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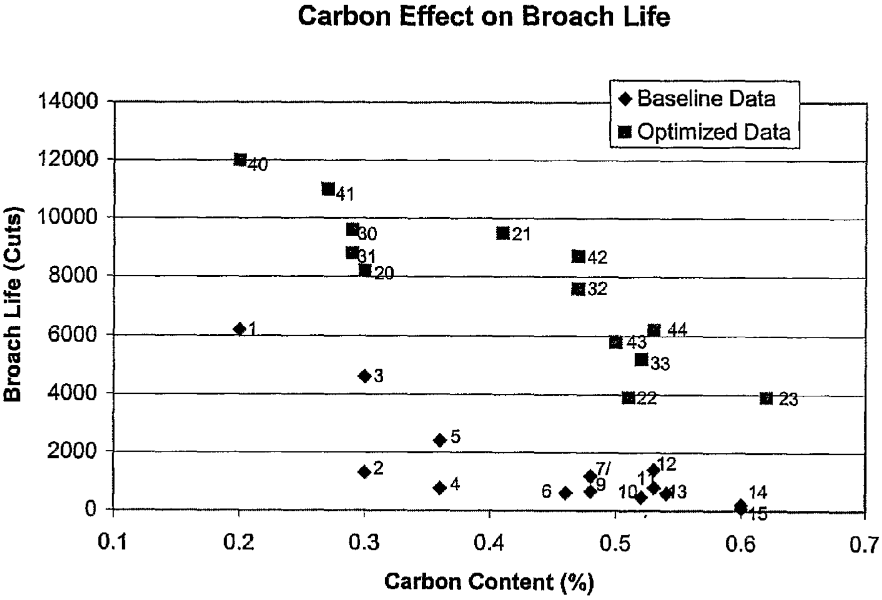
(54) Title: OPTIMIZATION OF STEEL METALLURGY TO IMPROVE BROACH TOOL LIFE



(57) Abstract: A steel for use as a broachable workpiece having a substantially pearlite-free microstructure whereby the service life of the broach tool is maximized. Formation of pearlite is suppressed by alloy modification; on-line processing; off-line processing; or combinations of these techniques which control the microstructure and hardness levels. The workpiece is broached into the form of a powertrain component such as, for example, a gear or race which can be surface hardened after broaching by one of carburizing, nitriding, or induction hardening depending upon the carbon content of the steel. Disclosed are steel compositions and processing methods for making the steel, the broachable workpiece and the broached and surface hardened powertrain article.

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OPTIMIZATION OF STEEL METALLURGY TO IMPROVE BROACH TOOL LIFE

CROSS-REFERENCE TO RELATED APPLICATION

This application claims the benefit of United States Provisional Application No. 60/606,816 filed September 2, 2004, entitled "Optimization of Steel Metallurgy to Improve Broach Tool Life", which is incorporated herein by reference in its entirety.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH

A portion of the work pertaining to this subject matter was partially funded by U.S. Department of Energy, under Contract No. DE-FC36-991D13819.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates generally to ferrous metallurgy and, more particularly, to steel compositions and microstructures used for making articles such as, for example, powertrain gears, races and like parts that are formed by broaching and hardened by carburizing or induction hardening. Still more particularly, the invention is directed to techniques for obtaining an optimized steel metallurgy microstructure which provides a steel workpiece material that significantly improves broach tool life, thus lowering the manufacturing costs per part. The present invention also relates to methods for obtaining the desired microstructures and properties in the steel workpiece as well as to the finished article.

2. Description of Related Art

Broaching is a machining technique commonly used to cut gear teeth or cam profiles for the high volume manufacture of powertrain parts, such as for automotive transmissions and the like. The part profiles can be formed in a single broaching operation with minimal overall time, making it ideal for such a cost-sensitive application. However, in order to accomplish the broaching operation in a single station, the broach machine must perform the entire roughing, shaping and finishing of the desired part profile using one long, high-speed steel broach tool which removes metal from a workpiece in a single motion. The broach tool is relatively expensive to manufacture and can only be redressed or sharpened a fixed number of times before the tool is no longer usable. The expense of the original broach tool and the redressing costs are a significant portion of the overall manufacturing cost of the finished part. The precise broaching and tooling cost per manufactured part is highly dependent upon the number of parts that can be manufactured between broach tool redressings. With tooling costs over the life of a helical broach bar on the order of $50,000 to $80,000, and total parts manufactured on a single broach bar currently in the range of 10,000 to 80,000 parts, the cost per part is typically in the range of $0.60 to $5.00. Hence, the broach tooling cost represents around 15% to 50% of the total manufacturing cost for a finished part. Therefore, whereas broaching represents a time and plant space efficient method to cut profiles into annular steel parts, the tooling cost to perform this operation represents a significant portion of the total manufacturing cost.

Previous attempts to improve the broach tool life by workpiece material modifications have included alternate material selection, varying traditional heat treat routes or the addition of alloy constituents to enhance machinability, such as, for example, sulfur and calcium. Producing optimized broaching performance has been inhibited in that prior material and heat treatment selection attempts have been made without full knowledge of the factors affecting broach tool life. In addition, only limited amounts of specific inclusion additions are permitted within these conventionally used workpiece steel grades. These prior attempts have provided only incremental improvements in tool life, ranging from 25% to 100% improvement, but they fall well short of the levels of improvement provided by the present invention due to the fact that they have not produced the optimal broaching microstructure and hardness combination. The prior approaches also include lowering of the alloy content to lower the hardness level and abrasiveness of the workpiece steel; increasing tempering temperature to lower the hardness level; and lowering carbon level or changing heat treat method to allow for the use of lower carbon, less abrasive steels. These approaches all produce only the incremental improvements noted above.

Workpiece steels used to manufacture profiled parts for powertrain gears and races can be broadly categorized as either carburizing/nitriding or induction hardening types, depending upon the method used to harden the load bearing surfaces of the finished part. Steels have historically been chosen broadly based upon the hardening method and subsequent carbon level, and heat treat hardenability requirements for the hardened surface in an effort to minimize cost to manufacture the part. The conventional workpiece steels so selected have been processed and/or heat treated to develop a ferrite/pearlite type microstructure, typically to a narrower aim/range within the overall broachable hardness range of 150 to 300 BHN. The resultant workpiece steel selection, processing and heat treatment to achieve the above microstructure and hardness has heretofore resulted in lower than optimal broach tool life, but has been considered acceptable based on historical data. The historical data has not often been questioned or improved upon in a systematic manner due to the exorbitantly high costs of testing potential new grades of workpiece steel on production equipment.

In powertrain components, such as gears, it is desirable to surface harden the broached gear teeth for wear resistance while maintaining lower hardness levels in the core of the gear for toughness. As alluded to above, the main techniques for obtaining localized surface hardening are carburizing, nitriding and induction hardening, depending upon the type of steel used to make the part. Generally, steel grades having less than about 0.32 wt.% C possess insufficient carbon at the surface to provide thermal hardening. Accordingly, this steel type is usually carburized (or nitrided) to diffuse a carbon-enriched layer (or nitrogen) in the load bearing surface of the part to permit subsequent thermal/heat treat hardening. On the other hand, steels having greater than 0.32 wt.% C, such as grades having about 0.35 to 0.80 wt.% C, may be surface hardened using the induction heating technique. The high frequency magnetic field of the inductor heats the surface layer of the broached part in a matter of mere seconds to a desired austenitizing temperature of, say, 1700-1800°F and the heated surface is then immediately quenched in water or other quench media. Since carburizing (and nitriding) usually is conducted in a controlled atmosphere furnace for 5-10 hours, carburizing and nitriding are considerably more time-consuming and expensive than the induction hardening technique. Heretofore, the higher carbon type of workpiece steel which is suitable for induction hardening yielded a shorter broach tool life than the lower carbon carburizing type, following the trend that broach tool life decreases with increasing carbon content of the workpiece steel. Thus, the economic benefit enjoyed by fast induction hardening has heretofore been offset by the increased broach tool cost per part.

Applicants are aware of prior work conducted in the industry to provide a broachable steel within the desirable broaching hardness range of about 150 to 240 BHN. This steel possesses a non-pearlitic microstructure obtained by off-line thermal processing performed as a means of optimizing the surface hardening response and not as a means of optimizing broach tool life. This steel, however, has a carbon range of between 0.25 to 0.31 wt.% and is subjected to nitriding heat treatment after broaching to achieve surface hardening for transmission gears.

Applicants are further aware of prior work involving broached powertrain parts that require a high core hardness prior to broaching to develop the desired mechanical properties for the part. The hardness range for these parts is typically from 250 to 300 BHN or higher. Most steels cannot achieve this hardness range while maintaining a pearlitic microstructure. As a result, the most common method to increase hardness to a level within this range is to perform an off-line heat treatment (quench and temper) to develop a non-pearlitic bainite/martensite tempered structure. The reason for obtaining this non-pearlitic structure is to develop the core hardness range and not to optimize broaching. Indeed, at these high hardness levels of 250 to 300 BHN or higher, broach tool life is sacrificed for high hardness.

SUMMARY OF THE INVENTION

The present invention solves the problems of the prior art by providing optimized steel microstructures in a workpiece for the manufacture of articles by broaching, which yield greatly improved broach tool life. The articles are useful as automotive, truck, tractor and like powertrain parts such as, for example, transmission gears and races. Still further, the present invention provides a steel for a workpiece that includes carburizing, nitriding and induction hardening types which significantly increases broach tool life for these steel types.

