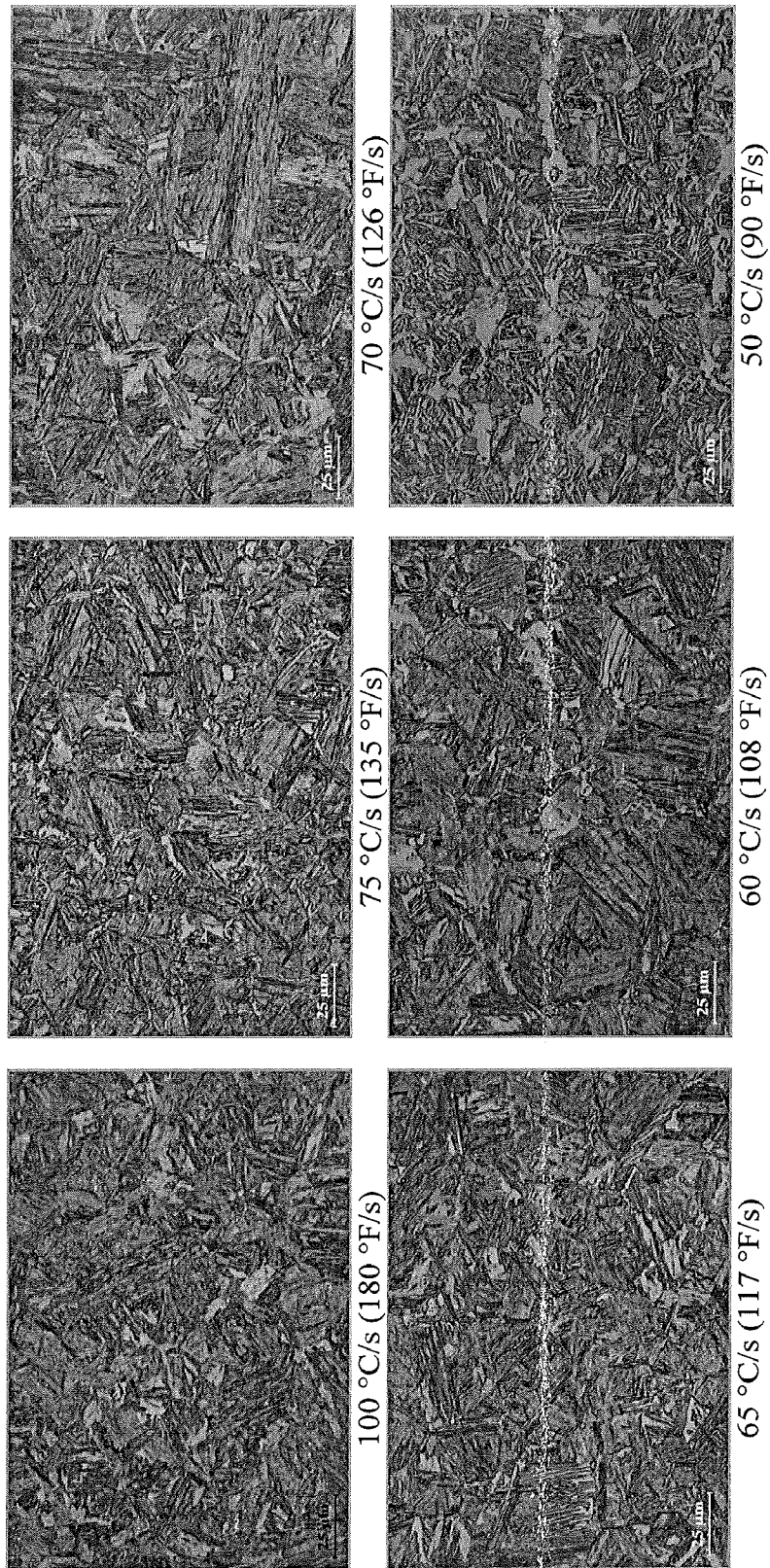


FIG. 6



