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Locally Austempered Ductile Iron (LADI)

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ABSTRACT

There are numerous component applications that would benefit from localized austempering (heat treating only a portion of the component) for either improved wear properties or fatigue strength. Currently available methods for "surface austempering" of ductile iron are often expensive and not as well controlled as would be desired. This study was undertaken to find a better process. Locally Austempered Ductile Iron (LADI) is the result of those efforts.

LADI is a surface hardening heat treatment process that will produce a localized case depth of an ausferrite microstructure (ADI) in a desired area of a component. This process has been jointly developed by Ajax Tocco Magnethermic Corporation (ATM) and Applied Process, Inc.- Technologies Division (AP) with support and collaboration from ThyssenKrupp Waupaca, Inc. (TKW). This paper describes the outcome of using this patent pending process (US #65/195,131).

INTRODUCTION

Austempered Ductile Iron (ADI) has become a popular material; competing cost effectively with steel and aluminum forgings, castings and weldments. Some components could benefit from austempering only a certain location and leaving the balance of the part as as-cast ductile iron for improved machining. For example, a process such as this could improve the component's abrasive wear resistance, bending or contact fatigue strength in a localized region.

In 1991, Kovacs, Keough, et al described, in US Patent 5064478[1], a method for austempering the entire surface of a cast iron part. That process was not suitable for surface hardening a specific location on a component. Current methods available for surface austempering a specific area on a part (typically based on flame heating) are relatively expensive, hard to control, and require expensive alloying in the casting to obtain the desired properties.

Investigators from Applied Process Inc. (AP) and Ajax Tocco Magnathermic (ATM) undertook a research project to test the hypothesis that a better controlled, lower cost, higher performing method of surface austempering could be developed. This work integrated knowledge gained from the work conducted in the early 1990's, austempering research and its industrial application, applied metallurgical theory and newly developed industrial process capabilities and controls. Locally Austempered Ductile Iron (LADI) is the result of this collaborative work.

In order to understand the LADI process, one must first be familiar with the production of Austempered Ductile Iron (ADI) because the LADI process is designed to create a layer of ADI on the surface of a cast iron component.

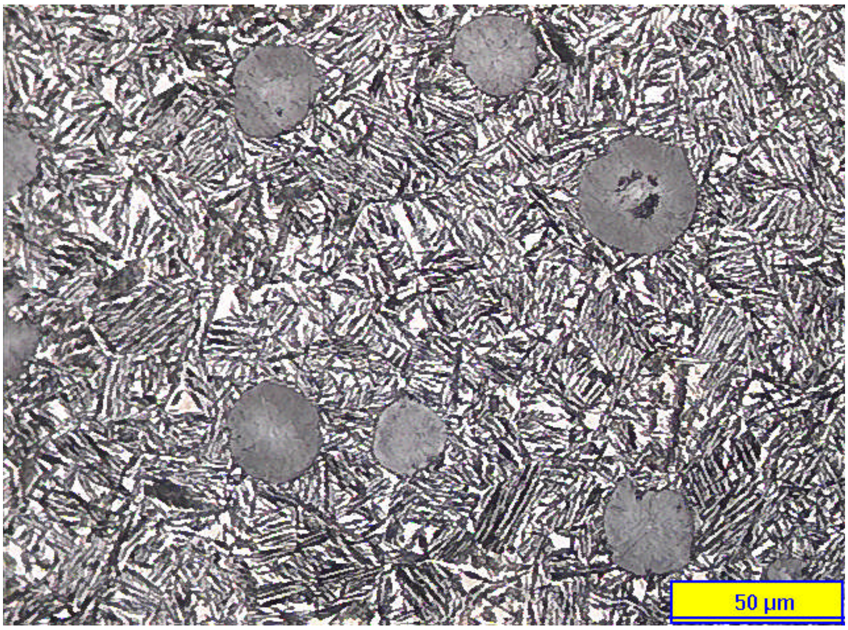
WHAT IS AUSTEMPERING?

