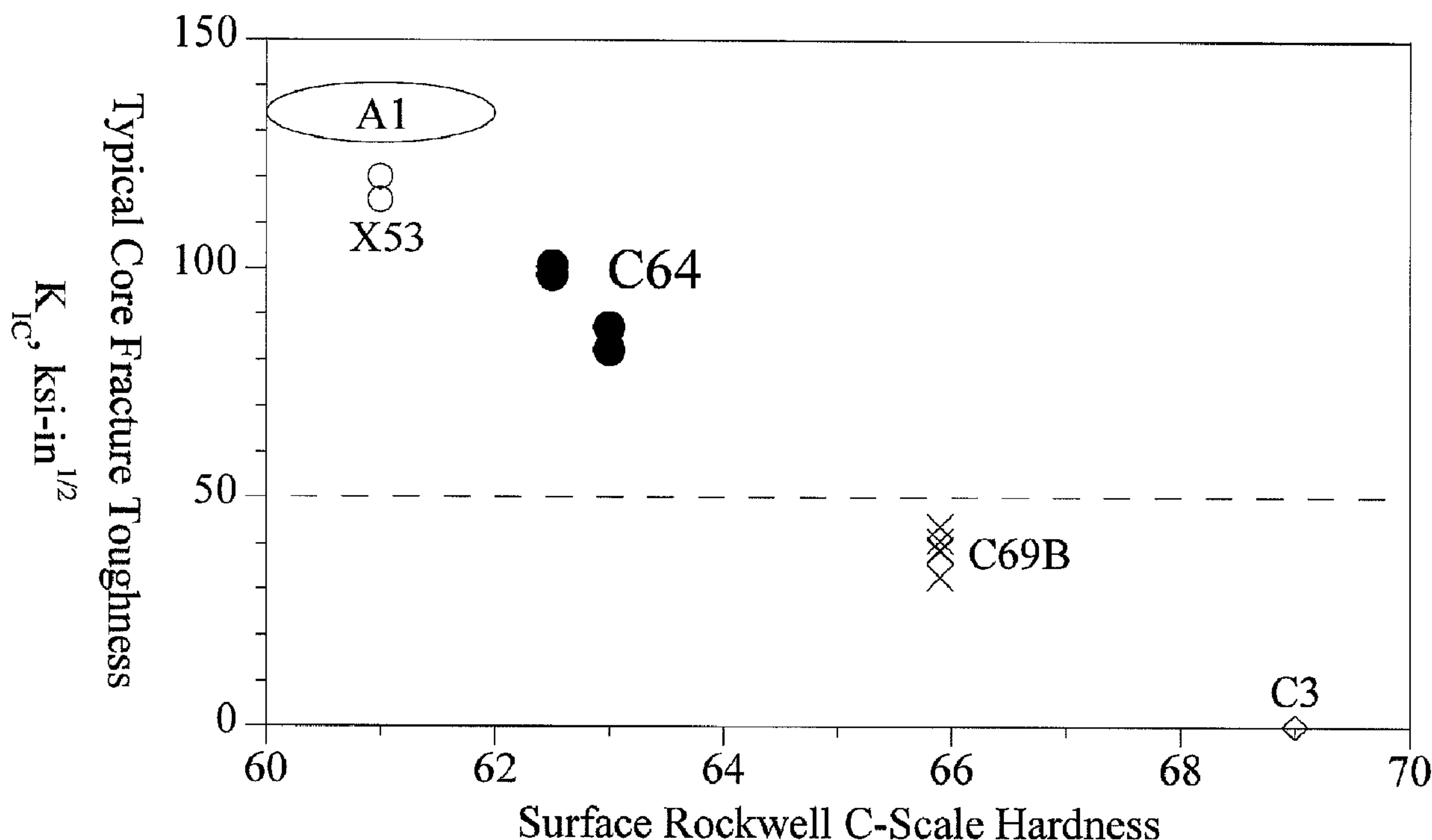




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(54) Title: SECONDARY-HARDENING GEAR STEEL



(57) Abrégé/Abstract:

A case hardened gear steel having enhanced core fracture toughness includes by weight percent about 16.3Co, 7.5Ni, 3.5Cr, 1.75Mo, 0.2W, 0.11C, 0.03Ti, and 0.02V and the balance Fe, characterized as a predominantly lath martensitic microstructure essentially free of topologically close-packed (TCP) phases and carburized to include fine M₂C carbides to provide a case hardness of at least about 62 HRC and a core toughness of at least about 50 ksiVin.

