Improved Broaching Steel Technology

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Helical broaching is a highly efficient machining technology used to cut tooth profiles in annulus planetary gears used in car and truck automatic transmissions. The operational costs largely depend on the life of the expensive broach bar, with rapid tooth wear rates leading to very high broaching costs. The wear rate of the broach bar teeth is dependent upon factors including the broach bar material, tooth design, surface treatments, lubricants and the properties of the gear blank material/condition. A laboratory broach machine was developed to study the impact of these variables on the wear rate and life of the broach tool material. Extensive testing has been performed utilizing this test, with an emphasis on the effects of the gear blank material on the life of the broach tool. Effects of base material composition, hardness and microstructure on the life of the broach tool have been studied in detail. Testing results reveal the current typical ferrite/pearlite microstructure of gear broach blanks can cause high tool wear rates, whereas a non-pearlitic structure can result in a 100% to 500% improvement in broach tool life. Tested steels include both carburizing (SAE 5120, 8620, 5130, etc.) and induction hardening (SAE 1050, 1552, 5150, etc.) grades, with ferrite/pearlite, ferrite/bainite and martensitic structures. This paper describes the laboratory broach test, a summary of the testing performed, significant findings resulting from the test and the metallurgical correlations between the base material and the broach tool life.

Introduction

Broaching is a machining technique commonly used to cut gear teeth or cam profiles for the high volume manufacture of power transmission parts used in vehicles (Refs. 1–2). The part tooth profiles can be formed in a single machining operation with minimal overall time, making it ideal for cost-sensitive applications. However, in order to accomplish the broaching operation in a single station and operation, the broach machine must perform the entire roughing, shaping and finishing of the desired part profile in one step using a long, multi-piece, high-speed steel broach tool. The broach tool is relatively expensive to manufacture and can only be redressed or sharpened a finite number of times before the tool is no longer usable (Ref. 2). 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 and redressing costs over the life of a helical broach bar on the order of $50,000–$100,000, and total parts manufactured on a single broach bar currently in the range of 10,000–80,000 parts, the cost to broach a part is typically in the range of $0.60–$5.00, or more. Hence the broach tooling cost represents around 15%–50% of the total manufacturing cost for a finished part. Therefore, whereas broaching represents a time- and space- efficient method to cut gear tooth profiles into annular

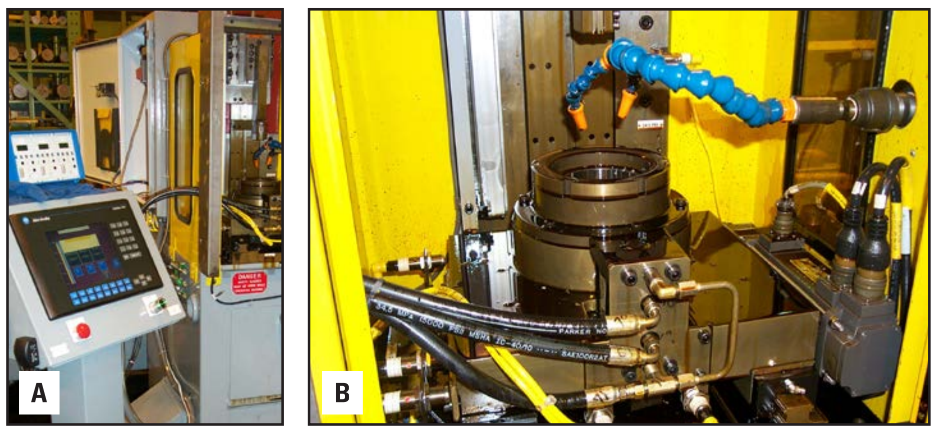

Figure 1 Shown: a) broach machine, control stand and dynamometer modules; b) control table, clamping device with test ring inside and coolant lines.