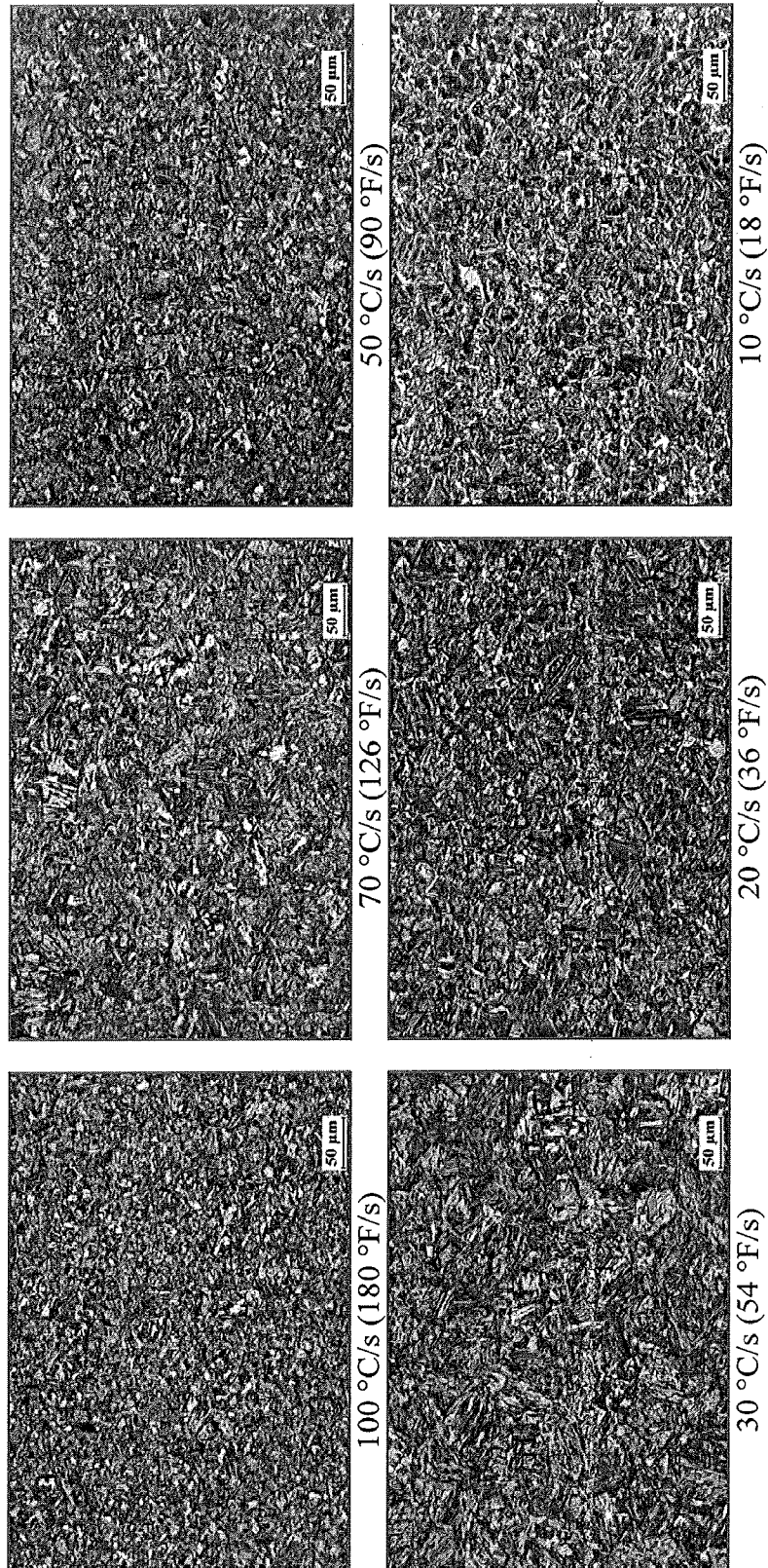


FIG. 7