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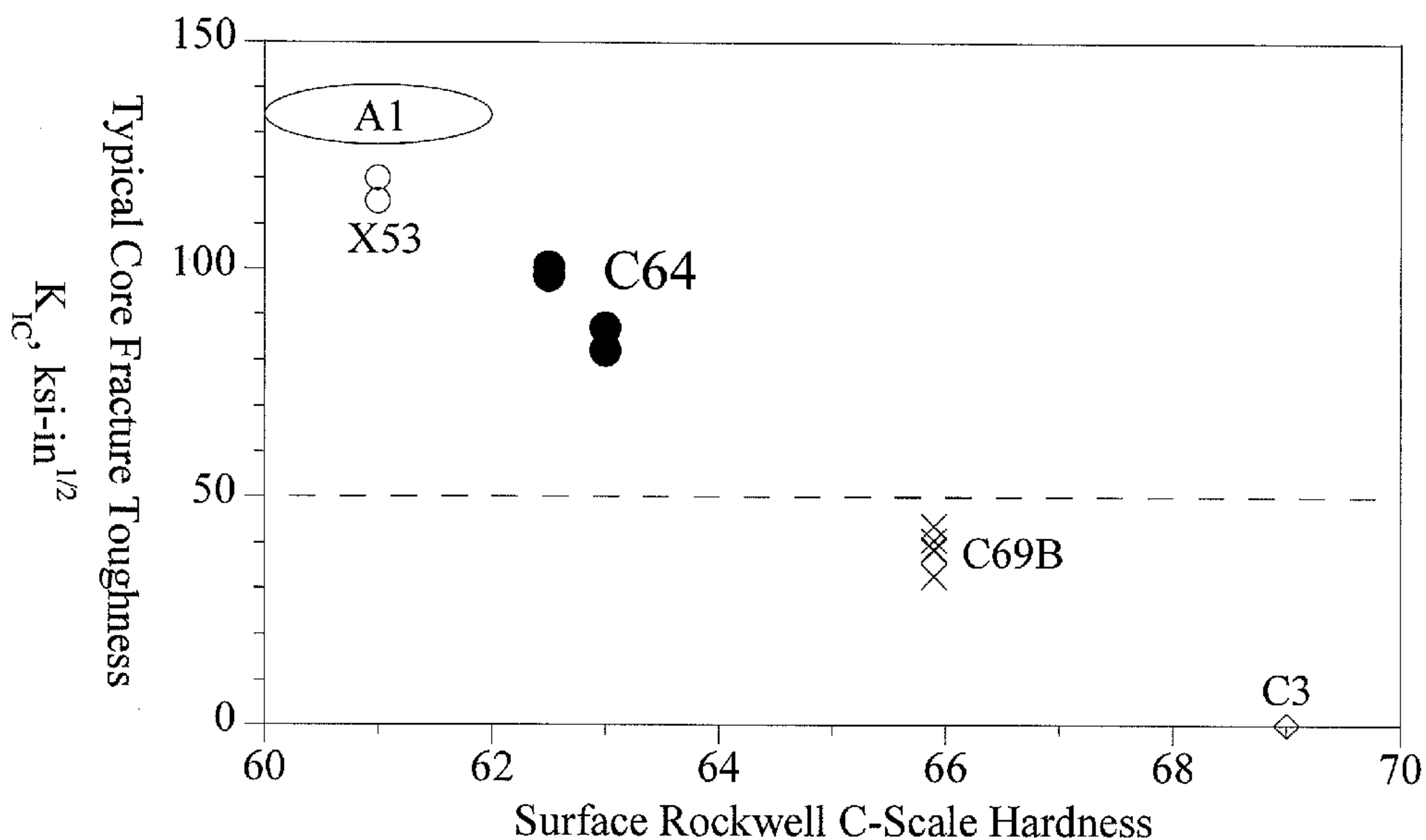
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[Continued on next page]

(54) Title: SECONDARY-HARDENING GEAR STEEL

FIGURE 3



(57) Abstract: A case hardened gear steel having enhanced core fracture toughness includes by weight percent about 16.3Co, 7.5Ni, 3.5Cr, 1.75Mo, 0.2W, 0.11C, 0.03Ti, and 0.02V and the balance Fe, characterized as a predominantly lath martensitic microstructure essentially free of topologically close-packed (TCP) phases and carburized to include fine M_2C carbides to provide a case hardness of at least about 62 HRC and a core toughness of at least about 50 ksiVin.

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SECONDARY-HARDENING GEAR STEEL**CROSS REFERENCE TO RELATED APPLICATIONS**

- [01] This is an international patent application claiming priority to the following provisional application: U.S. Serial No. 60/957,307 filed 22 August 2007 and US regular patent application No. 12/194,964 filed on 20 August 2008.

GOVERNMENT INTERESTS

- [02] Activities relating to the development of the subject matter of this invention were funded at least in part by United States Government, Naval Air Warfare Center Contract No. N68335-06-C-0339, and thus may be subject to license rights and other rights in the United States.

BACKGROUND OF THE INVENTION

- [03] In a principal aspect, the present invention relates to a high-performance carburized gear steel that can improve the performance of rotorcraft power transmissions, due to a unique and useful combination of surface hardness and core toughness. The U.S. Navy estimates that a 20% increase in gear durability would provide an annual cost saving of \$17 million to the Defense Logistics Agency. However, the rotorcraft industry has not adopted a new gear steel for over twenty years, and instead focused on surface processing optimizations such as laser-peening, super-finishing, and directional forging. Such processes are providing diminishing returns in durability improvements. The subject invention provides a solution complementary to process enhancements and enables high-performance gears having reduced size and weight which are capable of transmitting more power at increased operating temperatures.
- [04] Carburized X53 (U.S. Patent 4,157,258) is the incumbent material in rotorcraft transmissions. Compared to X53, the subject invention places an emphasis on increasing the case strength and the core fracture toughness, as well as increasing the thermal stability up to 450°C to provide hot hardness in high-temperature excursions. Patent No. 6,464,801 also discloses case-hardened steels. However, the embodiment A1 of Patent No. 6,464,801 shows

limited surface-hardness, i.e., Rockwell C scale hardness (HRC) of 60- 62. Another embodiment of Patent No. 6,464,801, steel C3, shows a greater surface hardness of 69 HRC, but the core of this steel lacks toughness. To be usable as a gear, the core fracture toughness of the steel must exceed 50 ksi√in. Thus, there has developed a need for a carburized gear steel with a surface hardness of HRC of at least about 62-64 at a usable core toughness exceeding 50 ksi√in.

SUMMARY OF THE INVENTION

[05] Briefly, the present invention comprises a high-performance gear steel which is especially useful for rotorcraft transmissions. The steel exhibits an increase in surface hardness and core fracture toughness compared to conventional carburized gear steels. The steel is designed for a reasonable carbide solvus temperature, which, in turn, enables gas or vacuum carburization. Upon gas quenching from the solution heat treatment temperature, the steel transforms into a predominantly lath martensitic matrix. During tempering, an optimal strengthening dispersion of secondary M_2C carbide precipitates, where M is Mo, Cr, W and/or V. The high tempering temperature of the steel enables higher operating temperatures in transmission components compared to conventional gear steels like X53 or 9310.

[06] To achieve high core toughness, the matrix composition is carefully balanced to ensure the ductile-to-brittle transition is sufficiently below room temperature. The designed composition also effectively limits the thermodynamic driving force for precipitation of embrittling Topologically-Close-Packed (TCP) intermetallic phases such as σ and μ . Toughness of the invented steel is further enhanced by the distribution of a fine dispersion of grain-pinning particles that are stable during carburization and solution heat treatment cycles. The grain-pinning particles are MC carbides, where M = Ti, Nb, Zr, V with Ti preferred, that dissolve during homogenization and subsequently precipitate during forging.