Austempering is a high performance isothermal heat treatment that imparts superior performance to ferrous metals. It is a multi-step process that includes austenitizing, followed by cooling rapidly enough to avoid the formation of pearlite to a temperature above the martensite start (Ms) and then holding until the desired microstructure is formed. In cast irons, this microstructure is called ausferrite.

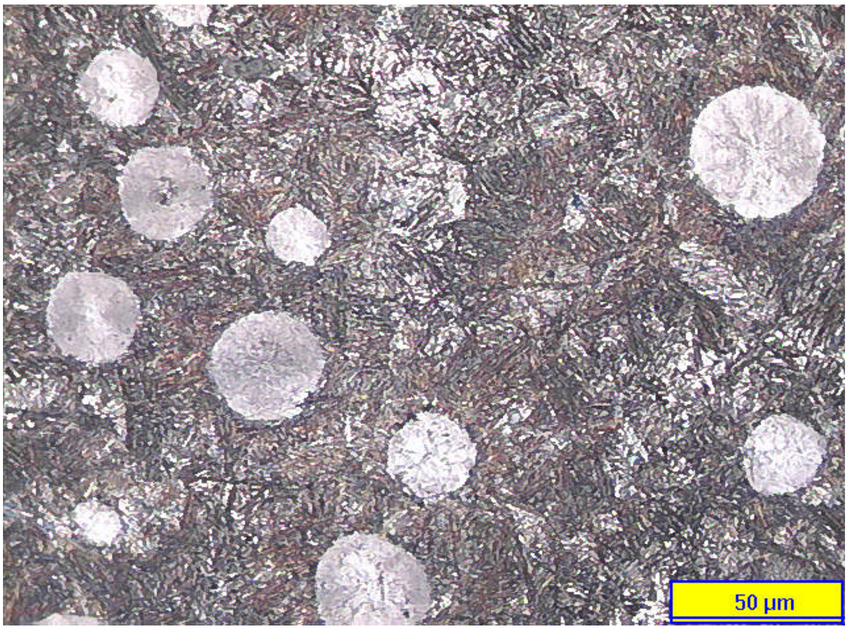
What is Ausferrite?

The ausferrite microstructure in austempered cast irons consists of a mix of acicular ferrite and high carbon austenite as shown in Figures 1A and B. The relative amounts of ferrite and austenite present as well as the microstructural scale (final properties) are dependent upon the choice of heat treatment parameters. See Table 1 for a list of the range of properties for ADI.

The austenite component of the ausferrite is thermodynamically, but not mechanically stable. When a high normal force is applied to an austempered cast iron component, a strain-induced transformation of austenite to martensite occurs. This results in the formation of a layer containing crystals of hard, wear resistant martensite supported in a tough ausferritic matrix.



(A) 371°C (700°F) quench



(B) 260°C (500°F) quench

Figure 1: Photomicrographs of Austempered Ductile Iron illustrating the range of ausferrite microstructures that can be produced by adjusting the heat treatment parameters. The microstructural scale of ausferrite decreases with decreasing quench temperature.

Table 1: ASTM A897/A897M-06 Grades of ADI

Tensile Strength (MPa / ksi)	Yield Strength (MPa / ksi)	Elongation (%)	Typical Hardness (HBW)
750 / 110	500 / 70	11	241 - 302
900 / 130	650 / 90	9	269 - 341
1050 / 150	750 / 110	7	302 - 375
1200 / 175	850 / 125	4	341 - 444
1400 / 200	1100 / 155	2	388 - 477
1600 / 230	1300 / 185	1	402 - 512

Figure 2 shows pin abrasion (high stress abrasion) test results for ADI and competitive materials. Note that the slope of the curve for the ADI results is relatively flat, indicating that the wear performance of ADI in a high stress environment is relatively independent of bulk hardness. As a result of this ability to strain transform, ADI can compete with much harder materials which rely on bulk hardness for abrasion resistance.