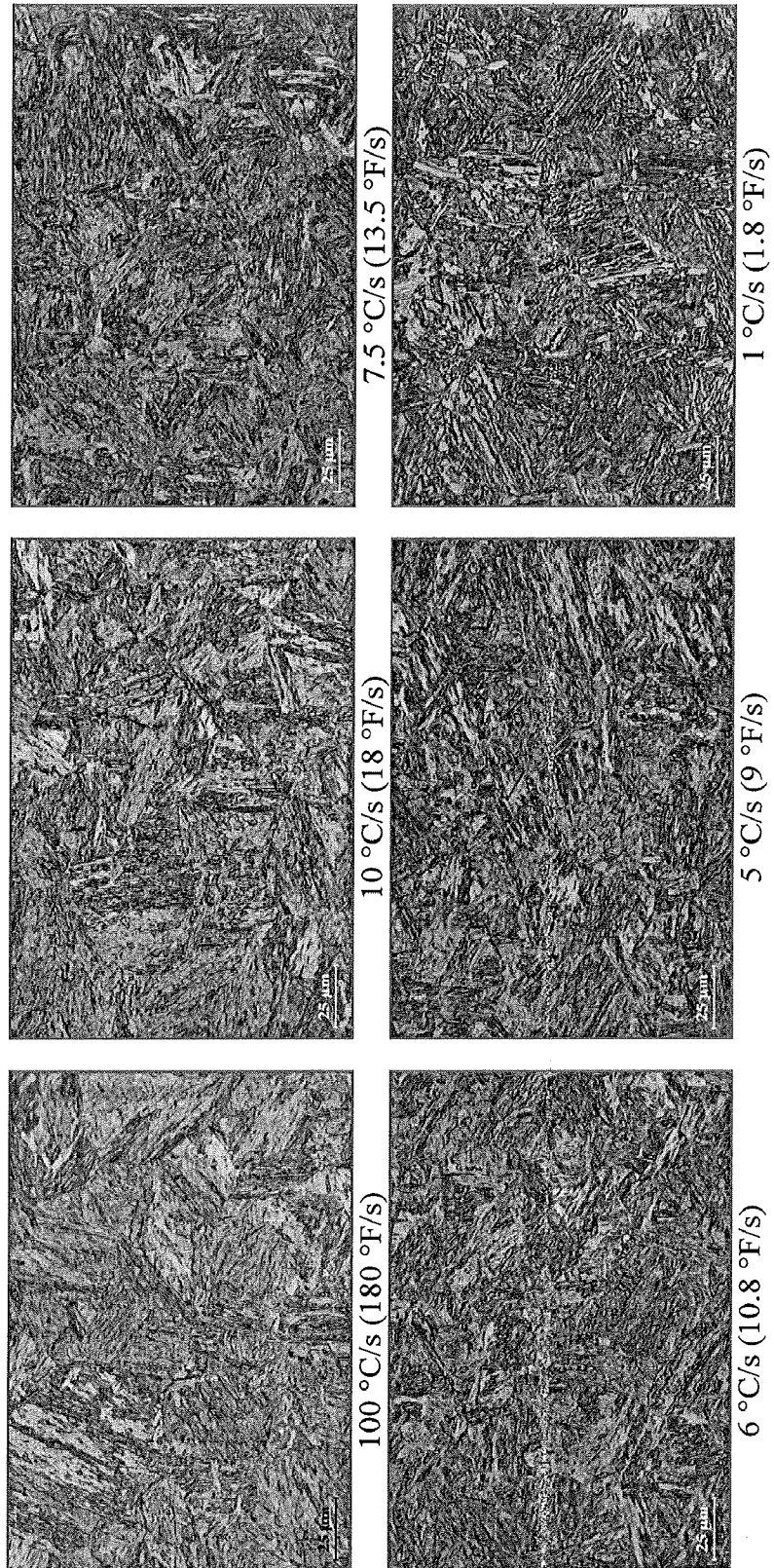


FIG. 8

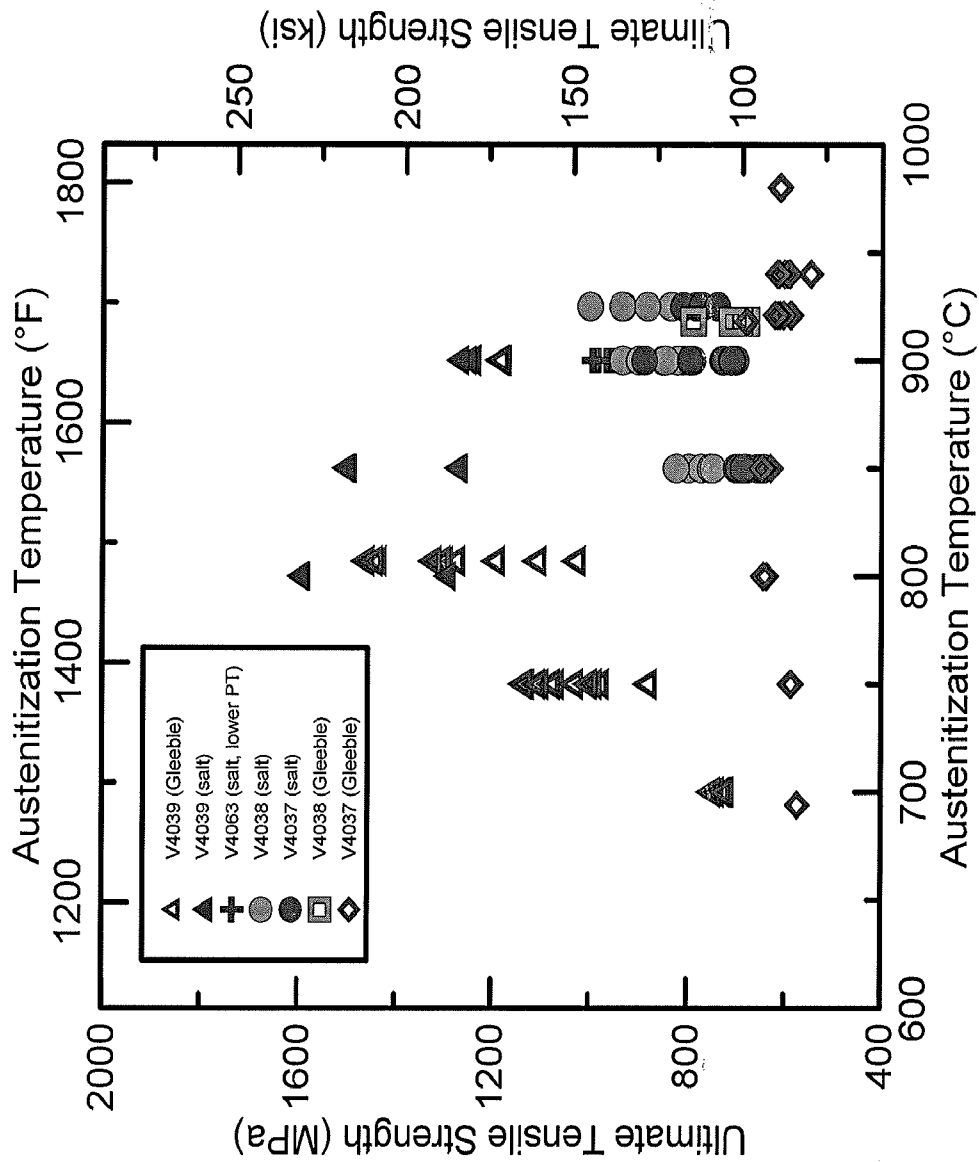