Briefly stated, the present invention contemplates an optimized steel metallurgy for the workpiece to be broached, wherein the microstructure substantially eliminates the presence of pearlite in favor of bainite, martensite and/or ferrite. The present invention provides this optimal steel metallurgy in a workpiece for broaching by at least one or more of the following processing techniques: (a) modification of the steel alloy composition to suppress pearlite formation; (b) on-line thermal processing to suppress pearlite formation; (c) off-line heat treatment to suppress the formation of the pearlite phase; and/or (d) combinations of one or more of the above techniques or use of other techniques to achieve the desired microstructure comprising bainite and/or tempered martensite with substantially no pearlite phase. A further aspect of the invention provides a steel workpiece suitable for surface hardening subsequent to broaching by one of carburizing, nitriding or induction hardening wherein the steel microstructure is substantially free of pearlite by modification of the steel alloy composition coupled with one or both of on-line or off-line thermal processing. A preferred hardness range for the workpiece material is between about 160 to 250 BHN and, more preferably, between about 170 to 245 BHN and, still more preferably, between about 180 to 240 BHN. The workpiece steel has a carbon content of between about 0.15-0.80 wt.% and, more preferably, between about 0.18-0.70 wt.% C, which, thus, includes carburizing, nitriding and induction hardening types of steel. One aspect of the invention contemplates a carbon content of about 0.15-0.35 wt.% and preferably between about 0.20-0.32 wt.% C to permit the broached workpiece to be carburized. A still further aspect of the invention includes a workpiece steel for broaching having about 0.32-0.80 wt.% C, more preferably between about 0.33-0.70 wt.% C, and still more preferably between about 0.35-0.65 wt.% C to permit the broached workpiece to be induction hardened. The invention includes the steel material for making the workpiece to be broached, the steel workpiece to be broached, the finished article made from the steel workpiece, as well as the process for making same.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a graph of broach tool life versus carbon content for baseline and optimized steel workpiece materials of the present invention;

Fig. 2 is a graph of broach tool life versus hardness for the steel workpieces tested in Fig. 1;

Fig. 3 is a graph of broach tool life versus carbon content for modified alloys composed primarily of fine bainite and baseline alloy workpieces having a ferrite/pearlite microstructure;

Fig. 4 is a graph of broach tool life versus carbon content for on-line thermally treated workpieces composed of tempered bainite and baseline alloy workpieces having ferrite/pearlite microstructures;

Fig. 5 is a graph of broach life versus carbon content for off-line heat treated workpieces composed of microstructures of the present invention and baseline alloy workpieces having ferrite/pearlite microstructures;

Fig. 6 is a photomicrograph of a conventional steel, baseline grade 5130 as rolled (Sample No. 2) exhibiting a typical microstructure containing pearlite and ferrite;

Fig. 7 is a photomicrograph of a conventional steel, baseline grade 5150 normalized and tempered (Sample No. 10) exhibiting a typical microstructure containing pearlite and ferrite;

Fig. 8 is a photomicrograph of a steel in an as-rolled condition (Sample No. 20) treated according to the invention, alloy optimized, exhibiting an acicular bainite microstructure;

Fig. 9 is a photomicrograph of a steel in an interrupted and tempered condition (Sample No. 30) treated on-line according to the invention exhibiting a microstructure containing spheroidized bainite and ferrite; and

Fig. 10 is a photomicrograph of a steel in a quenched and tempered condition (Sample No. 33) treated on-line in accordance with the invention, exhibiting a microstructure containing spheroidized martensite.

DETAILED DESCRIPTION OF THE INVENTION

A laboratory broach testing machine was devised and built to enable economical and efficient testing and comparison of the effects of metallurgical variables on broach tool life. The laboratory test utilized a reciprocating 3-tooth, high-speed steel broach tool made from M4 tool steel. This broach tool rapidly and efficiently cut the equivalent steel volumes that a typical broach tool contained in a production broach bar would cut over many parts. The laboratory test machine and procedure were designed to closely mimic a production broaching environment in all possible aspects, including the broach tool material and its heat treatment, the tool tooth design, the cutting depth per tooth, the cutting speed, the cutting lubricant type and lubricant delivery system, as well as the tool wear criterion limits. The broach tool was repeatedly pulled through the inner diameter of a ring-shaped, annular test steel workpiece utilizing an indexing table to properly position the annular test workpiece for each cut, employing the specific parameters established for each of the listed variables. The broach tool was periodically measured for wear and the laboratory test was deemed to be complete when the previously established wear criterion was met, assigning a number of cuts to broach tool failure for each material workpiece condition.

This laboratory broach test was performed on a large variety of steel types and conditions, with each steel/condition rated against one another based upon the number of cuts to the specific wear criterion limit. The database generated from this extensive testing reported in Table I indicates that an optimal workpiece steel broaching condition or microstructure/hardness exists for all steels, and that most steels are currently not being broached in this condition. The test also revealed the non-optimal workpiece steel condition for broaching and, surprisingly, that most steels are currently being broached in that non-optimal condition or in a slightly modified version of that condition. In addition, the steel alloy compositions reported in Table II, steel processing and heat treatment schemes reported in Table II have also been developed in accordance with the present invention that allow for development of optimized workpiece steel conditions for broaching over a wide range of overall parameters.

TABLE I

HARDNESS AND BROACH TOOL LIFE DETAILS
OF THE WORKPIECE STEELS BROACH TESTED

Sample No.	Material Grade	Percent Carbon	Material Condition	Material Microstructure	Brinell Hardness	Broach Tool Life (Cuts to Limit)
Baseline Data - Prior Art Comparative						
1	5120	0.20	As Rolled	Ferrite/Pearlite	210	6200
2	5130	0.30	As Rolled	Pearlite/Ferrite	210	1300
3	5130	0.30	Normalized	Ferrite/Pearlite	176	4600
4	15V38R*	0.36	As Rolled	Pearlite/Ferrite	237	760
5	5135	0.36	Normalized	Pearlite/Ferrite	195	2400
6	5046	0.46	Normalized	Pearlite/Ferrite	207	600
7	5046	0.48	Normalize/Temper	Pearlite/Ferrite	195	1200
8	1045	0.48	Normalized	Pearlite/Ferrite	197	1180
9	15V48R*	0.48	Normalized	Pearlite/Ferrite	220	660
10	5150	0.52	Normalize/Temper	Pearlite/Ferrite	201	460
11	1552	0.53	Normalize/Temper	Pearlite/Ferrite	213	780
12	1552	0.53	Normalize/Temper	Pearlite/Ferrite	201	1400
13	10V55*	0.54	Normalized	Pearlite/Ferrite	238	600
14	5060	0.60	Normalized	Pearlite/Ferrite	235	200
15	5160	0.60	Normalized	Pearlite	252	80
Optimized Data - Invention						
Alloy Optimized						
20	4030	0.30	As Rolled	Bainite/Ferrite	223	8200
21	4040	0.41	Rolled/Tempered	Bainite/Ferrite	188	9500
22	4050	0.51	Rolled/Tempered	Bainite/Ferrite	208	3900
23	4060	0.62	Rolled/Tempered	Bainite/Ferrite	210	3900
On-Line Optimized						
30	5130	0.29	On-line/Temper	Bainite/Ferrite	210	9600
31	5130	0.29	On-line/Temper	Bainite/Ferrite	190	8800
32	5046	0.47	On-line/Temper	Bainite/Ferrite	217	7600
33	5150	0.52	On-line/Temper	Bainite/Ferrite	215	5200
Off-line Optimized						
40	8620	0.20	Normalized	Bainite/Ferrite	177	12000
41	4027	0.27	Normalized	Bainite/Ferrite	176	11000
42	5046	0.47	Quench & Temper	Temper Mart.	207	8700
43	4150	0.50	Normalize/Temper	Bainite/Ferrite	215	5800
44	1552	0.53	Quench/Temper	Temper Mart.	195	6200

* V represents vanadium modified, and R represents resulfurized

TABLE II

COMPOSITIONS OF THE WORKPIECE STEELS BROACH TESTED

Sample No.	Material Grade SAE Designation	C	Mn	S	Si	Cr	Ni	Mo	Al	V
Baseline Data - Prior Art Comparative										
1	5120	0.21	0.88	0.032	0.29	0.86	0.1	0.03	0.033	0.002
2	5130	0.31	0.92	0.03	0.22	0.8	0.08	0.02	0.023	0.004
3	5130	0.3	0.92	0.029	0.22	0.81	0.1	0.03	0.022	0.003
4	15V38R*	0.36	1.37	0.054	0.54	0.13	0.06	0.02	0.024	0.09
5	5135	0.31	0.96	0.028	0.23	0.78	0.11	0.03	0.022	0.002
6	5046	0.48	1.06	0.029	0.27	0.2	0.09	0.03	0.028	0.001
7	5046	0.48	1.06	0.029	0.27	0.2	0.09	0.03	0.028	0.001
8	1045	0.5	0.82	0.04	0.19	0.08	0.08	0.02	0.028	0.001
9	1548R*	0.48	1.4	0.062	0.25	0.12	0.08	0.02	0.002	0.002
10	5150	0.52	0.92	0.034	0.26	0.86	0.12	0.08	0.028	0.002
11	1552	0.53	1.43	0.028	0.27	0.14	0.13	0.035	0.023	0.002
12	1552	0.53	1.43	0.028	0.27	0.14	0.13	0.035	0.023	0.002
13	10V55*	0.53	0.9	0.032	0.25	0.16	0.08	0.02	0.032	0.12
14	5060	0.61	0.85	0.025	0.25	0.5	0.09	0.03	0.033	0.001
15	5160	0.61	0.81	0.012	0.26	0.8	0.1	0.03	0.03	0.002
Optimized Data - Invention										
	Alloy Optimized**									
20	4030	0.3	0.86	0.019	0.25	0.11	0.11	0.25	0.025	0.001
21	4040	0.41	0.91	0.022	0.25	0.11	0.11	0.25	0.026	0.001
22	4050	0.51	0.89	0.021	0.25	0.11	0.11	0.25	0.03	0.001
23	4060	0.62	0.89	0.022	0.25	0.11	0.11	0.26	0.029	0.001
	On-line Optimized									
30	5130	0.3	0.86	0.033	0.18	0.84	0.11	0.04	0.032	0.002
31	5130	0.3	0.86	0.033	0.18	0.84	0.11	0.04	0.032	0.002
32	5046	0.47	1.05	0.032	0.26	0.19	0.1	0.03	0.034	0.001
33	5150	0.52	0.92	0.034	0.26	0.86	0.12	0.08	0.028	0.002
	Off-line Optimized									
40	8620	0.21	0.87	0.018	0.28	0.57	0.64	0.21	0.03	0.001
41	4027	0.27	0.83	0.03	0.23	0.18	0.07	0.27	0.026	0.001
42	5046	0.47	1.05	0.032	0.26	0.19	0.1	0.03	0.034	0.001
43	4150	0.5	0.88	0.024	0.27	0.98	0.11	0.18	0.033	0.002
44	1552	0.51	1.5	0.031	0.23	0.14	0.12	0.03	0.029	0.001

* V represents vanadium modified, and R represents resulfurized.