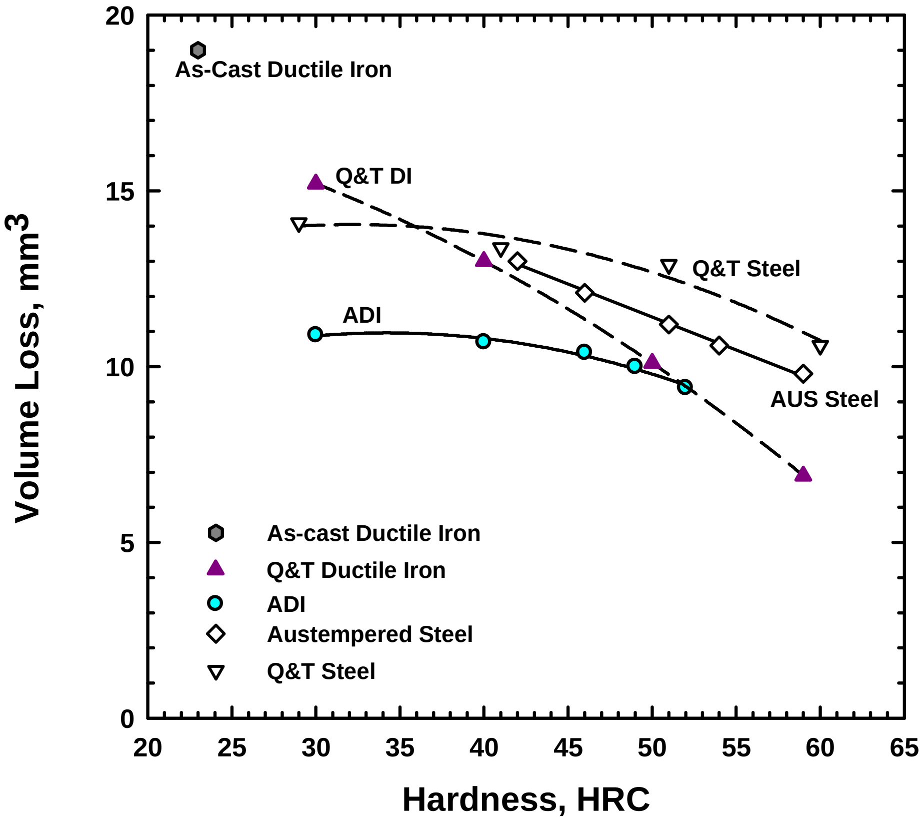


Figure 2: Pin abrasion results for ADI and various competitive materials.

<u>What is LADI?</u>

LADI refers to Locally Austempered Ductile Iron or the ability to produce ADI on the surface of a component in a specific location. This technology allows the end user to utilize the properties of ADI where they are needed without having to focus on the production of a through hardened component.

EXPERIMENTAL PROCEDURE

COMPONENT SELECTION

Engine camshafts are unique in that the manufacturing requirements are very different from the operating needs of the product. For instance, when selecting the proper material for a camshaft, one must balance the needs of a hard, strong and wear resistant material choice for the camshaft lobes with the ease of manufacturing, most notably the ability to machine the product. One way to achieve this balance is to use assembled camshafts, which can be a relatively costly solution. Another option is to use a localized heat treat process like LADI in order to produce the high performance material where it is needed without adversely affecting the manufacturability (or machinability) of the entire component. Camshafts were subsequently selected to validate the LADI process because it can provide an option that allows for both high performance and machinabililty in a single cast product.

BASE MATERIAL

ASTM A536-84(2004) 65-45-12 ductile iron was utilized for this process. The use of unalloyed 4512 iron allows the foundry to forego the use of expensive alloy additions to the base iron.

HEAT TREATMENT

The surface microstructure of LADI is produced by a two step proprietary process jointly developed by ATM and AP. The surface of the camshaft is heated (using computer controlled induction technology) to a temperature just below where incipient melting would occur and held for a time sufficient to form austenite with a uniform carbon content. Following austenitization, the surface is cooled to a temperature range of 205-230ºC by spraying with a liquid polymer quench. The camshaft is then held at this quench temperature until a surface layer of 3 to 5mm of ausferrite is formed.

MICROSTRUCTURE

Evaluation of the microstructure was accomplished by sectioning lobes perpendicular to the axis of the camshaft to reveal the depth of the heat treated layer (See Figure 3). Surfaces were polished using standard metallographic techniques. Lobes were etched with 5% Nital prior to examination. Two characteristics were monitored during evaluation.