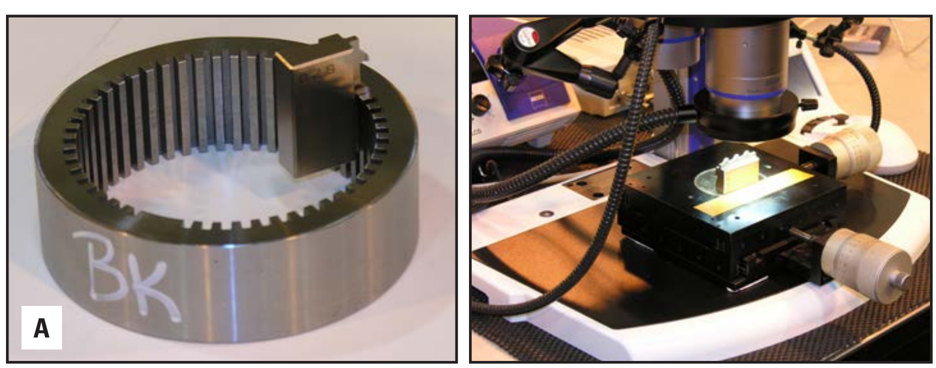

Figure 2 Shown: a) tested broach ring with broach tool resting in finished slot; b) a broach tool under microscopic examination for tool wear measurement.

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Table 1 Compositions of SAE grades tested, weight percent									
Grade*	C	Mn	P	S	Si	Cr	Ni	Mo	Cu
5120	0.21	0.88	0.009	0.032	0.29	0.86	0.10	0.03	0.20
8620	0.21	0.87	0.008	0.018	0.28	0.57	0.64	0.21	0.17
4027	0.27	0.83	0.008	0.030	0.23	0.18	0.07	0.27	0.19
15V27	0.28	1.50	0.016	0.048	0.59	0.15	0.09	0.03	0.21
5130	0.30	0.92	0.010	0.029	0.22	0.81	0.10	0.03	0.13
5135	0.36	0.76	0.012	0.024	0.32	0.98	0.10	0.04	0.21
4040	0.41	0.91	0.010	0.022	0.25	0.11	0.11	0.25	0.20
5046	0.46	1.06	0.008	0.029	0.27	0.20	0.09	0.03	0.15
1050	0.50	0.82	0.008	0.040	0.19	0.08	0.08	0.02	0.20
5150	0.52	0.92	0.010	0.034	0.26	0.86	0.12	0.03	0.21
1552	0.53	1.46	0.009	0.026	0.27	0.11	0.10	0.03	0.20
1060	0.60	0.72	0.007	0.016	0.28	0.12	0.09	0.04	0.20

*15V27 also contains 0.11 wt. %V, all are Al killed

Table 2 Structure, hardness and broach life of steels in each condition						
Grade (SAE)	Structure (+Ferrite)	Hardness HRB	Broach Life*	Structure (+Ferrite)	Hardness HRB	Broach Life*
5120	Pearlite	85.8	15,000		-	-
8620	-		-	Bainite	89.0	12000
15V27	-		-	Bainite	95.7	12000
4027	-	-	-	Bainite	88.0	11000
5130	Pearlite	88.6	4600	Bainite	95.3	9600
5135	Pearlite	92.2	2400	-	-	-
4040	-	-	-	Bainite	90.9	9500
5046	Pearlite	92.6	1200	Bainite	94.7	8700
1050	Pearlite	91.8	1200	-	-	-
5150	-	-	-	Bainite	95.7	8800
1552	Pearlite	94.3	900	Bainite	92.4	6200
1060	Pearlite	93.9	220	Bainite	98.6	3500

*Cuts to failure, 1.5" (38.1mm) each in length, average of two tests

steel parts, the tooling cost to perform this operation represents a significant portion of the total manufacturing cost.

Experimental Procedure

Reduction of broaching costs is typically accomplished through advancements in tooling materials, coatings, lubricants and processing parameters, without as much attention given to the influence of the material condition of the part being broached (Ref. 3). In order to study the influence of steel material condition on broach tooling life, a laboratory broach test machine was conceived, developed, built and used to perform numerous studies on the broaching characteristics of various steel grades and metallurgical conditions. The test unit enables the quantitative measurement of broach tool wear characteristics resulting from repeated broach operations for each of the input steel grades and conditions. The machine development and subsequent testing performed on the various material conditions resulted in a more thorough understanding of the metallurgical variables affecting broach tool life and subsequent part manufacturing costs. This paper describes the broach test unit and discovery of the optimal broaching condition for various steel types, and also provides a summary of testing performed to date.