** Alloy optimized grade designations created by the inventors.

TABLE III

PROCESSING DETAILS OF THE WORKPIECE STEELS BROACH TESTED

Sample No.	Material Grade SAE Designation	Material Condition	Steel Processing*
Baseline Data - Prior Art Comparative			
1	5120	As Rolled	Hot rolled, air cooled tubing
2	5130	As Rolled	Hot rolled, air cooled tubing
3	5130	Normalized	Normalized tubing
4	15V38R	As Rolled	Hot rolled, air cooled bar, bored ID
5	5135	Normalized	Normalized tubing
6	5046	Normalized	Normalized tubing
7	5046	Normalize/Temper	Normalized tubing, tempered at 1175°F, 2 hours
8	1045	Normalized	Normalized tubing
9	1548R	Normalized	Normalized tubing
10	5150	Normalize/Temper	Normalized tubing, tempered at 1330°F, 2 hours
11	1552	Normalize/Temper	Normalized tubing, tempered at 1275°F, 2 hours
12	1552	Normalize/Temper	Normalized tubing, tempered at 1275°F, 2 hours
13	10V55	Normalized	Normalized tubing
14	5060	Normalized	Normalized tubing
15	5160	Normalized	Normalized tubing
Optimized Data - Invention			
	Alloy Optimized		
20	4030	As Rolled	Hot rolled, air cooled
21	4040	Rolled/Tempered	Hot rolled, air cooled, tempered at 1300°F, 1 hour
22	4050	Rolled/Tempered	Hot rolled, air cooled, tempered at 1300°F, 1 hour
23	4060	Rolled/Tempered	Hot rolled, air cooled, tempered at 1340°F, 4 hrs
	On-line Optimized		
30	5130	On-line/Temper	Austenitized tubing, interrupt water quench, tempered at 1225°F, 2 hours
31	5130	On-line/Temper	Austenitized tubing, interrupt water quench, tempered at 1275°F, 2 hours
32	5046	On-line/Temper	Austenitized tubing, interrupt water quench, tempered at 1325°F, 2 hours
33	5150	On-line/Temper	Austenitized tubing, interrupt water quench, tempered at 1340°F, 4 hours
	Off-line Optimized		
40	8620	Normalized	Normalized tubing
41	4027	Normalized	Normalized tubing
42	5046	Quench/Temper	Austenitized Tubing, water quenched, tempered at 1325°F, 2 hours
43	4150	Normalize/Temper	Normalized tubing, tempered at 1340°F, 3 hours
44	1552	Quench/Temper	Austenitized tubing, water quenched, tempered at 1300°F, 4 hours

* Austenitizing performed at standard temperatures (based on carbon level) and times (based on section size), and air cooling for normalized entries. Hot rolling performed at standard temperatures, based on carbon level. Interrupt quench was sufficient to avoid pearlite formation, and varied in time based on grade and section size.

The steels tested included composition ranges as follows, in % by weight:

C - 0.18% to 0.62%
Mn - 0.55% to 1.60%
Si - 0.15% to 0.70%
S - 0.010% to 0.060%
Cr - 0.10% to 1.0%
Ni - 0.05% to 0.55%
Mo - 0.02% to 0.30%
V - 0.01% to 0.12%
Al - 0.002% to 0.035%
Fe - Balance, plus trace impurities or additions of ≤ 0.05 each.

The steel conditions tested included: as hot worked and air cooled; hot worked and slow cooled; fine and coarse grain normalized; fine and coarse grain normalized and tempered; quenched and tempered; interrupted quench and tempered; and annealed. Typical parameters for these conditions are as follows.

The steel samples (Nos. 1-15, 30-33 and 40-44) reported in Tables I-III were melted in a production electric furnace operation and ladle refined in accordance with the compositions set forth in Table II. The steel samples were continuously cast into blooms and then heated to 2250°F, hot rolled into round billets, subsequently reheated to 2250°F and pierced to provide an as-rolled tubular shape. The tube was then cut to form a ring-shaped, annular steel workpiece for testing or for further thermal treatment in accordance with Table III prior to test broaching. The resultant microstructures for the various steel samples, as reported in Table I, included a mixture of ferrite, pearlite, bainite and/or martensite in both tempered and non-tempered versions with varying degrees of carbide spheroidization. The hardness levels of the various steels tested ranged from 150 BHN to 330 BHN, with most of the hardness levels being in the broachable range from 160 BHN to 260 BHN. As shown in Table I, a presently preferred broachable hardness range is from about 150 to 250 BHN and, more preferably, between 175 to 240 BHN. The analysis of the wide range of steel compositions, shown in Table II, processing schemes (Table III), microstructure and hardness levels (Table I) has enabled the identification of the critical metallurgical variables to optimize broach tool life according to the present invention.

Historical broaching knowledge and expertise has heretofore indicated that higher carbon contents and hardness levels negatively impact broach tool life with traditional processing methods. Those results are supported in the broach test data generated (Table I), where the broaching results for numerous conventional "baseline" workpiece steel grades, Sample Nos. 1 to 15, are shown as a function of carbon level ranging from 0.20 wt.% to 0.60 wt.% (Fig. 1) and hardness level (Fig. 2).

More specifically, it will be seen in Fig. 1 and in Table I that a baseline workpiece steel (Sample No. 1) having a carbon content of 0.20 wt.% and a Brinell hardness of 210 BHN yielded a broach tool life of 6,200 (cuts to limit). As the baseline steel carbon content increased to 0.6 wt.% (Sample No. 15), the Brinell hardness rose to 252 BHN and the broach tool life decreased to 80 (cuts to limit). The microstructure of these conventional baseline workpiece steel grades was predominantly ferrite and pearlite, as shown in Fig. 6 and in Fig. 7. In the photomicrographs of Figs. 6 and 7, the ferrite appears as the light regions and the pearlite appears as the darker regions. Fig. 6 shows a baseline 5130 grade steel (Sample No. 2) microstructure containing ferrite and pearlite in the as rolled condition and Fig. 7 depicts a baseline 5150 grade (Sample No. 10) microstructure containing ferrite and pearlite in the normalized and tempered condition. These ferrite and pearlite microstructures are typically specified as an acceptable broaching microstructure for most conventional broaching applications.

In contrast, the present invention encompasses the discovery that at the same carbon and hardness levels as shown in the baseline steels in Table I, broach tool life can be increased by 2 to 10 times by altering some stage of the metallurgical processing to suppress or minimize formation of the pearlitic microstructure and, in its place, forming a finer acicular carbide microstructure which preferably may tend towards spheroidization. The preferred microstructure of the invention is substantially pearlite-free and consists of either predominantly bainite and/or martensite and ferrite, and may be tempered into a desired hardness range of 160 to 260 BHN at higher carbon levels. Some pearlite phase may be present, up to a maximum of about 20% lamellar pearlite by volume, and preferably no more than 10% lamellar pearlite by volume maximum, and still more preferably no more than 5% lamellar pearlite by volume. Ideally, substantially no lamellar pearlite is present in the microstructure. As used herein, the phrase "substantially pearlite-free" or "minimal pearlite" means a microstructure containing up to about 20% by volume lamellar pearlite and, more preferably, 0%, unless otherwise qualified.

A desired acicular bainite microstructure is shown in Fig. 8; a desired spheroidized bainite microstructure is shown in Fig. 9; and a desired spheroidized martensite and ferrite microstructure is shown in Fig. 10. Fig. 8 is an alloy modified 4030 grade (Sample No. 20) in the as rolled condition; Fig. 9 is an on-line quenched and tempered 5130 grade (Sample No. 30); and Fig. 10 is an on-line quenched and tempered grade 5150 steel (Sample No. 33), all produced according to the present invention.

The substantially pearlite-free microstructures of the invention containing one or more of bainite, martensite, and ferrite with zero or minimal pearlite are formed by a variety of techniques including, but not necessarily limited to, (1) modification of the alloy makeup to suppress pearlite formation in the hot worked, air-cooled condition (Sample Nos. 20-23); and/or (2) on-line hot processing to suppress the pearlite formation on cooling from hot working temperatures (Sample Nos. 30-33); and/or (3) off-line heat treatment to suppress the pearlite formation (Sample Nos. 40-44); or by some combination of these techniques, or by other techniques such as by isothermal transformation below pearlite formation temperatures. The final bainite/martensite/ferrite, substantially pearlite-free microstructure can, of course, then be tempered into the desired broaching hardness range, if desired.

The resultant effect of this microstructure modification can be observed by comparing the previously mentioned broach tool life trends for various carbon and hardness levels having a predominantly pearlitic microstructure with the optimized broach tool life results for similar steels substantially pearlite-free within the same carbon levels (Fig. 1) and hardness ranges (Fig. 2). As can be readily noted, the improvement in broach tool life is on the order of 200% to 1000%, comparing the same or similar initial carbon contents and broach tool life, all within similar hardness ranges. For example, the broach tool life of prior art baseline 5120 grade workpiece steel (Sample No. 1) having 0.20% C with a ferrite/pearlite microstructure yielded a broach tool life of 6200 (cuts to limit). This may be compared with off-line normalized 8620 grade (Sample No. 40), also having a 0.20% C content, but with a bainite/ferrite microstructure of the invention which provided a broach tool life of 12,000 (cuts to limit), providing nearly double the broach tool life of the conventional workpiece steel. Similar improvements in broach tool life realized with increasing carbon contents are seen graphically in Figure 1. This significant level of broach tool life improvement directly translates into a large reduction in broach tooling cost per part. More specifically, the present invention provides a 40% to 80% reduction in tooling cost per part, and, thus, allows the part manufacturer to realize a significant overall reduction in the part manufacturing cost. As alluded to above, this cost savings is of utmost importance in the production of high volume precision automotive parts.