[07]

Table I

wt% Alloy	Fe	Cr	Co	Mo	Ni	V	W	C	Ti	Mn	Si	Cu
C64	Bal.	3.5	16.3	1.75	7.5	0.02	0.2	0.11	0.03			
A1	Bal.	3.5	18.0	1.10	9.5	0.08	0.0	0.20	0.03			
C2	Bal.	4.8	25.0	0.03	3.8	0.06	0.0	0.237				
C3	Bal.	5.0	28.0	1.75- 2.50	3.25- 3.15	0.025	0.0	0.05- 0.18				
C69B	Bal.	4.5	16.1	1.80	4.3	0.10	0.1	0.12	0.02			
X53	Bal.	1.0	0.0	3.25	2.00	0.10	0.0	0.10		0.35	1.00	2.00
9310	Bal.	1.2		0.115	3.25			0.145		0.55	0.25	

[08]

The exemplary steel of the invention is designated as C64 in the above table. By virtue of inclusion of W, this steel is distinct from the steels disclosed in Patent No. 6,464,801 (i.e. A1, C2, and C3). Inclusion of W increases the M_2C driving force similar to Cr or Mo, and uniquely limits the thermodynamic driving force for precipitation of undesirable TCP phases. Whereas Mo and Cr preferentially promote σ -phase more than μ -phase, W provides a reverse effect. Thus, by adding W, the total driving force for σ - and μ -phases is balanced and precipitation of either TCP phase is avoided.

[09]

Alloy C69B is a counterexample. Although alloy C69B does include W and successfully tends to avoid the precipitation of TCP phases, insufficient Ni in the matrix places the ductile-to-brittle transition above room temperature. The Ni content is thus greater in alloys of the embodiment of the invention to place the ductile-to-brittle transition above room temperature and concurrently maximize the driving force for M_2C , enabling the highest surface hardness at a usable toughness compared to any other known secondary-hardening steel.

[10]

Due to high surface hardness, good core toughness, and the high-temperature capability, the disclosed steel is considered especially utilitarian with respect to gears for helicopter transmissions. Other uses of the steel include vehicle gearing and armor. With respect to the

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constituents in the exemplary steel set forth above, the alloy preferably includes a variance in the constituents in the range of plus or minus five percent of the mean value.

One aspect of the invention relates to a steel alloy comprising in weight percent: about 3.5 Cr, about 16.3 Co, about 1.75 Mo, about 7.5 Ni, about 0.02 V,
5 about 0.20 W, about 0.11 C, about 0.03 Ti, and the balance Fe with a carburized case having a hardness greater than about 62 HRC and a core having a core fracture toughness greater than about 50 ksi√in at room temperature wherein said alloy comprises a predominantly lath martensitic microstructure matrix essentially free of topologically close-packed (TCP) phases, and said alloy further comprises fine M₂C carbides.

10 Another aspect of the invention relates to a steel alloy consisting essentially of in weight percent about 3.5 Cr, about 16.3 Co, about 1.75 Mo, about 7.5 Ni, about 0.02 V, about 0.20 W, about 0.11 C, about 0.03 Ti, and the balance Fe initial melt constituency; said alloy comprising a predominantly lath martensitic microstructure matrix and having a hardened carburized case with a case hardness of at least 62 HRC and a core with a fracture
15 toughness of at least about 50 ksi√in at room temperature.

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BRIEF DESCRIPTION OF THE DRAWING

- [11] In the detailed description which follows, reference will be made to the drawing comprised of the following figures:
- [12] FIG. 1 is a systems design chart representing the interactions among the desired hierarchical microstructure, the required processing and the property objectives for the alloy of the invention.
- [13] FIG. 2 schematically illustrates the time-temperature processing steps for the subject alloy.
- [14] FIG. 3 is a graph plotting the maximum surface hardness and core fracture toughness of various steels possibly useful for power transmission gears. Typical embodiments of the claimed invention are also plotted and identified as alloy C64.
- [15] FIG. 4 is a graph plotting the Charpy V-Notch (CVN) impact energy of alloys C64 and C69B, in solid and open circles respectively, at various test temperatures.
- [16] FIG. 5 is a graph depicting the hardness profile achieved for the carburized sample of alloy C64 and the alloy A1 of patent 6,464,801, in solid and open circles, respectively.

DESCRIPTION OF THE PREFERRED EMBODIMENT

- [17] In general, the subject matter of the invention comprises a secondary-hardening carburized gear steel with surface hardness of HRC of at least about 62-64 and core fracture toughness greater than about 50 ksi√in. The interactions among the desired hierarchical microstructure, the processing and the property objectives are represented by the systems design chart in Figure 1. An ultimate goal of this invention was to optimize the whole system by controlling each subsystem and provide the most useful combination of surface hardness, core fracture toughness, and temperature resistance.