Test set-up. The broach test machine was developed to simulate the machine design, operation parameters, tooling material and cut design, lubricant system/type, and part geometry of a production-type broaching operation (Fig. 1). A 2-ton, vertical-surface broach machine was integrated with an automated indexing control table and three-axis dynamometer, allowing for monitoring and capture of the actual loads occurring on the tooling during each broach stroke. A tool was designed with three teeth — each cutting 0.0015" (0.038 mm) during the cut operation for a total of 0.0045" (0.114 mm) taken per stroke. The tool broaches inner-diameter splines inside a steel tube slug — 1.5" (38.1 mm) in length, 40-cuts-per-slot — at ram speeds up to 50-surface-feet-per-minute (sfm) (15.24 smm) (Fig. 2). The tool is inspected periodically during the test until 0.005" (0.127 mm) flank wear is measured on two of the three teeth, at which time the test is considered completed and the number of cuts to reach that limit (average of two tools) then characterizes the broaching characteristics of the steel being tested. Controlled test variables (beyond the steel type and condition) include the ram speed, lubricant type/flow rate and tool material/surface condition. The baseline test conditions utilize an M4 tool steel tool with no surface treatment, a chlorinated/sulfinated blended mineral oil lubricant, and a ram speed of 40 sfm (12.2 smm).

Results and Discussion

A series of steels typical of both carburizing and induction hardening gear applications were selected for testing. The steels were tested in both the typical baseline, ferrite/pearlite, and modified conditions, with the intent to improve upon the baseline broach life results. These steels and the heat chemistries are listed in Table 1 and include low-to-medium carbon grades (0.20–0.60 wt.% C), with varying alloying combinations (Mo; Cr; Cr-Mo; Cr-Ni-Mo; Mn; Mn-V) and hardness levels.

Seamless mechanical tubing of the appropriate broach test size range was acquired for each steel grade. Normalizing each steel prior to testing (fully austenitized and air-cooled) developed a uniform, fine grain size and an equivalent processing method for each grade. In addition, the same or similar grades were processed to achieve a non-pearlitic structure and similar hardness range for comparison with the ferrite/pearlite steels. The hardness, microstructure and broach life results for each steel condition are presented in Table 2, and representative photomicrographs are presented (Fig. 3).

The tool wear results for the baseline ferrite/pearlite condition show a clear difference between grades based on carbon