1. Surface Microstructure – to verify the presence of ausferrite.
2. Depth of heat treated layer – defined to be the distance from the surface to first appreciable proeutectoid ferrite.

Both surface microstructure and depth of heat treatment were analyzed using a Zeiss Axiovert 40 metallograph with a Buehler Omnimet (version 5.40) image analysis system.

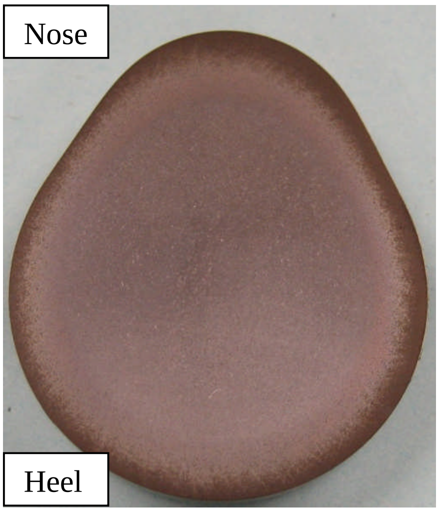


Figure 3: Example of a cam lobe section used for microstructural evaluation. Note the dark colored LADI layer on the surface.

HARDNESS

Microhardness traverses were completed from the surface of the lobe through the heat treated zone. A lobe sample was mounted and polished using standard metallographic procedures. Knoop hardness tests were completed using a Buehler Micromet 2104 microhardness tester outfitted with Omnimet MHT software. A 500 gram load was applied to the lobe at varying depths from the surface. Measurements started at a distance of 0.125 mm from the surface and were repeated every 0.168 mm to a total depth of 6 mm (36 readings).

Microhardness traverses were evaluated for effective depth of heat treatment or the distance from the surface to 50 HRC. The corresponding microstructures at each hardness indentation were also examined.

X-RAY DIFRACTION (XRD) ANALYSIS

A specimen for XRD was prepared from the heat treated layer in the nose of a lobe. XRD data was collected in the range from 35° - 125° 2θ using a step size of 0.03° 2θ and a 25 second count time. A Scintag XDS-2000 θ/θ diffractometer equipped with a copper target x-ray tube was utilized.

The angular range that was examined includes peaks for austenite (γ) and ferrite (α). The integrated intensities of each peak were used to calculate the relative amounts of the phases present, $X\gamma$ and $X\alpha$.

CAMSHAFT BENCH TESTING

The LADI process was applied to an eight lobe section of a full camshaft after heat treatment parameters were optimized. Four lobes of this section were bench tested as shown in Figure 4. Test parameters were selected to match the operating conditions of a current production OEM V8 engine. The test parameters are listed in Table 2. It should be noted that OEM engineering department recommends a 1000 hour bench test at 300 RPM (or 18 million cycles). Although this test used a modified speed and duration, the total number of test cycles exceeded 18 million.

Table 2: Camshaft Bench Testing Parameters

Duration	472.5 Hours
Speed	660 RPM
Lubrication	5W-20 - GF3
Spring Weight	159 Grams
Lifter Weight	130 Grams
Lifter Material	Steel – 61.5 HRC
Load @ Nose	3447 N [775 lbs]
Load @ Heel	2491 N [560 lbs]

The lobes were visually checked every 24 hours during bench testing. Figure 5 shows the camshaft bench tester used for this study.