- [18] Failure modes in gears are generally grouped into three categories: bending fatigue, contact fatigue, and temperature-induced scoring. Bending fatigue as well as contact fatigue can be limited by a high surface-hardness. To achieve high surface-hardness, the steel of the invention employs efficient secondary hardening by coherent M_2C carbides which precipitate during tempering. The high Co content of the steel retards dislocation recovery and reduces the density of dislocations in response to thermal exposure. M_2C carbides precipitate coherently on these dislocations during tempering and provide a strong secondary hardening response, enabling a surface hardness of 62-64 HRC.
- [19] The steel alloy of the invention also limits temperature-induced scoring. Subsurface scoring results if the alloy's contact fatigue strength drops below the applied stress at any point below the surface. To provide adequate fatigue strength and avoid subsurface scoring, typically at least about a 1 mm-deep hardened case is preferred. The steel of the invention achieves this desirable case depth via a carbon content gradient achieved during carburization.
- [20] The steel comprises a predominantly lath martensitic matrix free of TCP-phases, and is strengthened by a fine-scale distribution of M_2C carbides. In order to produce a predominantly lath martensitic matrix, the martensite-start temperature (M_s) must be higher than about 100°C at the carburized surface. To this end, the invention has carefully optimized the Ni content. While Ni is desirable for cleavage resistance, it also stabilizes austenite and thus, depresses M_s . The Ni content is chosen to place the ductile-to-brittle transition of the steel sufficiently below room temperature, preferably below -20°C, while maintaining a sufficiently high M_s . The Ductile-to-Brittle Transition Temperature (DBTT) of the steel can be characterized by measuring the CVN impact energy at varying temperatures. As shown in Figure 3, while earlier prototype alloy C69B shows susceptibility to cleavage up to 150°C, the optimized composition of alloy C64 of the invention successfully depresses the DBTT to about -20°C.
- [21] To further enhance toughness, the average grain diameter must be less than about 50 μ . To prevent undesirable grain growth during solution treatment, the steel employs a grain-pinning dispersion of MC particles, where M may be Ti, Nb, Zr, or V, with Ti preferred. To improve the grain-pinning efficiency, the particle size of the grain-pinning dispersion should be refined. A refined size of the MC particles is achieved by designing a system wherein the

particles dissolve during homogenization and subsequently precipitate during forging. The MC particles remain stable during subsequent carburization and solution heat treatment cycles.

[22] The resulting lath martensitic matrix is free of undesirable TCP-phases. TCP-phase precipitation is to be avoided during tempering because such phases can reduce the alloy ductility and toughness. The thermodynamic driving force for precipitation of TCP phases is limited in the invention by the contents of Cr, Mo, and W.

[23] Following are examples of the experiments relating to development of the alloy of the invention:

[24] EXAMPLE 1

[25] A 3,000-lb vacuum induction melt of Fe-16.1Co-4.5Cr-4.3Ni-1.8Mo-0.12C-0.1V-0.1W-0.02Ti (wt%) was prepared from high purity materials. The melt was converted to a 1.5-inch-square bar. The optimum processing condition was to solutionize at 1050° 90 minutes, quench with oil, immerse in liquid nitrogen for 1 hour, warm in air to room temperature, temper at 468°C for 56 hours, and cool in air. The DBTT in this condition was between 150°C and 250°C.

[26] EXAMPLE 2

[27] A 30-lb vacuum induction melt of Fe-17.0Co-7.0Ni-3.5Cr-1.5Mo-0.2W-0.12C-0.03Ti (wt%) was prepared from high purity materials. M_s of the case material was measured as 162°C from dilatometry, in agreement with model predictions. The carburization response of this prototype was determined from hardness measurements. The optimum processing condition was to carburize and concurrently solutionize the steel at 927°C for 1 hour, quench with oil, and immerse in liquid nitrogen. A subsequent tempering at 482°C for 16 hours resulted in a surface-hardness of 62.5 HRC. The case depth of the carburized sample was about 1 mm. An atom-probe tomography analysis of the steel verified the absence of TCP phases.

[28] EXAMPLE 3

[29] A 300-lb vacuum induction melt of Fe-17.0Co-7.0Ni-3.5Cr-1.5Mo-0.2W-0.12C (wt%) was prepared from high purity materials. Because this prototype did not include Ti, the grain-pinning dispersion of TiC particles could not form. As a result, the average grain diameter was

83 μ and toughness was very low. The CVN impact energy of the core material from this prototype was 5 ft·lb at an Ultimate Tensile Strength (UTS) of 238 ksi.

[30] EXAMPLE 4

[31] A second 300-lb vacuum induction melt of Fe-17.0Co-7.0Ni-3.5Cr-1.5Mo-0.2W-0.12C-0.03Ti (wt%) was prepared from high purity materials. This composition did include Ti, and the average grain diameter was 35 μ . Toughness improved substantially. The CVN impact energy of the core material from this prototype was 23 ft·lb at a UTS of 238 ksi. The corresponding processing condition was to carburize and concurrently solutionize the steel at 927°C for 8 hours, quench with oil, immerse in liquid nitrogen for 1 hour, temper at 496°C for 8 hours, and cool in air. The fracture toughness in this condition was 100 ksi $\sqrt{\text{in}}$. The DBTT in this condition was around room temperature.

[32] EXAMPLE 5

[33] A 10,000-lb vacuum induction melt of Fe-16.3Co-7.5Ni-3.5Cr-1.75Mo-0.2W-0.11C-0.03Ti-0.02V (wt%) was prepared from high purity materials. Half of the melt was converted to a 6.5-inch-diameter barstock, while the other half was converted to a 4.5-inch-diameter barstock. The optimum processing condition was to carburize the steel at 927°C for 3 hours, cool in air, solutionize at 1000°C for 40 minutes, quench with oil, immerse in liquid nitrogen for 2 hours, warm in air to room temperature, temper at 496°C for 8 hours, and cool in air. The average grain diameter in this condition was 27 μ and the fracture toughness was 85 ksi $\sqrt{\text{in}}$ at a UTS of 228 ksi.

[34]

TABLE II

	1	2	3	4	5 (C64)
C	0.12	0.12	0.12	0.12	0.11
Co	16.1	17.0	17.0	17.0	16.3
Cr	4.5	3.5	3.5	3.5	3.5
Ni	4.3	7.0	7.0	7.0	7.5
Mo	1.8	1.5	1.5	1.5	1.75
V	0.1				0.02
W	0.1	0.2	0.2	0.2	0.2
Ti	0.02	0.03		0.03	0.03
Fe	Bal.	Bal.	Bal.	Bal.	Bal.
Average Grain Diameter (μ)			83	35	27
TCP	Absent	Absent	Absent	Absent	Absent
Fracture Toughness ksi\sqrt in				100	85
UTS			238	238	228
HRC		62.5			
DBTT ($^{\circ}$C)	150-250			25	

[35]

Table II summarizes the information with respect to the examples set forth above and also indicates an embodiment of the invention (alloy C64). While an embodiment of the invention is disclosed, it is to be understood that the invention is to be limited only by the following claims and equivalents thereof.