Obtaining the optimal steel workpiece condition for broaching can be realized in accordance with the invention by any individual or combination of the three aforementioned techniques including, but not necessarily limited to: (1) modification of the alloy makeup to suppress or minimize pearlite formation in the hot worked, air cooled condition; (2) designing the on-line hot processing to suppress the pearlite formation on cooling from the hot working temperature; and/or (3) off-line heat treatment to suppress the pearlite formation, followed by a temper operation, when necessary.

Other techniques for the suppression of the unwanted formation of a pearlite microstructure may occur to persons of skill in the art and those techniques will fall within the spirit and scope of the present invention. Examples of the presently preferred inventive techniques are discussed hereinafter.

1. Alloy Modification

Alloy compositions can be designed to suppress pearlite formation by the addition of several potential chemical elements and addition levels, individually or in combinations, depending upon the base steel composition. An example of the alloy modification approach was demonstrated by melting a series of laboratory vacuum induction melted heats at four carbon levels (0.3%C, 0.41%C, 0.51%C and 0.62%C), where approximately 0.25% Mo was added to a base carbon and manganese composition to suppress the pearlite formation. It will be understood, unless noted otherwise, that all percentages are in % by weight. More specifically, the alloy compositions for these sample Nos. 20-23, designated grades 4030, 4040, 4050 and 4060, respectively, had the compositions shown in Table II with carbon levels ranging from 0.30 to 0.62 wt.%. As seen in Table III, the ingots were hot rolled and air-cooled, fashioned into test rings and tempered as necessary to achieve a desired broaching hardness range of between about 180 - 240 BHN (Table I). The microstructure of these steels was primarily composed of a fine bainite/ferrite. The microstructure tended to spheroidization, if the steel had been tempered as in Sample Nos. 21-23. An example of a spheroidized bainite microstructure is shown in Fig. 9.

Fig. 3 graphically depicts the broach test results for the alloy modified inventive steels (Sample Nos. 20-23) in comparison to a conventional baseline set of ferrite/pearlite containing steels (Samples 3, 5, 7, 11 and 14) covering a similar carbon range of 0.3 to 0.60% C. The baseline steels exhibit a steady decrease in broach tool life with increasing carbon level from 4600 cuts to limit at 0.30% C (Sample No. 3), down to only approximately 200 cuts to limit at 0.60% C (Sample No. 14). However, the alloy modified steels of the invention show 9500 cuts to limit at 0.41% C (Sample No. 21), and then nearly 4000 cuts to limit at 0.62% C (Sample No. 23). The modified steel composition of the present invention shows well in excess of an order of magnitude improvement in broach tool life over the conventional baseline steel at comparable carbon levels. Therefore, an alloying modification approach of the invention to optimize the microstructure and broach tool life of grades with varying carbon levels has been demonstrated to be successful and effective, as evidenced by the test data.

Presently preferred modified steel compositions of the present invention which suppress or minimize the formation of a microstructure containing pearlite in the hot rolled, air cooled condition (with optional tempering) are listed below in Table IV in % by weight.

TABLE IV

Element (wt.%)	Broad Range	Mid-Range	Narrow Range	Nominal
C	0.2 – 0.80	0.25 – 0.65	0.35 – 0.6	0.3 – 0.6
Mn	0.5 – 1.75	0.7 – 1.5	0.80 – 1.30	1.0
S	0.010 – 0.10	0.015 – 0.07	0.018 – 0.030	0.025
Si	0.10 – 0.70	0.15 – 0.35	0.20 – 0.30	0.25
Cr	0.01 – 0.50	0.03 – 0.35	0.05 – 0.25	0.1
Ni	0.01 – 1.0	0.03 – 0.25	0.05 – 0.20	0.1
Mo	0.10 – 0.50	0.15 – 0.40	0.20 – 0.30	0.25
Al	0.001 – 0.07	0.01 – 0.05	0.015 – 0.04	0.03
V	0.001 – 0.20	0.01 – 0.10	0.01 – 0.03	0.001
B	0.005 – 0.03	0.007 – 0.025	0.010 – 0.02	0.015
Fe	Balance*	Balance*	Balance*	Balance*

* Balance iron plus incidental additions and impurities less than 0.05% each.

More specifically, presently preferred alloy modified compositions for achieving the desired properties of the invention are also set forth in Table II, for Sample Nos. 20-23, appearing under the heading "Alloy Optimized".

2. On-Line Processing

The second technique for improving broach tool life according to the invention involves on-line processing to achieve the desired microstructure. On-line thermal treatment involves hot working and cooling, using thermomechanical processing schemes that can be devised whereby the unwanted pearlite phase is suppressed upon cooling from hot working, such as hot rolling, without having to modify the steel composition at all or to a lesser extent. The term "on-line" optimization or processing as used herein means a thermomechanical steel process scheme directly coupled with the final hot working operation (rolling, forging, etc.) whereby the pearlite phase is avoided or minimized and the bainite/martensite/ferrite phases are promoted.

An example of this on-line technique was demonstrated by austenitizing at 1600°F grades 5130 and 5046 steel tubing, Sample Nos. 30 and 32, respectively, to varying austenite grain structures (simulating the final as hot worked microstructure range), followed by performing an interrupted quench in water to avoid pearlite formation and then tempering at 1225°F for 2 hours (Sample No. 30) and tempering at 1325°F for 2 hours (Sample No. 32) to bring the steel into the desired hardness range (about 180 - 240 BHN). The microstructures and hardness levels of both grades were composed of a tempered bainite tending to spheroidize, with hardnesses in the range of 200 to 235 BHN. Fig. 4 shows the results of the broach testing performed on the on-line processed grades of the invention in comparison to the various conventional baseline ferrite/pearlite grades tested and shown previously in Fig. 3 (Sample Nos. 3, 5, 7, 11 and 14). The broach tool life test results for the on-line optimized grades 5130 and 5046 (Sample Nos. 30 and 32) were two to six times greater than the baseline level reported, which illustrates the success of this approach to optimize broach tool life for both the carburizing and induction hardening grades of steels. It will be noted that grade 5130 (Sample No. 30) contained 0.29 wt.% C and is a carburizing type of steel, while grade 5046 (Sample No. 32) contained 0.47 wt.% C and is an induction hardening type of steel.

By way of direct comparison of nearly identical compositions regarding the baseline grades 5130 (Sample Nos. 2 and 3) and grade 5046 (Sample Nos. 6 and 7) with on-line optimized grades 5130 (Sample Nos. 30 and 31) and grade 5046 (Sample No. 32), attention is directed to Tables I, II and III. The on-line optimized Sample No. 30 grade 5130 (0.29 wt.% C) steel had a broach tool life of 9600 cuts to limit and Sample No. 31 had a broach tool life of 8800 cuts to limit compared to the baseline grade 5130 with a life of only 1300 cuts to limit (Sample No. 2 as rolled) and 4600 cuts to limit (Sample No. 3, normalized), both containing 0.30 wt.% C. Higher carbon level conventional grade 5046 (Sample No. 6) containing 0.46 wt.% C in the normalized condition had a broach tool life of 600 cuts to limit compared with on-line optimized grade 5046 (Sample No. 32) also containing 0.46 wt.% C, on-line processed and tempered, had a broach tool life of 7600 cuts to limit, which represents more than a twelvefold increase in broach tool life.

3. Off-Line Processing

A further inventive technique for obtaining a desired microstructure in a broachable workpiece involves off-line processing. The term "off-line" processing or optimization as used herein means a thermal processing method performed at some time subsequent to hot working whereby the pearlite phase is substantially avoided and the bainite/martensite/ferrite phases are promoted. The off-line optimization scheme can be performed on a wide variety of steel types and section sizes to totally suppress or otherwise minimize pearlite formation. Such thermal treatments are most often followed by tempering into the appropriate broaching hardness range, which typically is 180 to 240 BHN. Off-line heat treatments according to the invention usually involve the following steps: austenitizing the steel test section at 1500°F to 1750°F; fully or interrupted quenching of the steel section in the appropriate quench media, such as water, to avoid pearlite formation based on classical steel hardenability calculations. Quenching is normally followed by tempering at 1100° to 1350°F for 1 to 4 hours (depending on steel type and temperature) to form the desired microstructure (substantially free of pearlite phase) and to provide a desired hardness for broaching between about 180 - 240 BHN.

Table I shows that off-line optimized Sample Nos. 40 (grade 8620) containing 0.20 wt.% C and 41 (grade 4027) containing 0.27 wt.% C were in the normalized condition and provided the highest broach tool life of any of the samples tested, *viz.*, 12,000 cuts to limit and 11,000 cuts to limit, respectively. Normalizing involves heating the steel to a temperature above the transformation range and then cooling in still air at room temperature. The resultant microstructure for Sample Nos. 40 and 41 was a bainite/ferrite with no pearlite in the microstructure.

Sample No. 43 (grade 4150) containing higher carbon at 0.50 wt.% C was also subjected to a normalizing treatment and subsequently tempered at 1340°F for 3 hours and, likewise, exhibited a bainite/ferrite microstructure, free of pearlite. The workpiece from Sample No. 43 yielded a broach tool life of 5,800 cuts to limit in the broaching test, compared to 460 cuts to limit for Sample No. 10 (conventional grade 5150 steel) of comparable carbon content and hardness (Table I) to Sample No. 43.