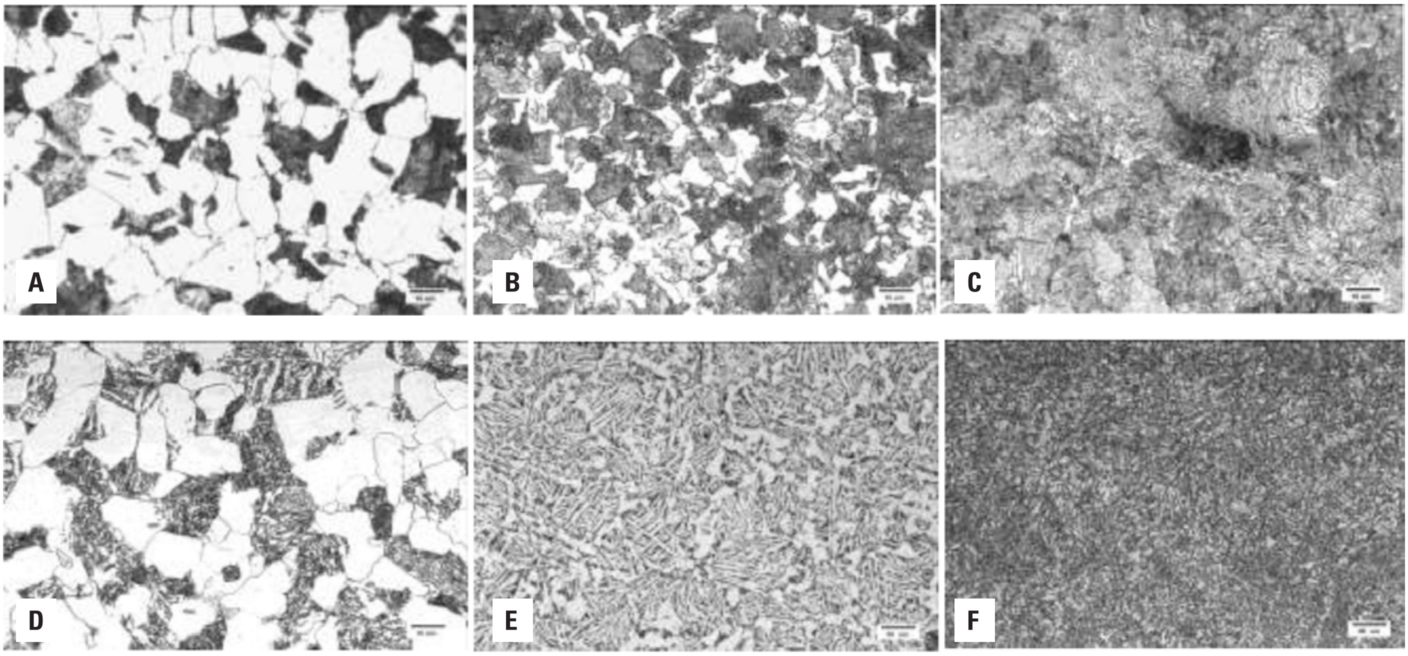

Figure 3 Representative photomicrographs of ferrite/pearlite: a) low-carbon; b) medium-carbon; c) high-carbon steels, and ferrite/bainite; d) low-carbon; e) medium-carbon; f) high-carbon steels.

and hardness level. These trends (Figs. 4 and 5) show the apparent negative effects of carbon level and hardness on broach tool life (exponential trends). Whereas both carbon level and hardness appear to influence tool life, this is not necessarily the case, as carbon level and hardness are significantly correlated to one another (Fig. 6). These results would tend to indicate that lower, carbon carburizing grades would be much less costly for gear broaching, while higher, carbon induction hardening grades could be prohibitively expensive. Further investigation is necessary to determine which of these factors truly influences broach tool life, and if any opportunities exist to improve upon these baseline results.

Whereas these traditional grades and conditions tend to be dominated by ferritic/pearlitic structures (baseline), investigation into alternate material conditions was also explored. The results obtained from numerous internal studies (Refs. 4–5) have shown that non-pearlitic structures provide advantages in many machining operations, and therefore these types of conditions were generated and tested over a similar range of steel types and carbon levels. Creating the non-pearlitic conditions was achieved through a combination of alloying approaches, modifications to prior austenitic grain size (i.e., hardenability approaches), and/or rapid cool-

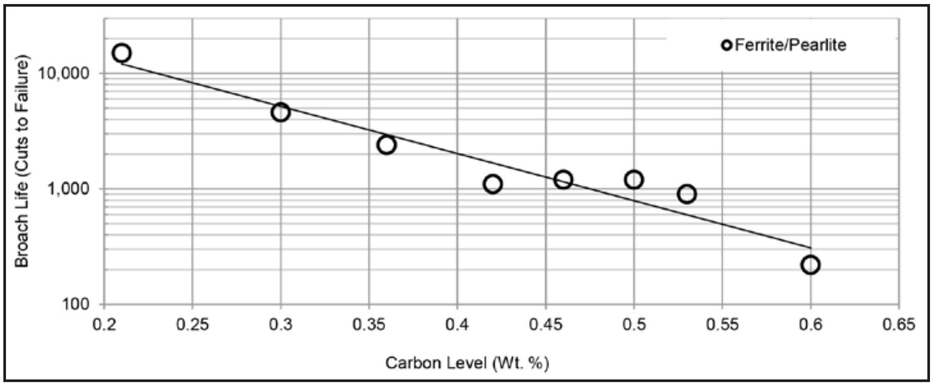

Figure 4 Effect of carbon content on broach tool life for normalized baseline steels composed of ferrite/pearlite microstructure.