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CLAIMS:

1. A steel alloy comprising in weight percent: about 3.5 Cr, about 16.3 Co, about 1.75 Mo, about 7.5 Ni, about 0.02 V, about 0.20 W, about 0.11 C, about 0.03 Ti, and the balance Fe with a carburized case having a hardness greater than about 62 HRC and a core
5 having a core fracture toughness greater than about 50 ksi√in at room temperature wherein said alloy comprises a predominantly lath martensitic microstructure matrix essentially free of topologically close-packed (TCP) phases, and said alloy further comprises fine M₂C carbides.
2. The alloy of claim 1 wherein the alloy is in the form of an article of manufacture having a case thickness of about at least 1 mm.
- 10 3. The alloy of claim 1 made by a process comprising the steps of:
 - (a) carburizing the alloy at about 927°C for about 3 hours;
 - (b) cooling the alloy to about ambient temperature;
 - (c) solutionizing the alloy at 1000°C for about 40 minutes;
 - (d) quenching the alloy in a fluid bath to about ambient temperature;
 - 15 (e) immersing the alloy in liquid nitrogen for about 2 hours;
 - (f) warming the alloy to about ambient temperature;
 - (g) tempering the alloy at about 496°C for about 8 hours; and
 - (h) cooling the alloy to about ambient temperature.
4. The method of claim 3 including the step of forming the alloy prior to
20 carburizing.
5. The method of claim 3 including one or more of the preliminary steps prior to carburizing of homogenizing, forging, normalizing and annealing.

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6. The alloy of claim 1 wherein M includes at least one selected from a group consisting of: Mo, Cr, W, and V.
7. The alloy of claim 1 wherein the alloy comprises a fine dispersion of grain pinning MC carbide particles, wherein M includes at least one selected from a group
5 consisting of: Ti, Nb, Zr, and V.
8. The alloy of claim 1 wherein the alloy has a ductile-to-brittle transition temperature below room temperature.
9. The alloy of claim 8 wherein the alloy has a ductile-to-brittle transition temperature below -20°C.
- 10 10. The method of claim 3 wherein the carburization creates a hardened carburized case on the alloy having a depth of at least 1 mm.
11. A steel alloy consisting essentially of in weight percent about 3.5 Cr, about 16.3 Co, about 1.75 Mo, about 7.5 Ni, about 0.02 V, about 0.20 W, about 0.11 C, about 0.03 Ti, and the balance Fe initial melt constituency; said alloy comprising a
15 predominantly lath martensitic microstructure matrix and having a hardened carburized case with a case hardness of at least 62 HRC and a core with a fracture toughness of at least about 50 ksi√in at room temperature.
12. The alloy of claim 11 wherein said alloy comprises a predominantly lath martensitic microstructure matrix essentially free of topologically close-packed (TCP) phases.
- 20 13. The alloy of claim 12 wherein said alloy comprises fine M₂C carbides.
14. The alloy of claim 13 wherein M includes at least one selected from a group consisting of: Mo, Cr, W, and V.
15. The alloy of claim 11 wherein the alloy comprises a fine dispersion of grain pinning MC carbide particles, wherein M includes at least one selected from a group
25 consisting of: Ti, Nb, Zr, and V.

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16. The alloy of claim 11 wherein the alloy has a ductile-to-brittle transition temperature below room temperature.

17. The alloy of claim 16 wherein the alloy has a ductile-to-brittle transition temperature below -20°C.

5 18. The alloy of claim 11 wherein the alloy in the form of an article of manufacture has a hardened carburized case having a depth of at least 1 mm.

19. The alloy of claim 3 wherein the alloy is transformed into the predominantly lath martensitic microstructure upon quenching from a solution heat treatment temperature, without cold working.

10 20. A case hardened steel alloy comprising in weight percent: about 3.5 Cr, about 16.3 Co, about 1.75 Mo, about 7.5 Ni, about 0.02 V, about 0.20 W, about 0.11 C, about 0.03 Ti, and the balance Fe initial melt consistency with a carburized case having a hardness greater than about 62 HRC and a core having a core fracture toughness greater than about 50 ksi√in at room temperature wherein said alloy comprises a predominantly lath
15 martensitic microstructure matrix and said alloy further comprises fine M₂C carbides.

21. The article of claim 20 wherein M includes at least one selected from a group consisting of: Mo, Cr, W, and V.

22. The article of claim 20 wherein the alloy comprises a fine dispersion of grain pinning MC carbide particles, wherein M includes at least one selected from a group
20 consisting of: Ti, Nb, Zr, and V.