Off-line optimized Sample No. 42 (grade 5046) containing 0.47 wt.% C and Sample No. 44 (grade 1552) containing 0.53 wt.% C were austenitized, water quenched, and then tempered at 1325°F for 2 hours for Sample 42 and tempered at 1300°F for 4 hours for Sample No. 44. The quenching and tempering produced a tempered martensitic microstructure free from pearlite according to the present invention. Broach tool life was 8,700 cuts to limit for Sample No. 42 and 6,200 cuts to limit for Sample No. 44, which is a significant improvement in these high carbon, induction hardening steel types.

Fig. 5 shows the broach tool life for each of these steels versus the baseline ferrite/pearlite grades, which illustrates the same trends with carbon level and similar or greater levels of improvement over the baseline grades, as compared to the other techniques. Accordingly, it will be understood that the off-line processing optimization approach represents another technique to optimize broach tool life according to the present invention.

4. Combinations of the Optimization Techniques

Two or more of the above-discussed optimization techniques 1-3 can be combined to provide the microstructure and properties desired in a broachable workpiece according to the present invention.

For example, Sample Nos. 40 and 41 were off-line treated grades 8620 and 4027, discussed above, and were also subjected to alloy optimization with Mo additions: 0.21 wt.% Mo (Sample No. 40) and 0.27 wt.% Mo (Sample No. 41), see Table II. These off-line normalized alloy modified steels provided the highest broach tool life of all samples tested, thus evidencing the effectiveness of the combined alloy and heat treatment optimization techniques of the invention.

Surface Hardening

As discussed hereinabove, it is beneficial in powertrain components to provide a hardened outer surface for improved wear resistance of the broached gear teeth and a lowered hardness core to provide internal toughness to the part. Known techniques for surface hardening of broached powertrain components include carburizing, nitriding and induction hardening, and the particular technique employed is dependent upon the carbon content of the steel. Generally, steels containing less than about 0.32 wt.% C have insufficient carbon levels for thermally induced surface hardening as provided by induction hardening. Thus, these steels require additional carbon or other constituent to permit surface hardening. Steels having carbon contents less than about 0.32 wt.% are generally carburized or nitrided to obtain enhanced surface hardening.

The above-discussed test results clearly demonstrate that the present invention provides a marked improvement in broach tool life for broaching a variety of workpiece steels, and some aspects of alloy modifications and material process schemes by which these improvements are realized have been described herein. The target broaching workpiece microstructure has been shown to be a non-pearlitic, fine carbide bainite/martensite microstructure ideally tending towards spheroidization. Alloy and process schemes to develop the target microstructure/hardness combinations in the workpiece steels have been shown and described in connection with the above sample steels. The data indicate that the present invention is applicable over a wide range of steel compositions and processing alternatives, given that the final target metallurgical characteristics are achieved. It will occur to those skilled in the art that there may be alternate alloying modifications and/or steel processing schemes in addition to the specific examples set forth above that can be used to obtain the target non-pearlitic, fine carbide microstructure, preferably tending towards spheroidization. It is, of course, understood that those alternate and/or additional methods would also be expected to achieve the beneficial broach tool life results set forth herein, and that such additional modifications are deemed to fall within the spirit and scope of the present invention.

WHAT IS CLAIMED IS:

1. A steel suitable for making a broachable workpiece, said steel having a substantially pearlite-free microstructure and a hardness of between 150 to 250 BHN prior to broaching and subsequent surface hardening by one of carburizing or induction hardening.

2. The steel of claim 1 wherein the microstructure comprises one or more of bainite, martensite and ferrite phases and a hardness of between 160 to 240 BHN.

3. The steel of claim 1 wherein said steel has a carbon content between 0.15-0.35 wt.% and is suitable for carburizing after broaching.

4. The steel of claim 1 wherein said steel has a carbon content between 0.32-0.80 wt.% and is suitable for induction hardening after broaching.

5. A steel workpiece for broaching, said steel workpiece having a substantially pearlite-free microstructure and a hardness of between 150 to 250 BHN, wherein said workpiece is suitable for surface hardening subsequent to broaching by one of carburizing or induction hardening.

6. The steel workpiece of claim 5 wherein the microstructure comprises one or more of bainite, martensite and ferrite phases and a hardness of between about 160 to 240 BHN.

7. The steel workpiece of claim 5 wherein said steel is one of a carburizing type having a carbon content of between 0.15-0.35 wt.%.

8. The steel workpiece of claim 5 wherein said steel is an induction hardening type having a carbon content of between about 0.35 to 0.80 wt.%.

9. A broached steel article suitable for use as a powertrain component, said article having a substantially pearlite-free microstructure and a

broached surface profile wherein said surface profile has a hardened surface applied by one of carburizing or induction hardening.

10. The article of claim 9 in the form of one of a gear or race.

11. The article of claim 9 wherein the microstructure comprises one or more of bainite, martensite and ferrite phases.

12. The article of claim 11 in the form of one of a gear or race.

13. The article of claim 9 wherein said steel has a carbon content of between 0.20-0.32 wt.% and is surface hardened by carburizing.

14. The article of claim 13 in the form of one of a gear or race.

15. The article of claim 9 wherein said steel has a carbon content of between about 0.33 to 0.70 wt.% and is surface hardened by induction hardening.

16. The article of claim 15 in the form of one of a gear or race.

17. A steel composition suitable for broaching comprising, in % by weight: 0.15 - 0.65% C; 0.5-1.75% Mn; 0.010 - 0.10% S; 0.10 - 0.70% Si; 0.1 - 0.50% Cr; 0.01 - 1.0% Ni; 0.10 - 0.50% Mo; 0.001 - 0.07% Al; 0.001 - 0.20% V; 0.005-0.03% B; and balance Fe plus incidental additions and impurities, less than 0.05% each..

18. The steel of claim 17 comprising 0.20 - 0.65% C; 0.7 - 1.5% Mn; 0.015 - 0.07% S; 0.15 - 0.35% Si; 0.03 - 0.35% Cr; 0.03 - 0.25% Ni; 0.15 - 0.40% Mo; 0.01 - 0.05% Al; 0.01 - 0.10% V; and 0.007 - 0.025% B.

19. The steel of claim 17 comprising 0.3 - 0.6% C; 0.80 - 1.30% Mn; 0.018 - 0.030% S; 0.20 - 0.30% Si; 0.05 - 0.25% Cr; 0.05 - 0.20% Ni; 0.20 - 0.30% Mo; 0.015 - 0.04% Al; 0.01 - 0.03% V; and 0.010 - 0.02% B.

20. The steel of claim 17 comprising 0.3 - 0.6% C and nominally: 1.0% Mn; 0.025% S; 0.25% Si; 0.1% Cr; 0.1% Ni; 0.25% Mo; 0.03% Al; 0.001% V; and 0.015 B.

21. The steel of claim 17 in one of a hot worked or normalized condition containing bainite, martensite and/or ferrite and having a substantially pearlite-free microstructure and suitable for surface hardening by one of carburizing or induction hardening.

22. A method for making a workpiece material to be subjected to broaching and subsequent surface hardening by one of carburizing or induction hardening, comprising the steps of:

(a) providing a steel; and

(b) subjecting the steel to one or more treatments comprising: alloy modification, on-line thermal treatment, and off-line thermal treatment to thereby provide a steel having a substantially pearlite-free microstructure and a hardness between 150 to 250 BHN prior to broaching.

23. The method of claim 22 wherein the alloy modification treatment comprises adding one or more alloying elements to the steel for suppressing the formation of pearlite in the steel.

24. The method of claim 23 wherein Mo is added to the steel in the amount of 0.15 to 0.40 wt.% to suppress the formation of pearlite.

25. The method of claim 22 wherein the on-line thermal treatment includes the steps of austenitizing and interrupt quenching to produce a microstructure containing bainite martensite and/or ferrite.

26. The method of claim 25 including the step of tempering after the quenching step.

27. The method of claim 26 wherein the tempering step is conducted at a temperature of 1100°F to 1340°F for 1 to 4 hours.

28. The method of claim 22 wherein the off-line thermal treatment includes one of normalizing, normalizing and tempering, and austenitizing, quenching and tempering.

29. The method of claim 28 wherein the steel is one of normalized or normalized and tempered to produce a microstructure containing bainite and ferrite.

30. The method of claim 28 wherein the steel is austenitized, quenched and tempered to produce a microstructure containing tempered martensite.

31. The method of claim 28 wherein the tempering in the off-line thermal treatment is conducted at 1200° to 1340°F for 1 to 4 hours.

32. The method of claim 22 including the step of forming the steel into a hot rolled tubular shape to provide a workpiece for broaching powertrain gears and races.

33. The method of claim 22 wherein said steel is subjected to at least two of said treatments.

34. A method for making a powertrain component comprising the steps of:

(a) providing a molten steel having a carbon content between about 0.15 to 0.80 wt.% C and optionally subjecting the molten steel to an alloy modification treatment to suppress the formation of a pearlite phase;

(b) subjecting the steel to one or more treatments including on-line thermal treatment and off-line thermal treatment to suppress the formation of the pearlite phase;

(c) providing a steel workpiece for broaching having a substantially pearlite-free microstructure and a hardness between 150 to 250 BHN;

(d) broaching the steel workpiece to form a broached powertrain component; and

(e) surface hardening the broached powertrain component by selecting one of carburizing or induction hardening.

35. The method of claim 34 wherein the steel contains between 0.2 to about 0.32 wt.% C and the surface hardening step selected is carburizing.

36. The method of claim 35 wherein the steel contains greater than 0.32 wt.% C up to 0.65 wt.% C and the surface hardening step selected is induction hardening.

37. The method of claim 34 wherein the optional alloy modification treatment in step (a) comprises adding 0.10 to 0.50 wt.% Mo to the molten steel.