Figure 5 Hardness versus broach tool life for normalized baseline steels composed of ferrite/pearlite structure.

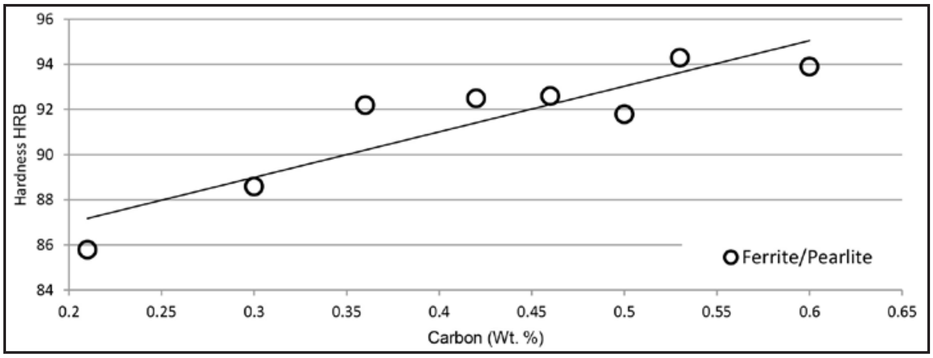

Figure 6 Correlation between hardness and carbon level for normalized baseline steels composed of ferrite/pearlite structure.

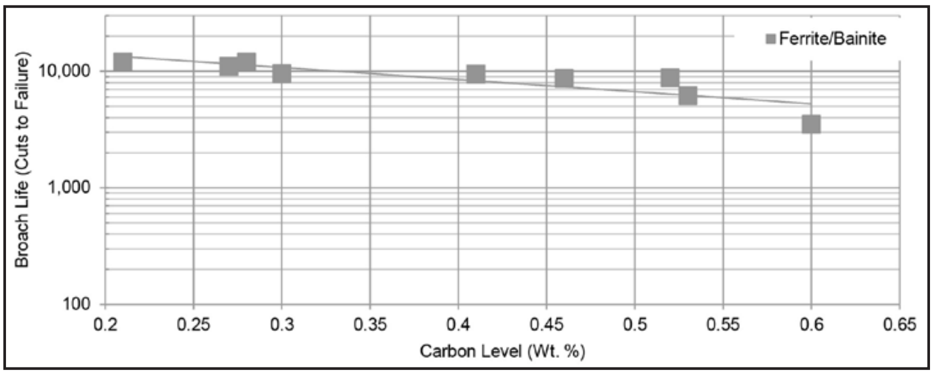

Figure 7 Effect of carbon level on broach life of steels composed of ferrite/bainite structure.

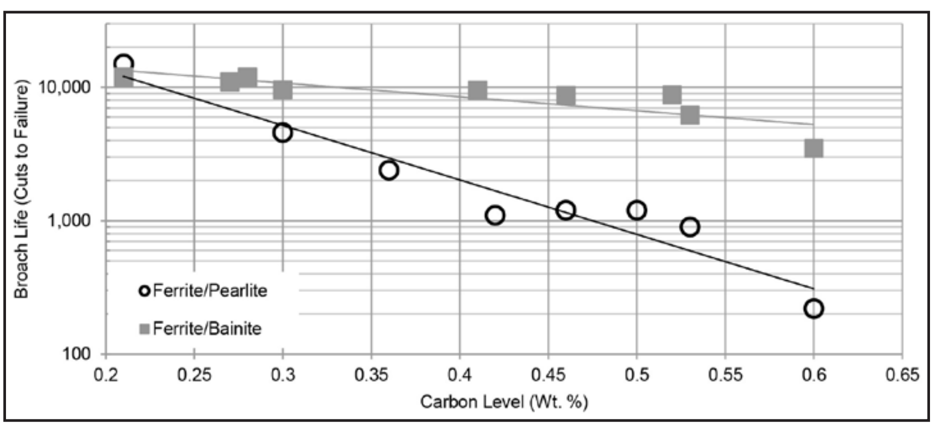

Figure 8 Comparison of effect of carbon level on broach life for both structure types.