23. The article of claim 20 wherein the alloy has a ductile-to-brittle transition temperature below room temperature.

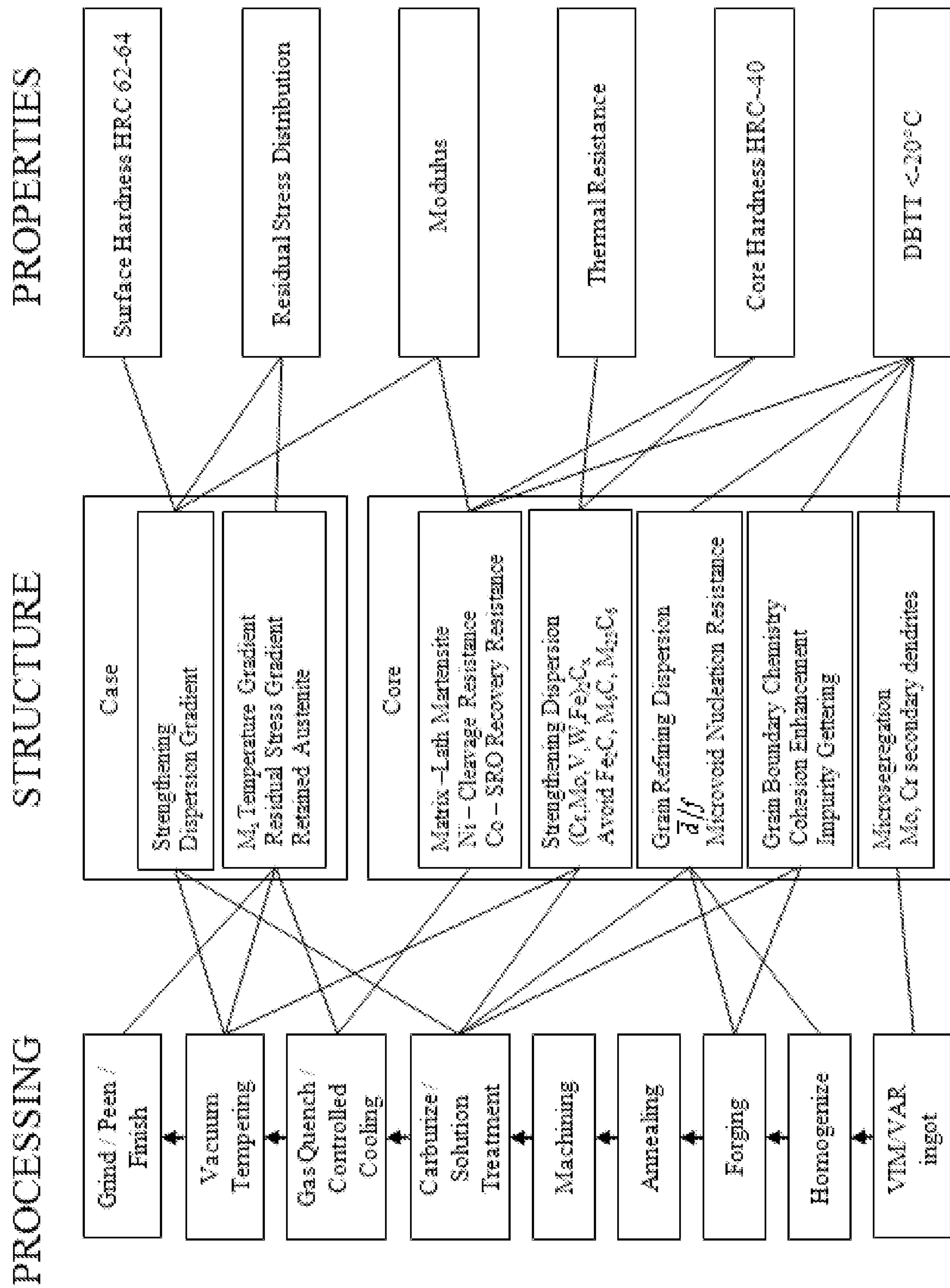


FIGURE 1

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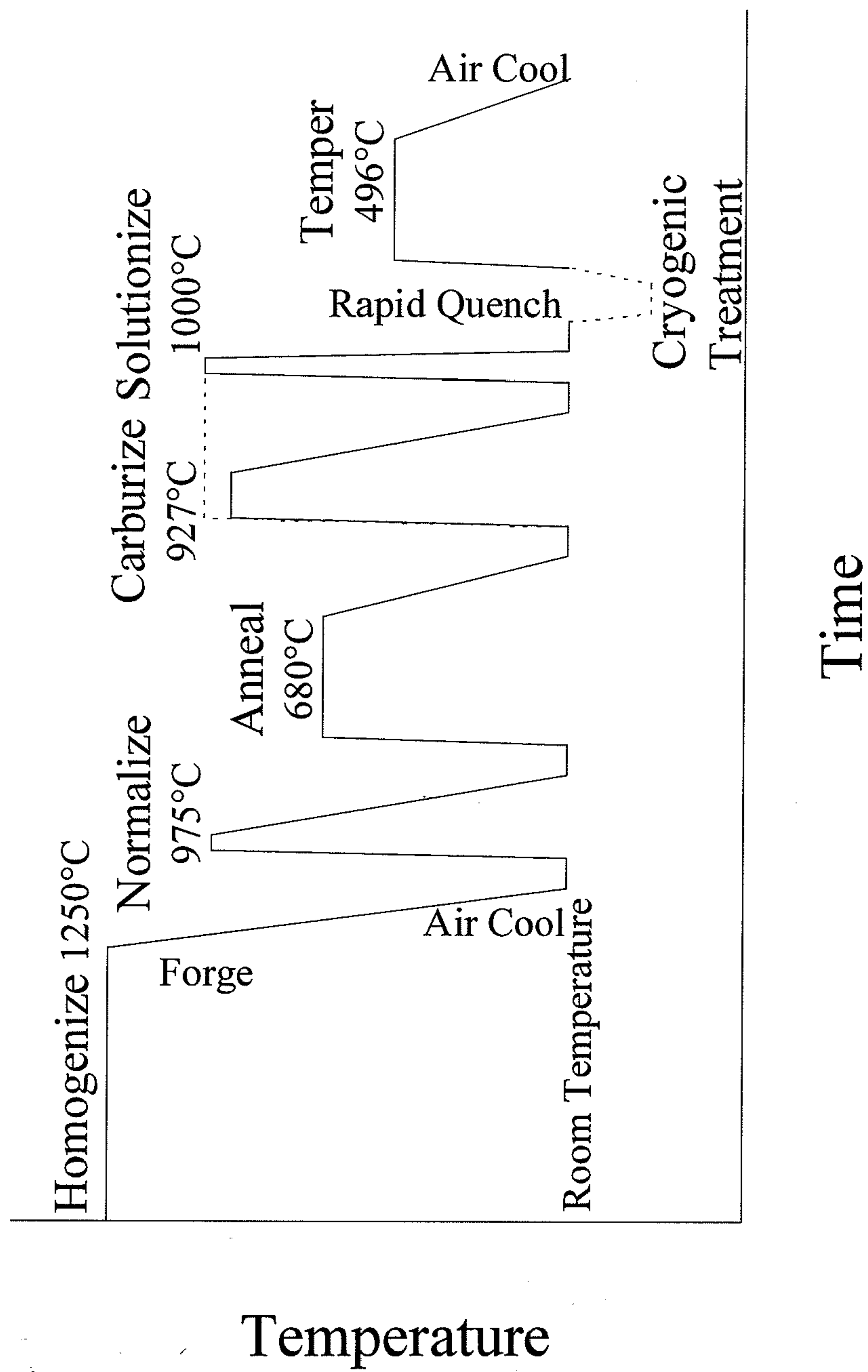