38. A method for making a powertrain component comprising the steps of:

(a) providing a molten steel having a carbon content between about 0.15 to 0.80 wt.% C;

(b) subjecting the molten steel to an alloy modification treatment to suppress the formation of a pearlite phase;

(c) subjecting the steel to one or more of on-line thermal treatment and off-line thermal treatment to suppress the formation of a pearlite phase and provide a workpiece for broaching having a substantially pearlite-free microstructure;

(d) broaching the workpiece to form a broached powertrain component; and

(e) surface hardening the broached powertrain component by one of carburizing, nitriding or induction hardening.

39. The method of claim 38 wherein the steel contains between 0.2 to about 0.32 wt.% C and the surface hardening step is one of carburizing or nitriding.

40. The method of claim 38 wherein the steel contains between 0.35 to 0.65 wt.% C and the surface hardening step selected is induction hardening.

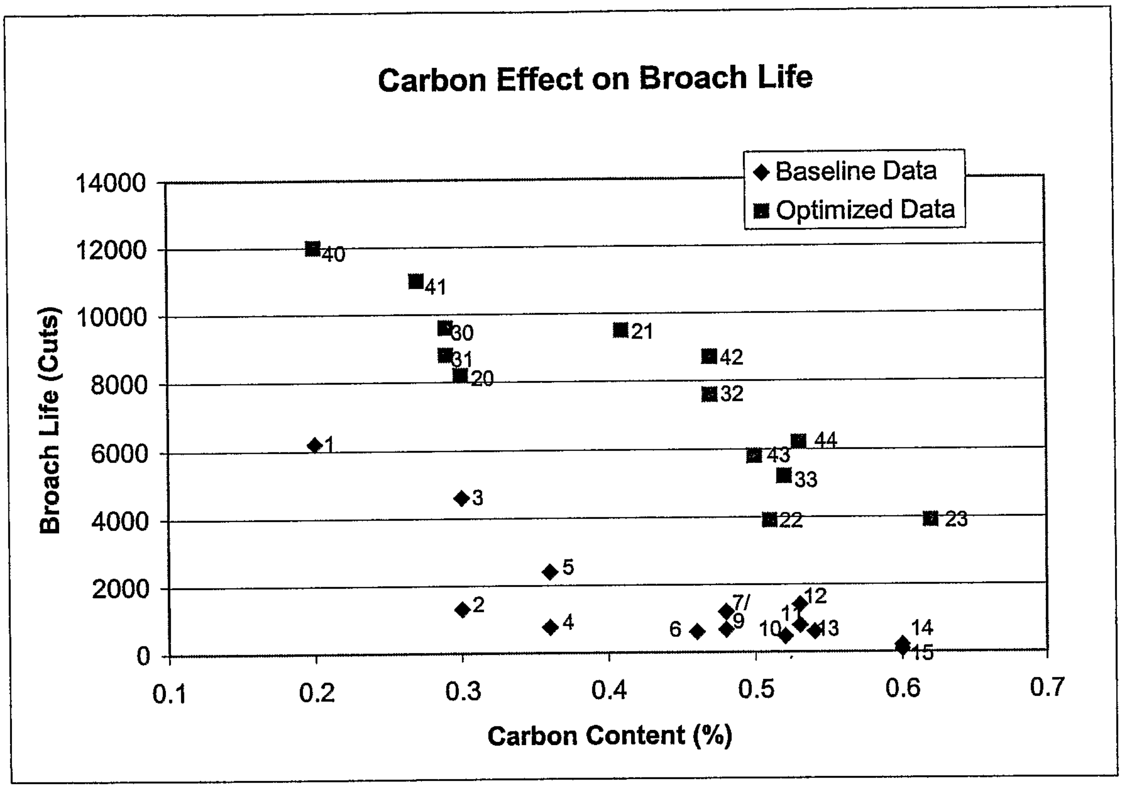
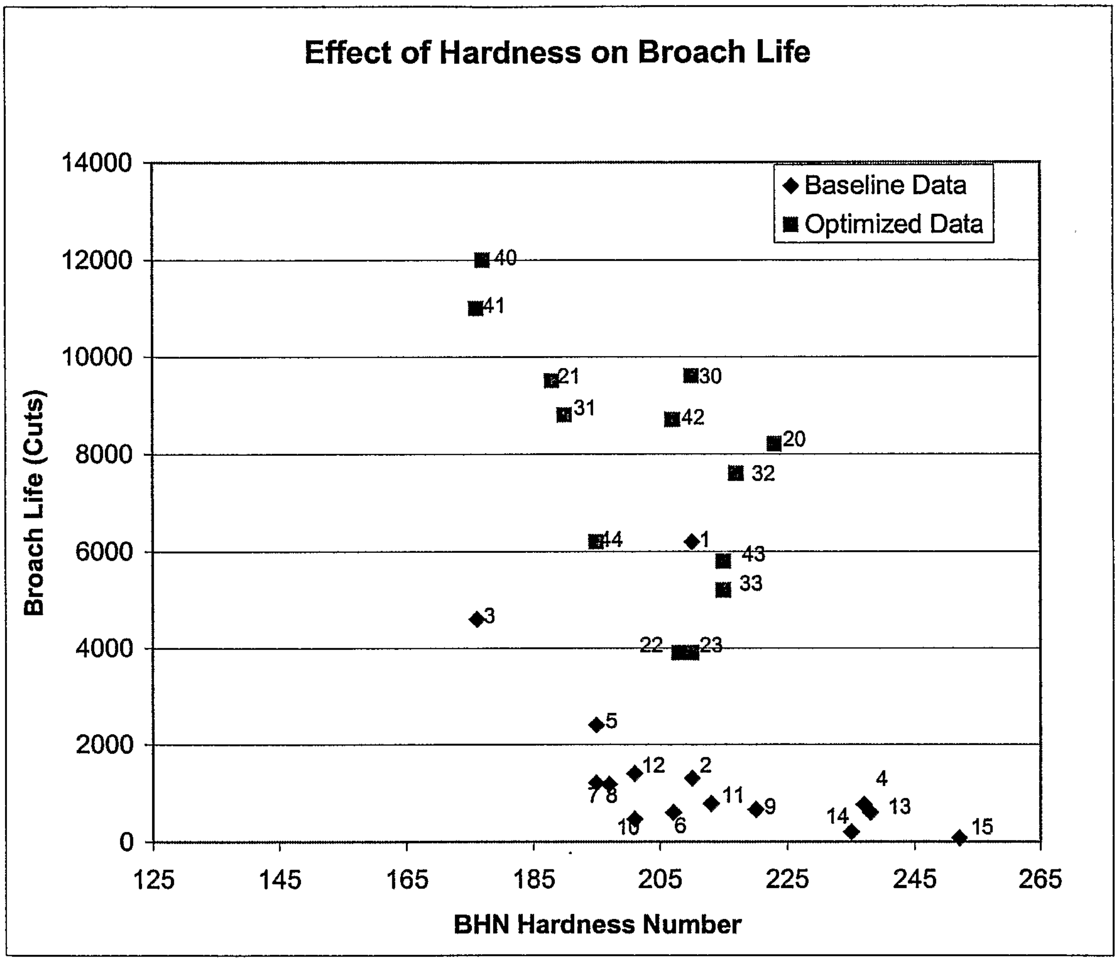

Carbon Effect on Broach Life
◆ Baseline Data
■ Optimized Data
Broach Life (Cuts)
14000
12000
10000
8000
6000
4000
2000
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Carbon Content (%)
40
41
30
31
20
21
42
32
44
43
33
22
23
1
3
5
2
4
6
7
9
10
11
12
13
14
15

FIG. 1


Effect of Hardness on Broach Life
Broach Life (Cuts)
BHN Hardness Number
0
2000
4000
6000
8000
10000
12000
14000
125
145
165
185
205
225
245
265
◆ Baseline Data
■ Optimized Data
40
41
21
30
31
42
20
32
44
1
43
33
3
22
23
5
12
2
4
7
8
11
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14
13
10
6
15

FIG. 2

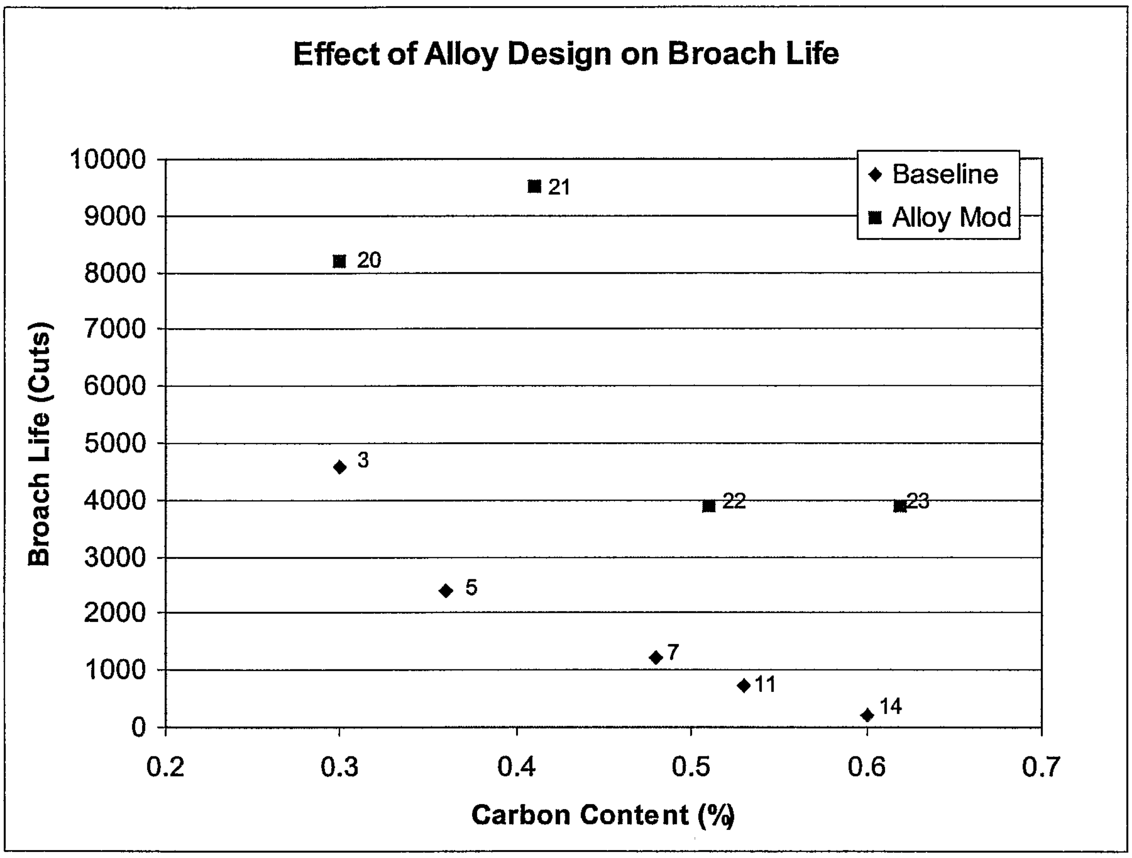

Effect of Alloy Design on Broach Life
Broach Life (Cuts)
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0.2
0.3
0.4
0.5
0.6
0.7
Carbon Content (%)
◆ Baseline
■ Alloy Mod
21
20
3
22
23
5
7
11
14