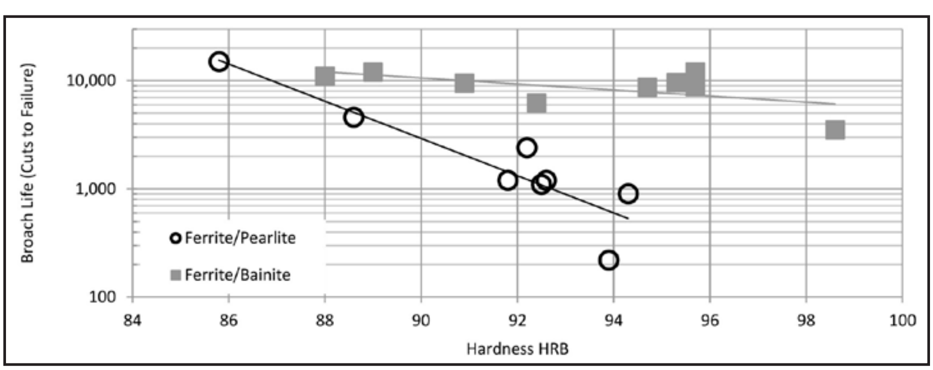

Figure 9 Comparison of trend between hardness and broach life for both structure types.

ing to bypass pearlitic transformation. Table 2 compares the results from these approaches with the baseline grades and conditions. A similar range of carbon level is shown for these modified conditions, while the hardness range is somewhat reduced and the hardness level is slightly increased, as compared with the baseline ferrite/pearlite conditions.

The apparent trends from this dataset deviate significantly from what was observed for the ferrite/pearlite baseline conditions. Figure 7 illustrates the same carbon level versus broach life plot as shown for the ferrite/pearlite conditions; however, in this case the effect of carbon level on broach life is much less pronounced. This becomes even more apparent when both conditions are plotted together (Fig. 8). The relative improvement in broach life for the non-pearlitic condition is much more pronounced for the higher-carbon steels, elevating broach life of the higher carbon steel to levels approaching the lower carbon ferrite/pearlite steels. Plotting the non-pearlitic results against hardness levels for these conditions (Fig. 9) also indicates a reduced trend of hardness and broach life for the non-pearlitic conditions. These results suggest that higher carbon induction hardening gear steels can be economically broached in the non-pearlitic condition, with cost structures similar to lower carbon carburizing grades and while maintaining a sufficient level of core hardness for the application.

In addition to this study between various grades and conditions, selected studies concerning the impact of processing on individual grades have also been performed in an attempt to optimize broach life for a particular steel grade. One such grade of interest is the induction hardening grade SAE 5046, where both the ferrite/pearlite condition and bainitic conditions were tested (as previously reported), and where additional tests were performed on the bainitic condition after various tempering conditions. Table 3 summarizes those results for the ferrite/pearlite condition, and the ferrite/bainite condition following tempering within a range of 1,150°F–1,325°F. As seen in the table, while there is a significant improvement in broach life in going from the ferrite/pearlite to the non-pearlitic structure, the broach life of this condition

Table 3 5046 structure, hardness and broach life data			
Tempering Temperature (Deg F)	Microstructure	Hardness (HRB)	Broach Life (Cuts to Failure)
NA	Fenite/Pearlite	92.5	1200
1150	Ferrite/Bainite/ Martensite	98	3100
1200	Ferrite/Bainite/ Martensite	97	3800
1275	Ferrite/Bainite/ Martensite	95	7200
1325	Ferrite/Bainite/ Martensite	94	10000