FIG. 9

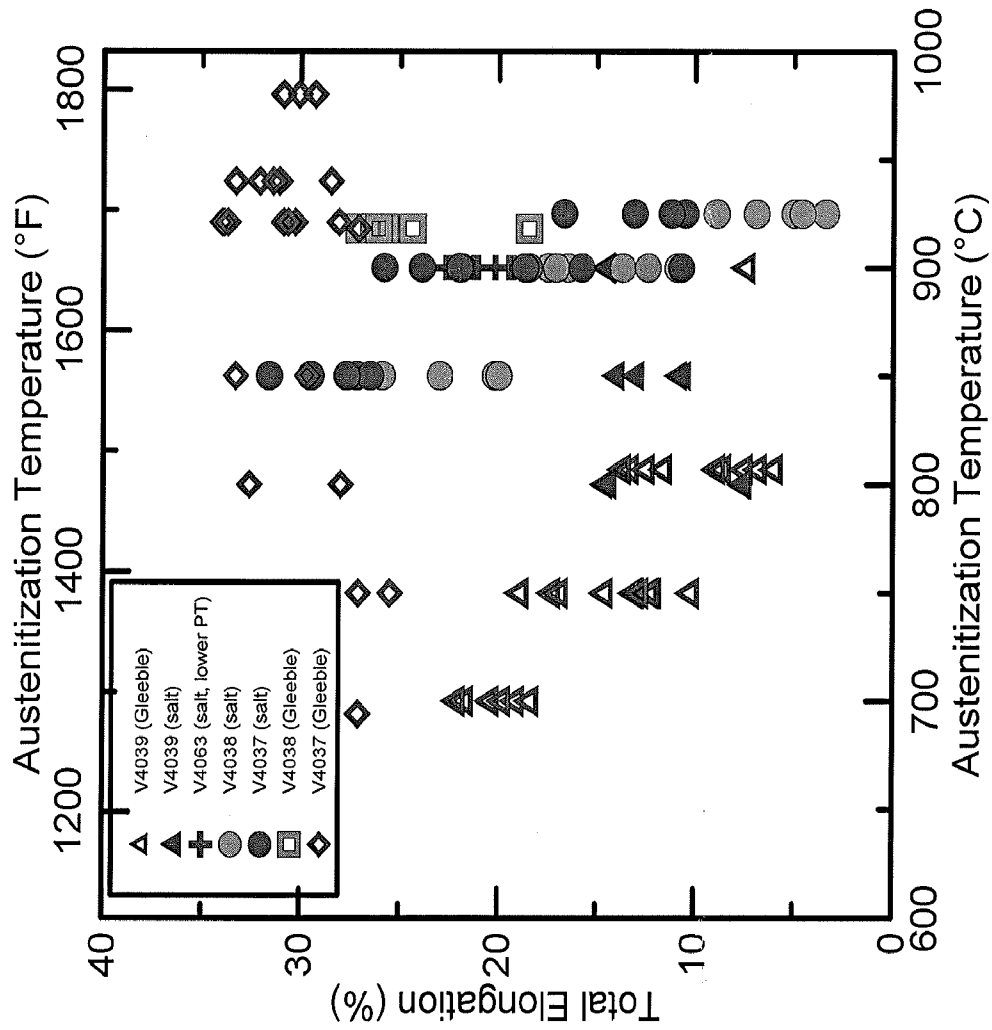