FIG. 3

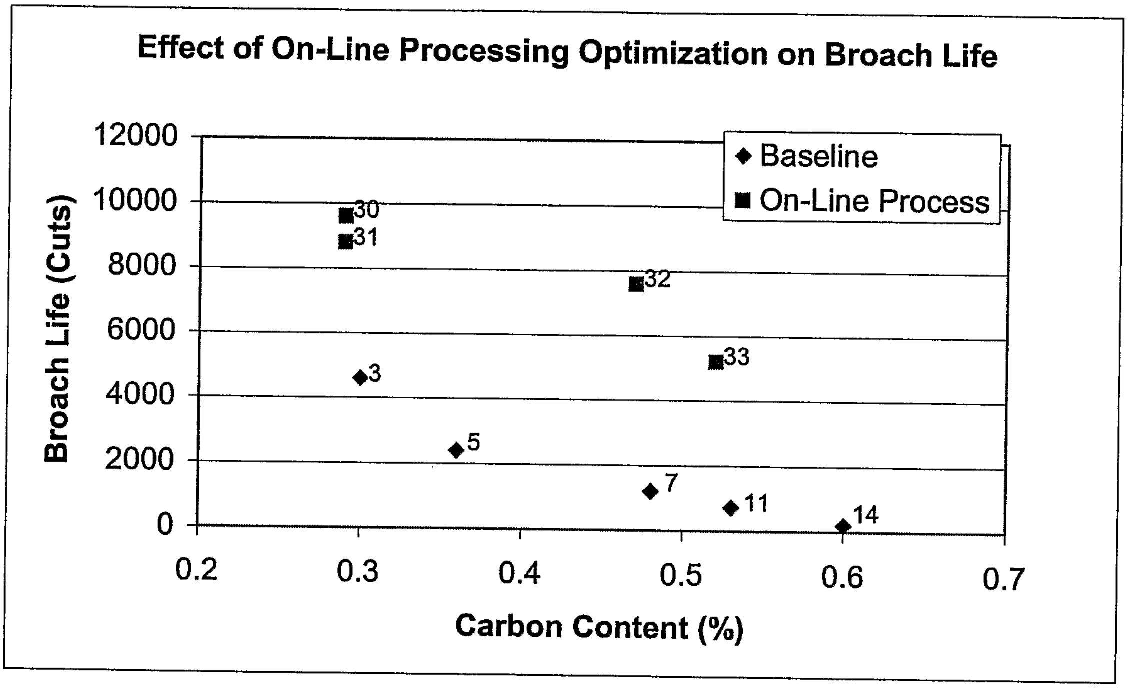

Effect of On-Line Processing Optimization on Broach Life
Broach Life (Cuts)
12000
10000
8000
6000
4000
2000
0
0.2
0.3
0.4
0.5
0.6
0.7
Carbon Content (%)
◆ Baseline
■ On-Line Process
30
31
32
33
3
5
7
11
14

FIG. 4

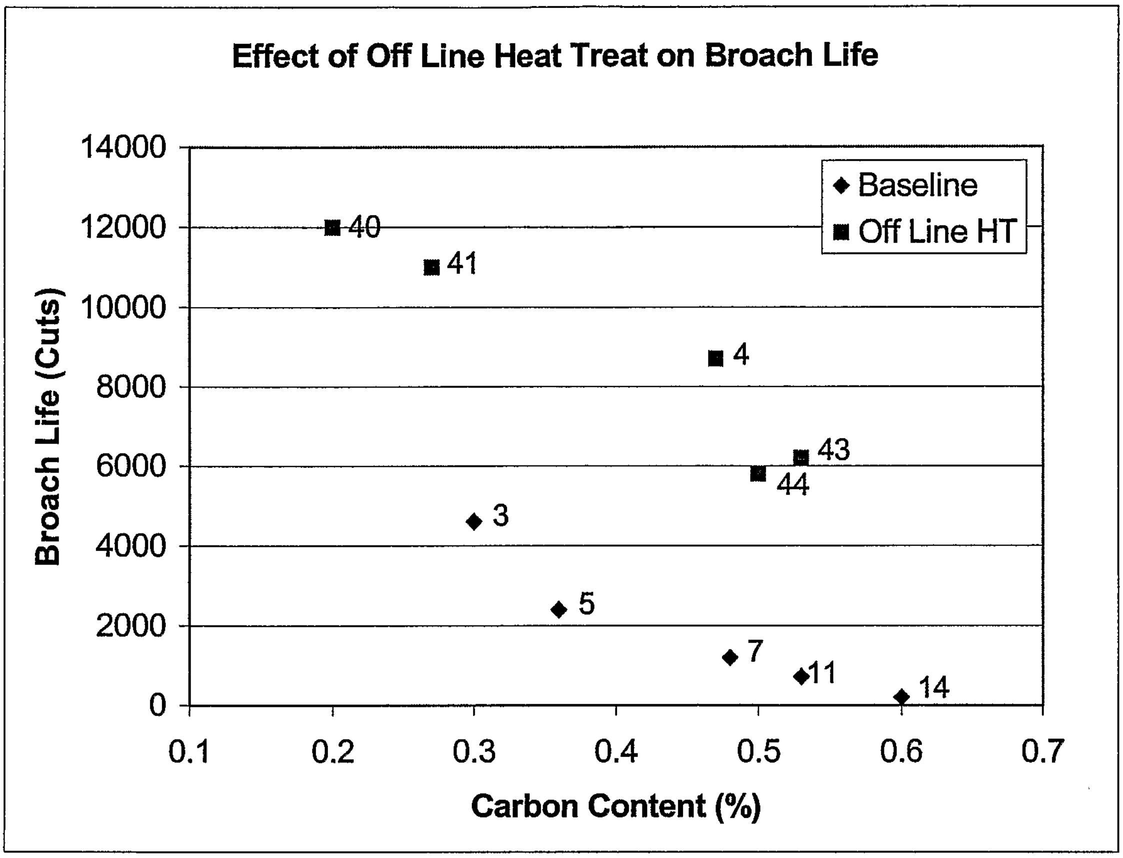
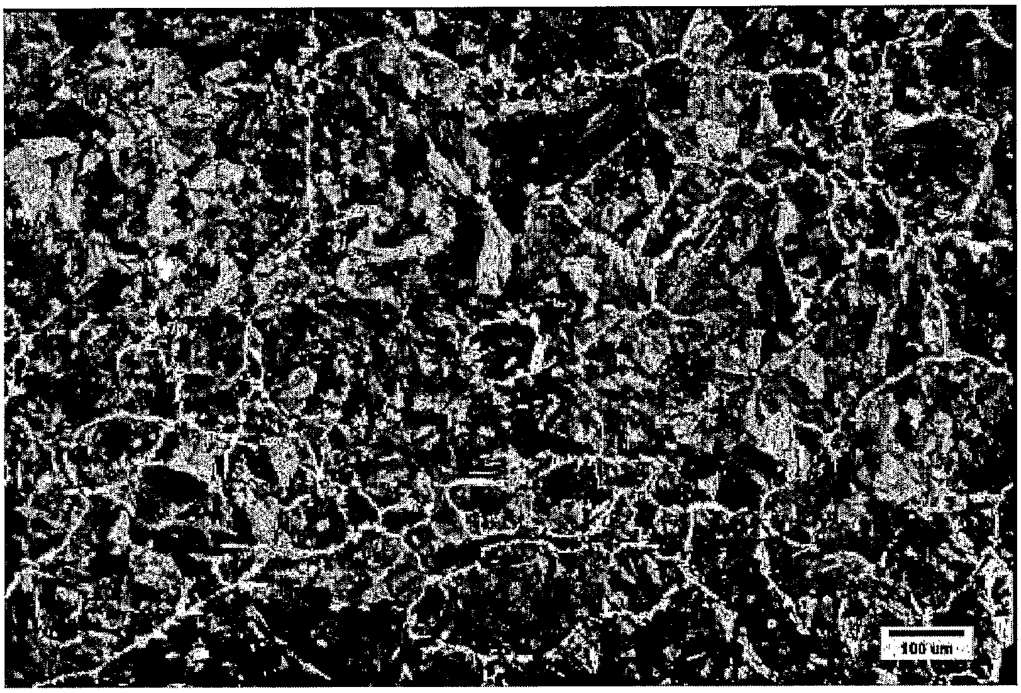
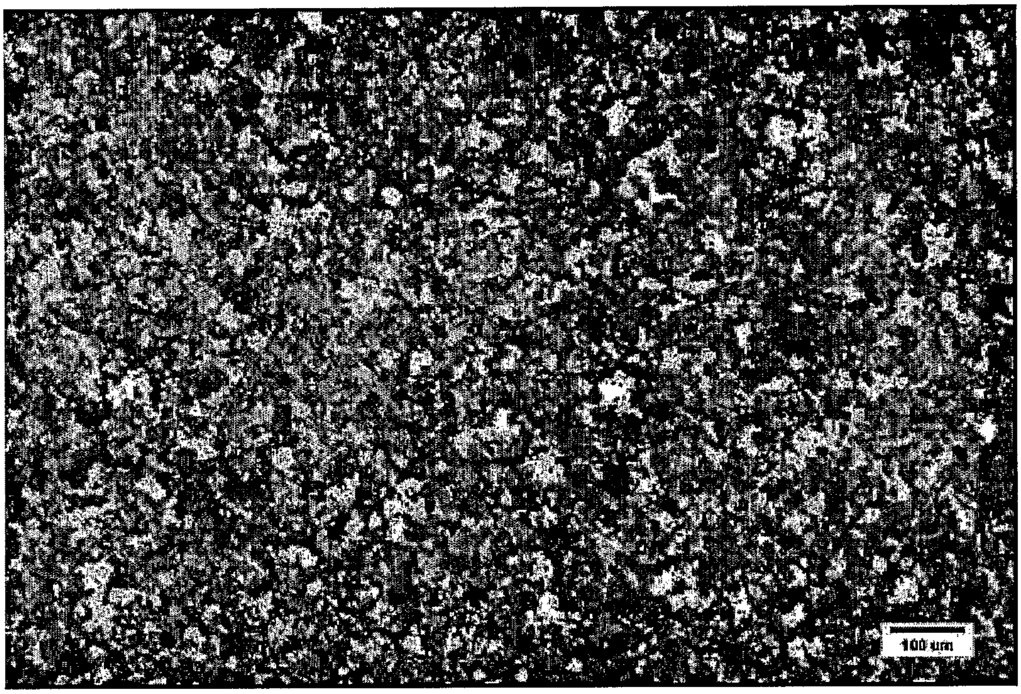