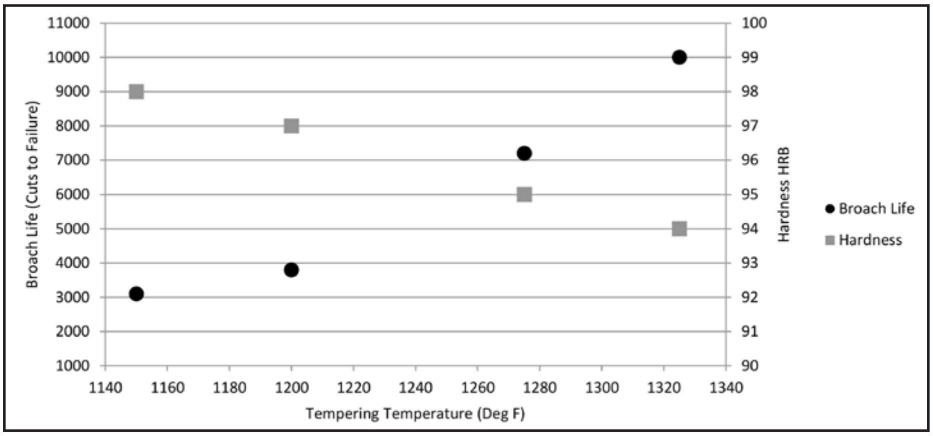

Figure 10 **Effect of increasing tempering condition of non-pearlitic 5046 material on both material hardness level and broach tool life.**

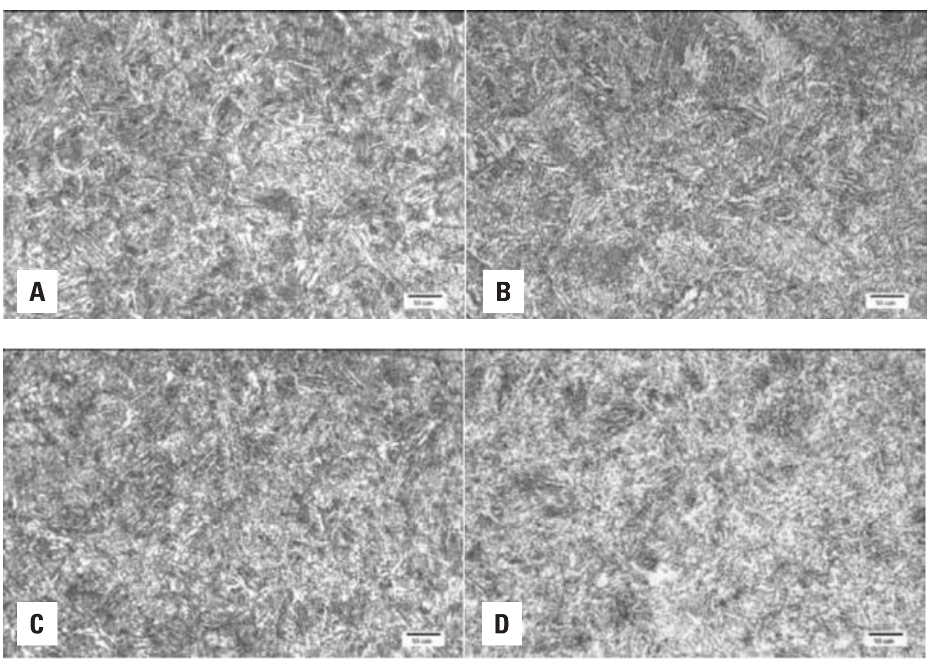

Figure 11 **Photomicrographs of 5046 bainite/martensite/ferrite conditions after tempering at a) 1,150°F; b) 1,200°F; c) 1,275°F; and d) 1,325°F, nital etch.**

is highly dependent upon the tempering condition employed. As depicted in Figure 10, a significant range in broach tool life results is realized by varying the tempering conditions for the bainitic structure — even over a fairly narrow range of hardness levels. Therefore, as has also been witnessed with other grades that have also been optimized in the non-pearlitic condition, the broach life is more dependent upon the tempering condition than the actual hardness level of the material.

Photomicrographs of the various tempered conditions are shown in Figure 11, and indicate that only subtle changes in the level of spheroidization of the fine carbides is revealed at maximum magnification under the light microscope. Whereas the microstructural changes are subtle under the light microscope, more significant changes to the level of carbide spheroidization are realized at higher magnification, which would account for the more dramatic shift in broach tool life. Figure 12 depicts the level of carbide spheroidization in two of the temper conditions — 1,200°F and 1,275°F — and it is evident that the carbide size has increased while the number of carbides has decreased with this level of increased tempering condition. As noted previously, this progressive carbide spheroidization with increasing tempering condition process appears to impact the tool wear characteristics to a greater extent than the hardness change in the material.