FIGURE 2

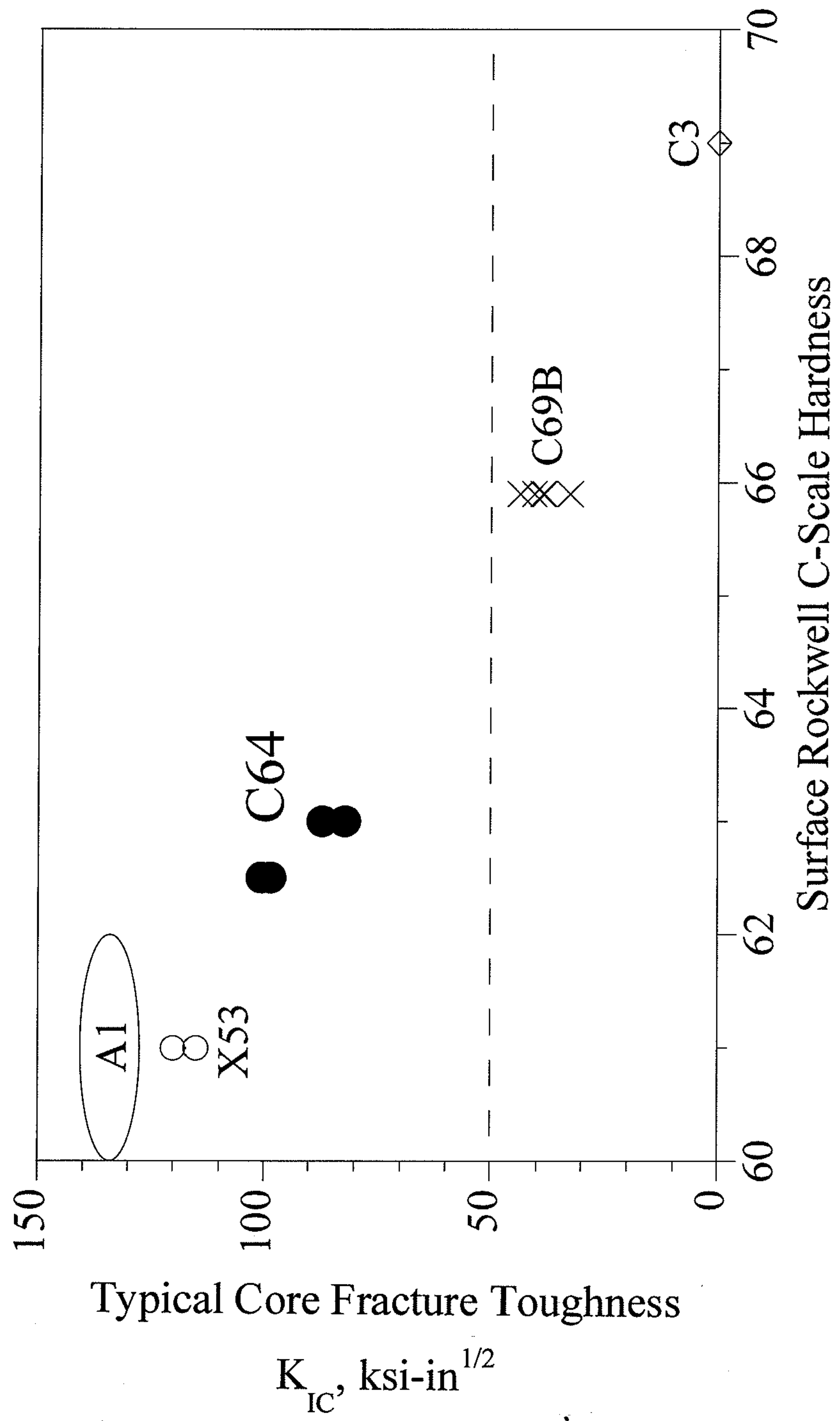


FIGURE 3

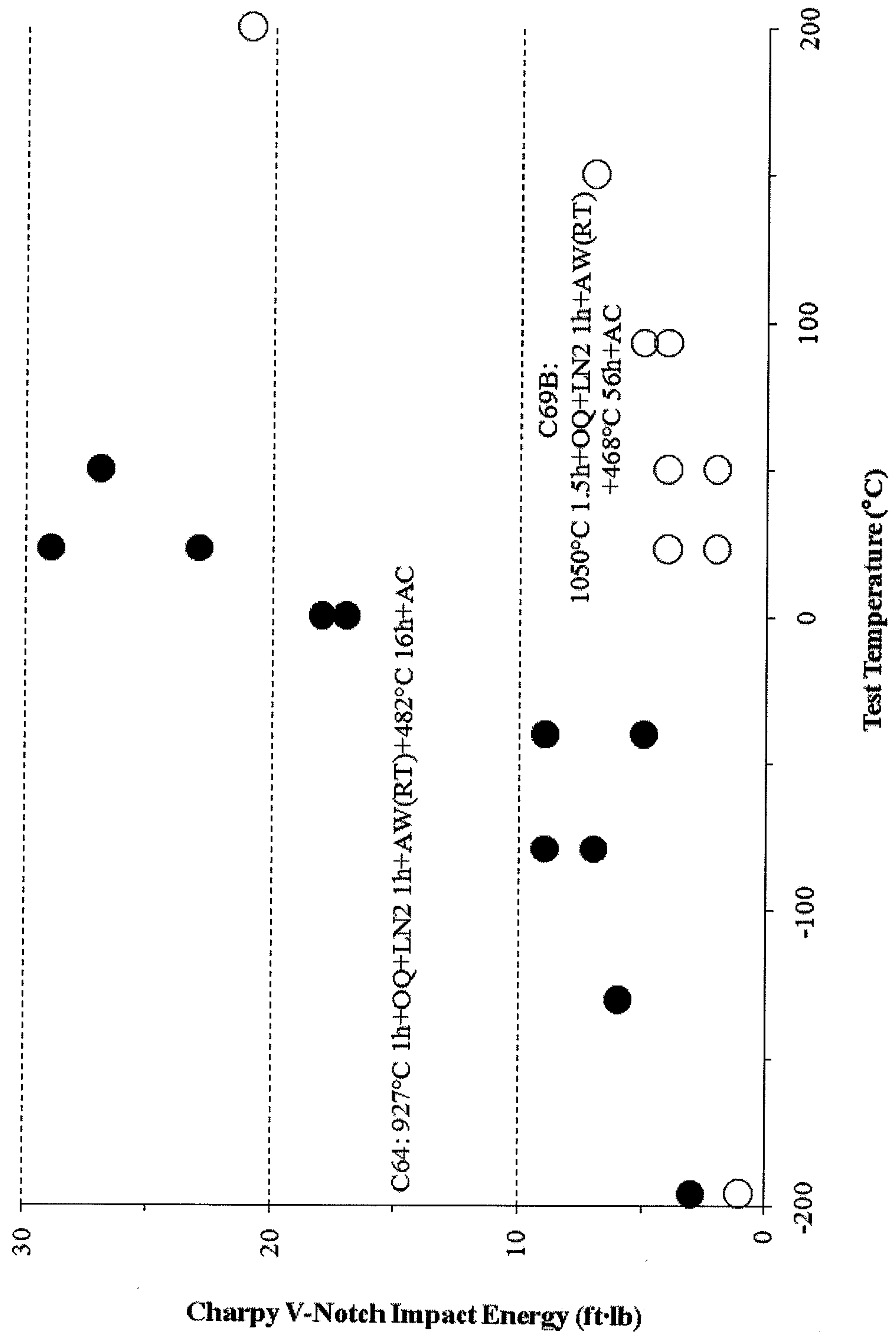


FIGURE 4