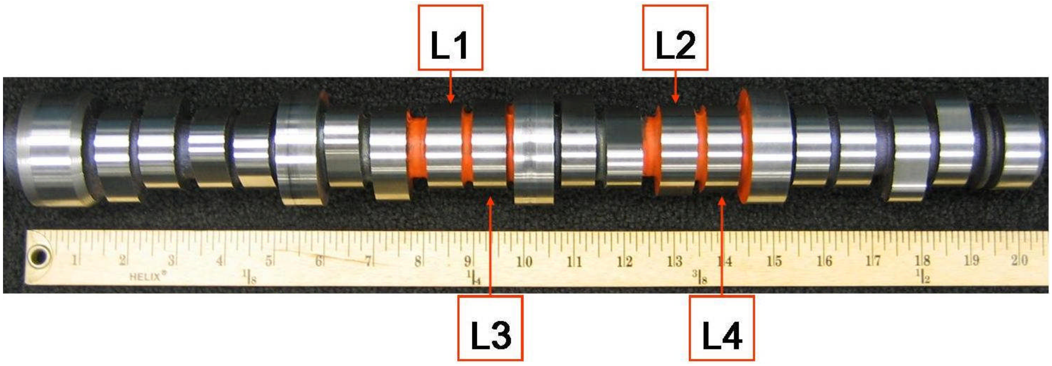


Figure 4: Camshaft that was bench tested. Lobes that had the LADI process applied are labeled.

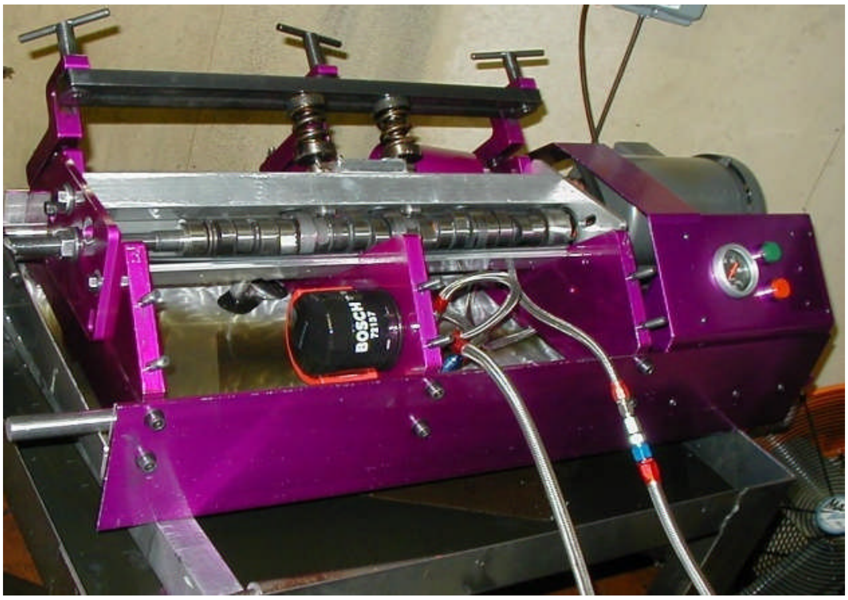


Figure 5: Camshaft Bench Tester used for this study. The tester has been partially disassembled to provide a clearer view of the camshaft.

RESULTS AND DISCUSSION

BASE MATERIAL & CHARACTERIZATION

The base microstructure of the 65-45-12 ductile iron camshafts was quantified prior to heat treatment. Chemical analysis was completed along with nodule count and nodularity measurements. A typical chemistry range for 65-45-12 iron is provided in Table 3.   Subsequent microstructure evaluation validated that the base iron was predominantly ferrite (See Figure 6).

Table 3: Typical chemistry range for ASTM 65-45-12 Ductile Iron

Chemical Composition							
%C	%Si	%Mn	%Cu	%Ni	%P	%S	%Mg
3.6 - 3.8	2.0 -2.4	0.2 -0.4	0.05 -0.20	trace	0.035	0.012	0.025-0.050