FIG. 10

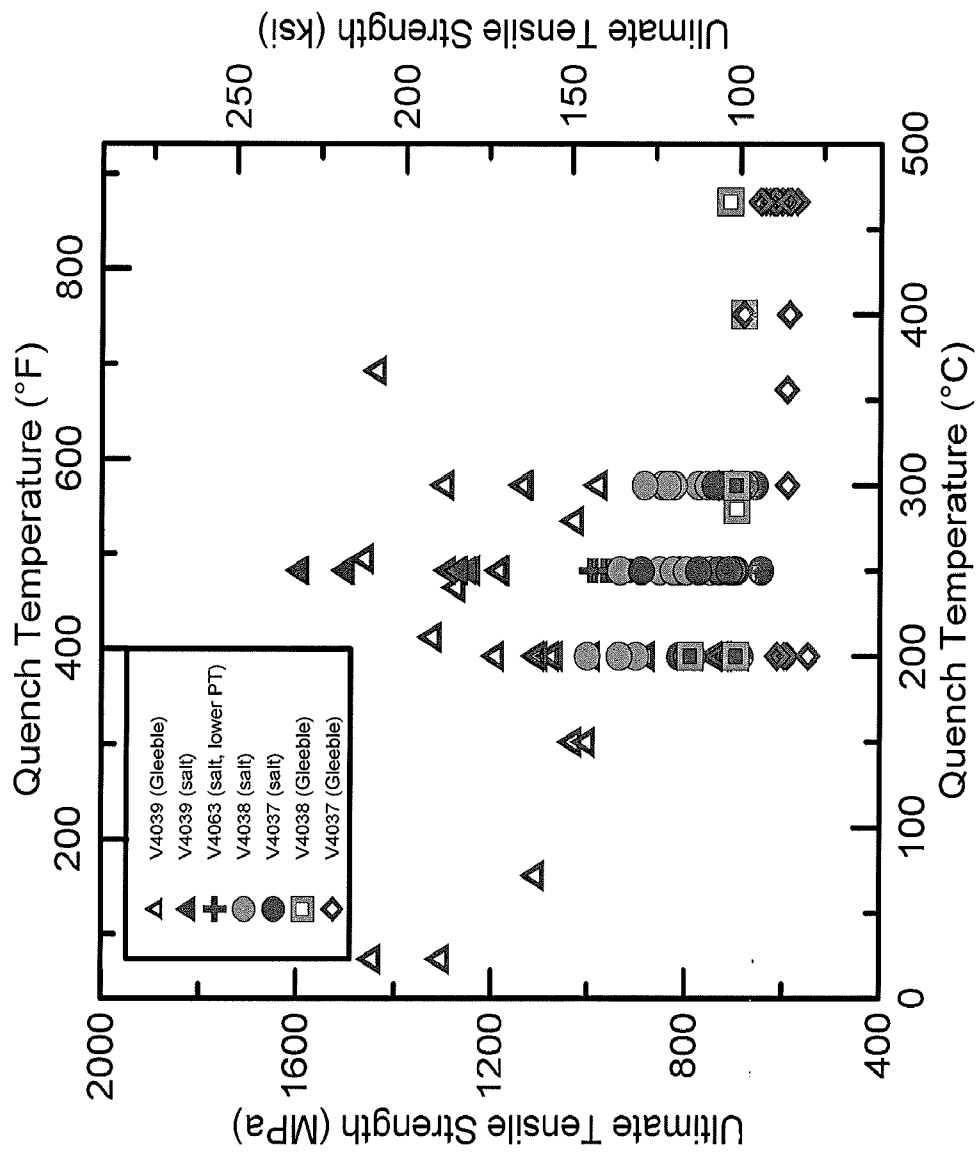