Discussion

The development of a laboratory broach testing machine has enabled a detailed exploration of the impact of workpiece material type and condition on the life of high-speed, steel broach tools, and the subsequent cost impact on profile broaching operations. Ferrite/pearlite steels were tested on this unit to determine the baseline broach tool wear rates. Results indicated that the carbon level of the steel had the primary impact on tool life. This is thought to result from the abrasive wear characteristics of the lamellar-type, pearlitic carbides on the tool cutting surface — and which increase exponentially as the carbon level and pearlite content increases. With decreasing levels of pro-eutectoid ferrite in the structure, the highly pearlitic structure rapidly abrades the tool. However, it has been discovered that these higher-carbon steels can achieve remarkable increases in broach tool life by avoiding the pearlitic structure altogether and developing a non-pearlitic, tempered bainite/martensite structure.

The non-pearlitic structure has been shown to achieve greatly increased broach life conditions over a similar range in hardness levels, as compared to the pearlitic conditions. These results allow for significant flexibility in steel selection and core hardness levels, while maintaining reasonable broach costs throughout. These structures develop an entirely different carbide structure, as compared to the pearlitic carbides. The fine, spheroidal-type carbides present in these tempered and non-tempered steels are much less abrasive to the broach tool and so provide greatly enhanced tool life. This is evident within a single grade in that as the tempering condition is increased, the level of carbide spheroidization progresses and positively impacts upon broach tool life to a much greater extent than the hardness level reduction. As such, utilizing this technology allows for achieving the lower tooth/profile cutting cost structure of the carburizing grades with the core properties and hardening characteristics required for induction hardened gears.

Conclusions

A laboratory broach test unit has been developed enabling the quantification of broach tool wear conditions that occur when cutting gear teeth in a variety of steel types and conditions.

A full characterization of baseline ferrite/pearlite steel conditions has been accomplished with this test, indicating an exponential effect of increasing carbon level on tool wear rates for this structure type.

A characterization of these same steels in an alternate, non-pearlitic condition, composed of ferrite and bainite and/or martensite at the same or higher hardness levels, shows that this material condition is much less abrasive on the broach tool, especially at higher carbon levels.

A study on the impact of tempering condition of a non-pearlitic SAE 5046 grade indicates that significant optimization of broach tool life can be accomplished by increasing the tempering level for this material type and condition.

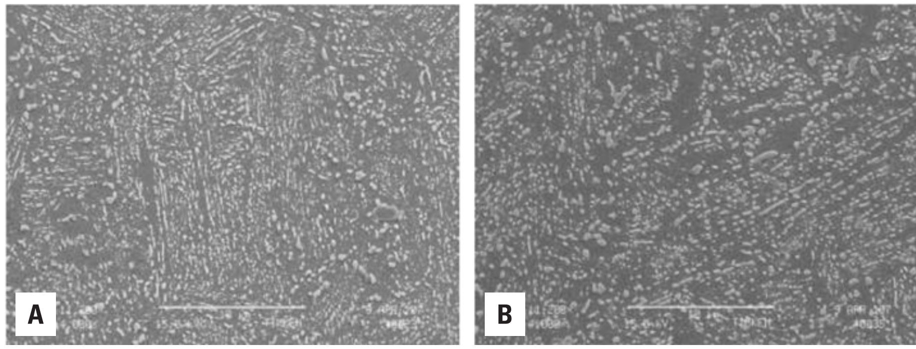

Figure 12 SEM photomicrographs of 5046 steels after tempering at a) 1,200°F temper and b) 1,275°F, picral etch.

The demonstrated improvements in tool wear characteristics for the non-pearlitic conditions allow for the attainment of the higher core properties and hardening response necessary for induction-hardened gears, at a cost level comparable to lower carbon, carburizing grades.

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