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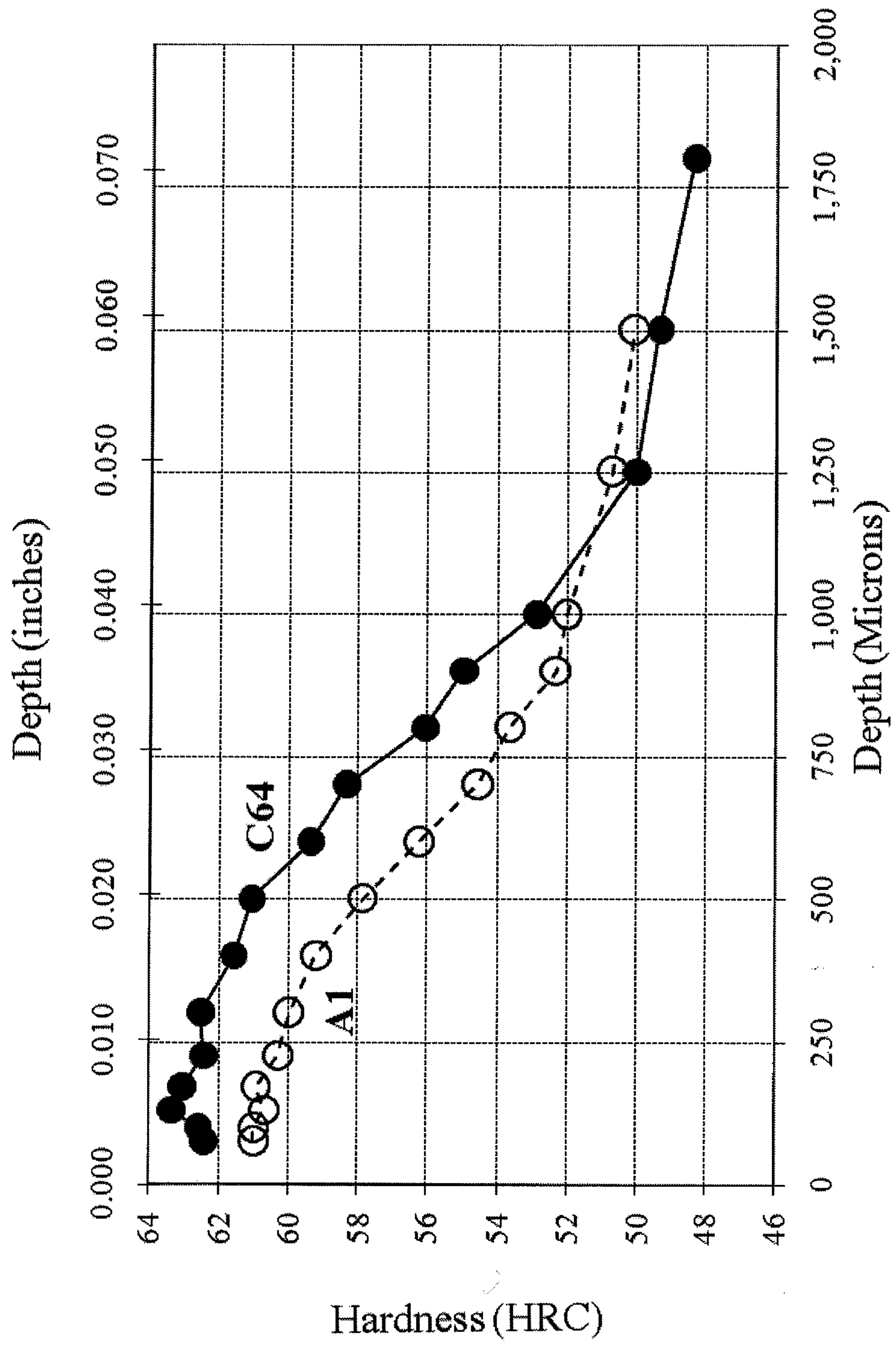


FIGURE 5

FIGURE 3