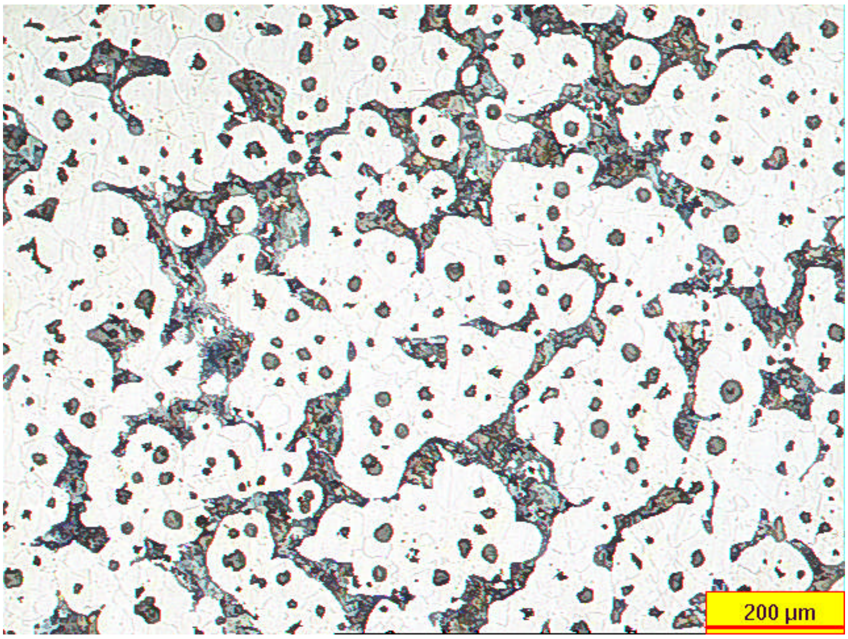


Figure 6: 65-45-12 Ductile Iron prior to heat treatment

Both the nodule count and nodularity exceeded the recommended minimums for high quality ductile iron for the production of ADI of 100 nodules per mm2 and 85%, respectively. Table 4 lists the results of the aforementioned measurements.

Table 4: Nodule Count and Nodularity Results

Measurement	Result	STD DEV
Nodule Count (#/mm2)	447	54
Nodularity (%)	88	N/A

There are several advantages to using a ferritic ductile iron as the base material for this process. Expensive alloy additions are not necessary to produce the ferritic microstructure. In addition, ferrite is much easier to machine in comparison to pearlitic ductile iron or other camshaft materials like quench and tempered steel.

MICROSTRUCTURAL ANALYSIS AFTER LADI PROCESS

After heat treatment, camshaft lobes were sectioned and prepared using standard metallorgraphic procedures as outlined above. The resulting microstructures within the LADI layer were compared to standard ADI microstructures. The predominant microstructure within the surface layer appeared to be ausferrite with a fine microstructural scale. In some instances, noticeable regions of austenite were observed. Figure 7 contains a photomicrograph of a typical microstructure located 0.645 mm from the nose of a lobe.

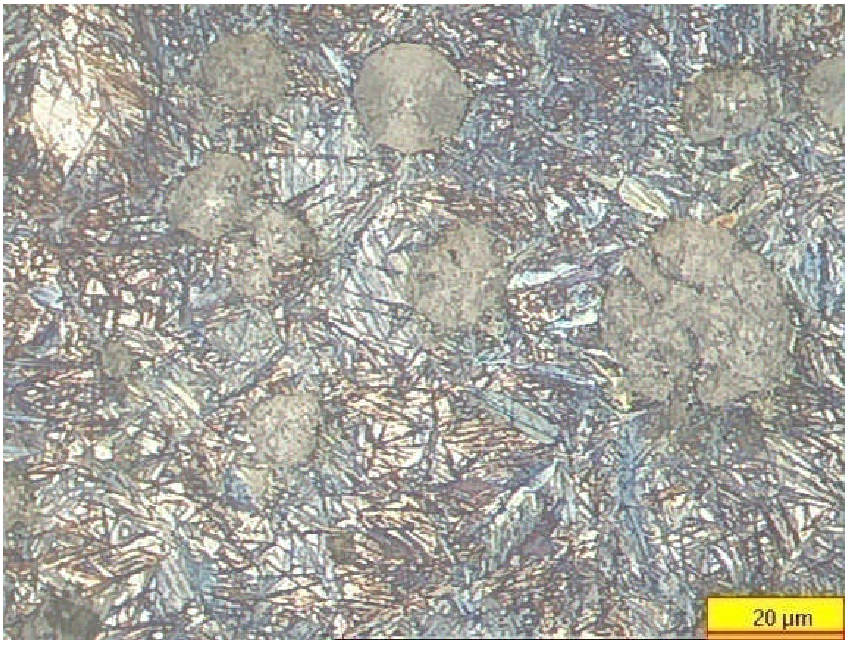


Figure 7: Lobe microstructure at a depth of 0.645 mm from lobe surface. The matrix microstructure appears to be ausferrite.