FIG. 11

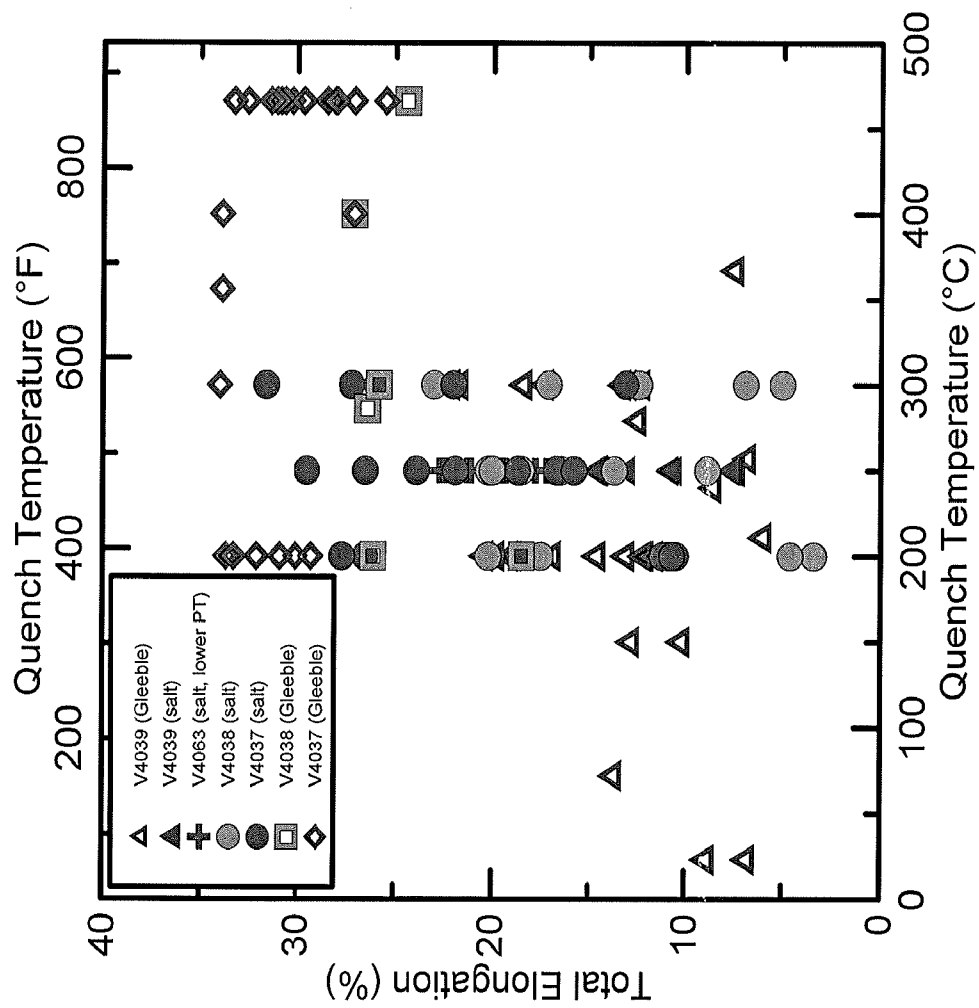


FIG. 12