Effect of Off Line Heat Treat on Broach Life
Broach Life (Cuts)
14000
12000
10000
8000
6000
4000
2000
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Carbon Content (%)
◆ Baseline
■ Off Line HT
40
41
4
43
44
3
5
7
11
14

FIG. 5



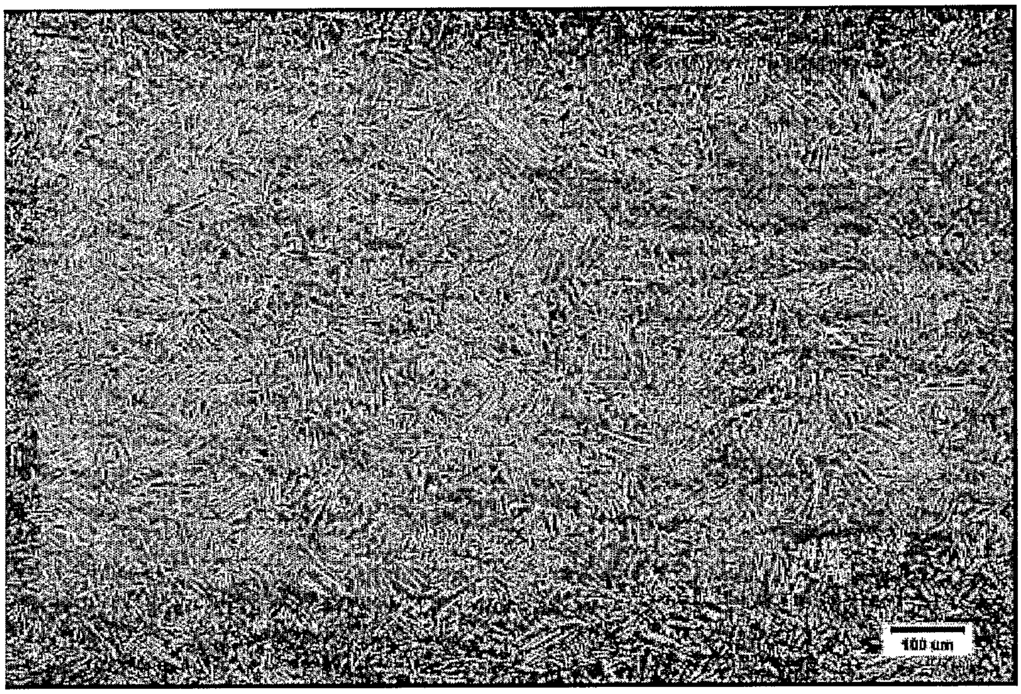
5130 As-Rolled Steel, 100X, Nital Etch, Pearlite and Ferrite
(Baseline - Sample No. 2)

FIG. 6



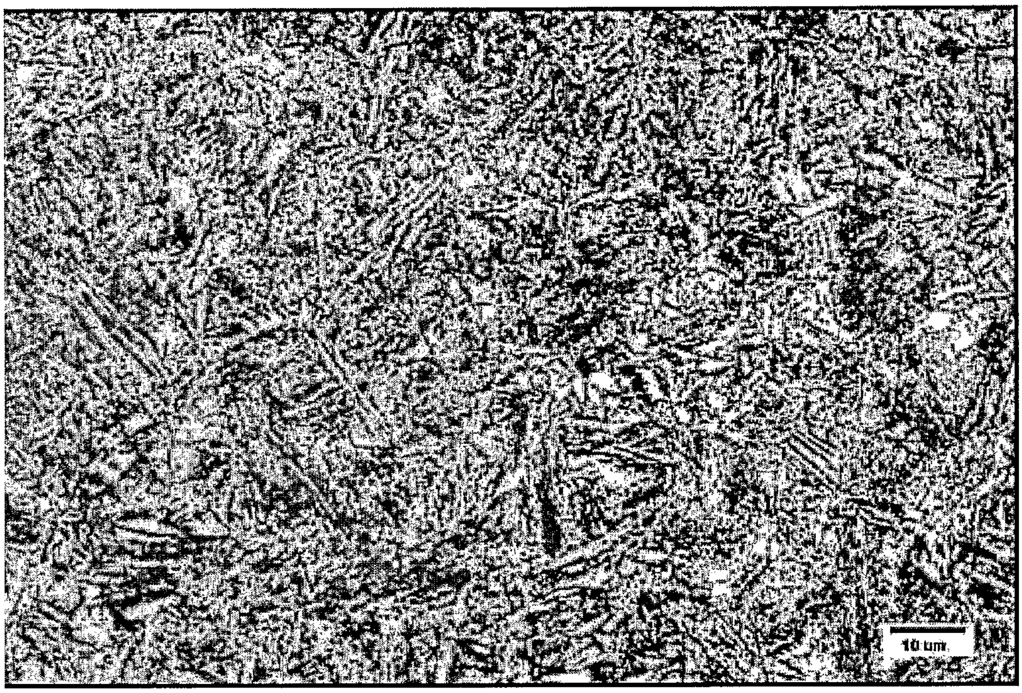
5150 Normalized and Tempered, 100X, Nital Etch, Pearlite and Ferrite
(Baseline - Sample No. 10)

FIG. 7



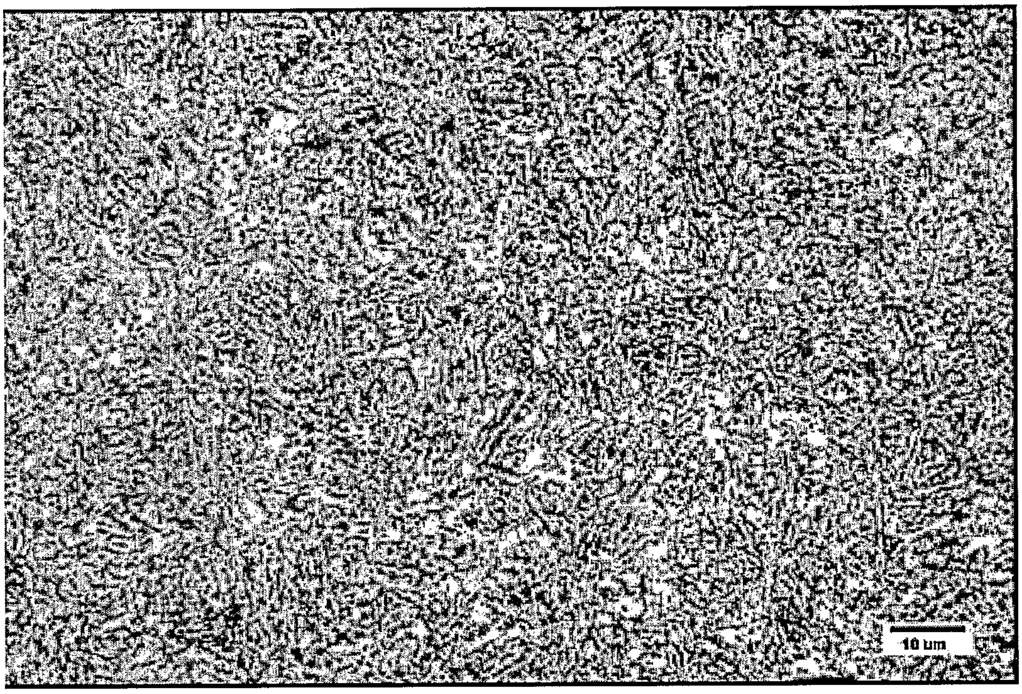
4030 As-Rolled, 100X, Nital Etch, Bainite (Alloy Optimized - Sample No. 20)

FIG. 8



5130 On-line Quenched and Tempered, 1000X, Nital Etch, Spheroidized Bainite (On-line Optimized - Sample No. 30)

FIG. 9



5150 Quenched and Tempered, 1000X, Nital Etch, Spheroidized Martensite (On-line Optimized - Sample No. 33)

FIG. 10