The LADI layer was defined as the distance from the surface to the first appreciable amount of proeutectoid ferrite. This measurement was made on polished and etched lobes in order to yield an understanding of the depth of the LADI layer as a function of the selection of heat treatment parameters. A total depth of 3 mm (prior to machining) was targeted with several heat treatment iterations required to meet said target. An example of an LADI layer measurement is shown in Figure 8. In this example, an LADI layer of 3.04 mm was measured. Also included is a photomicrograph that illustrates how the “first appreciable amount of proeutectoid ferrite” was qualitatively determined.

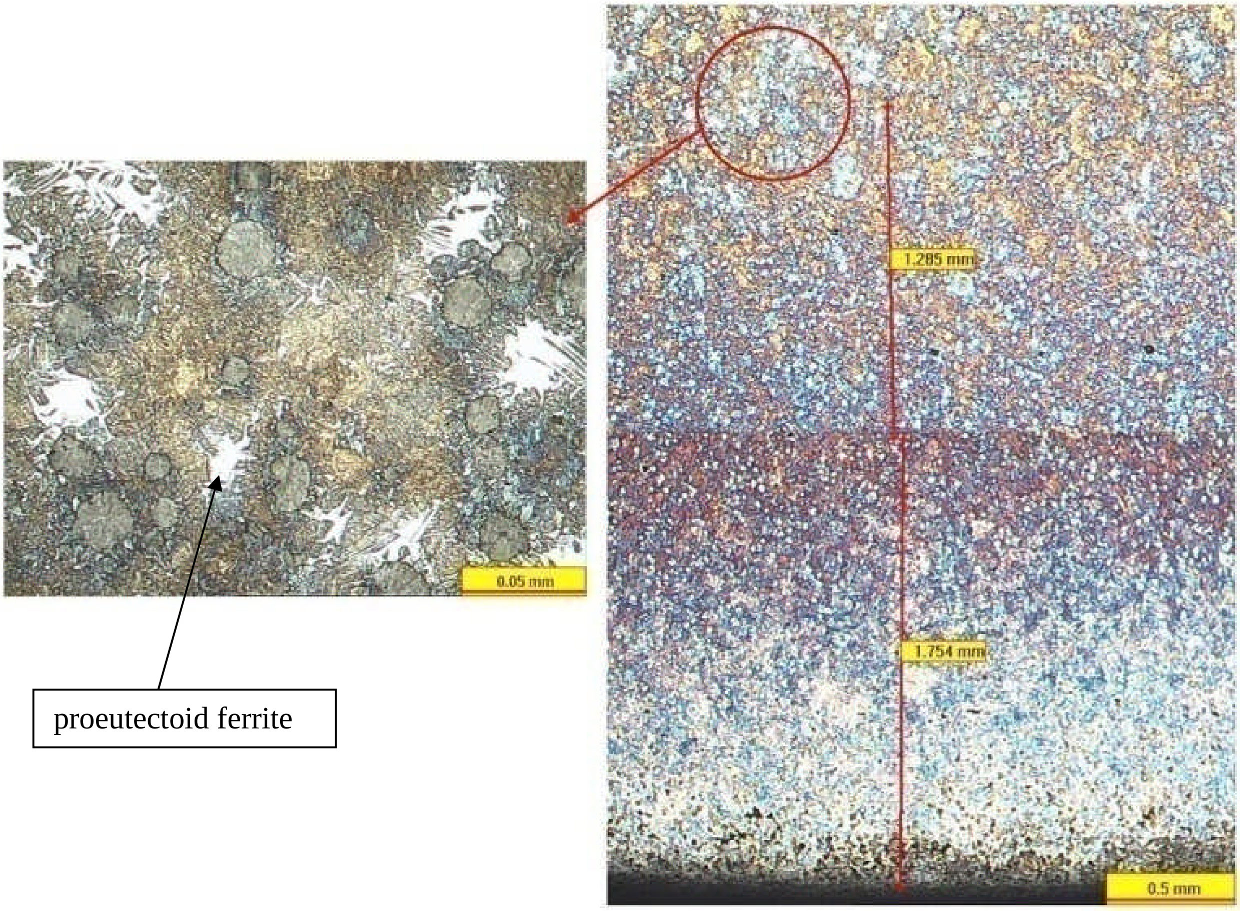


Figure 8: Photomicrographs that illustrate the measurement of the LADI layer. In this example, the LADI layer is approximately 3 mm. The photomicrograph from the circled region shows the matrix that includes the first appreciable amount of proeutectoid ferrite.

X-RAY DIFFRACTION (XRD) RESULTS

Examination of the XRD scans revealed the presence of ferrite, austenite and trace amounts of carbide. These results are consistent with those for ausferrite that is produced at low Austempering temperatures. [2]

If martensite is present in ADI, it appears as an asymmetry (a bump on the curve) on the low angle side of the ferrite (110) peak. Figure 9 shows the range of the XRD scan that includes both the austenite (111) and ferrite (110) peaks. The peaks are located in close proximity to each other so some overlap occurs. However, no prominent asymmetry is visible on the low angle side of the ferrite peak, which suggests an absence of any measurable amount of martensite.

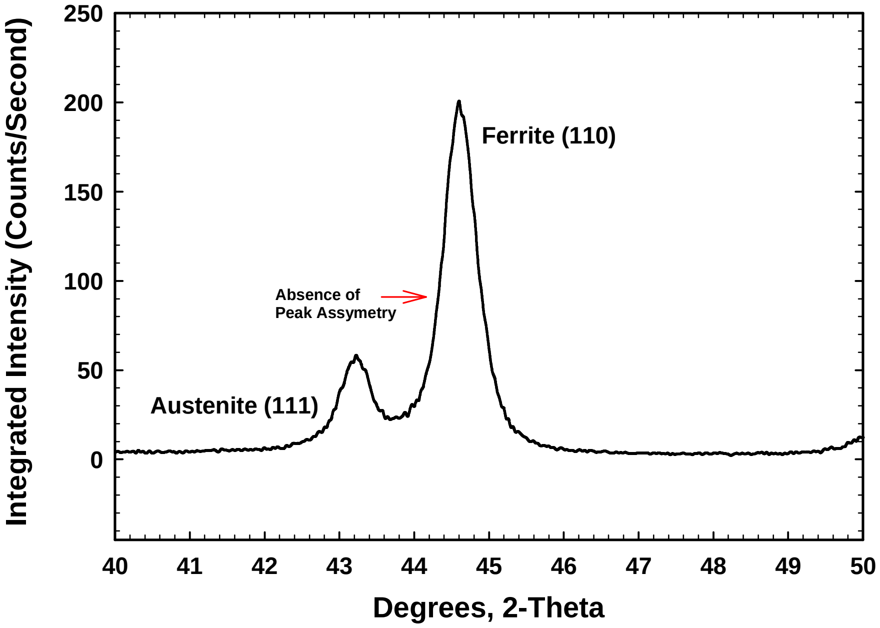


Figure 9: Results from an XRD scan that contain the ferrite (110) and austenite (111) peaks. Note the absence of martensite due to no apparent ferrite (110) peak asymmetry.

The relative amounts of ferrite and austenite were calculated using the assumption that they were the only two phases present. Results of the calculations showed an austenite volume of 22.3% and a ferrite volume of 77.7%. While small peaks were identified in locations that correspond to iron carbides, they were so small that their overall contribution to the matrix microstructure was considered to be negligible. Further details of how such calculations can be made are found in references 3 and 4.

HARDNESS PROFILES

The LADI process was designed to achieve the properties of an ASTM A897/A897M-06 Grade 1600-1300-01 ADI in the surface layer of a camshaft. Since tensile or impact bars could not be machined from the surface layer, hardness measurements were made. The typical hardness range for GR 1600 ADI is 402 – 512 HBW or 43 – 52 HRC.

Results from the hardness traverse depicted in Figure 10 show a hardness range of 50 to 54 HRC or 485 to 544 HBW across the LADI surface layer. (Results were converted from Knoop hardness measurements.) Note that soft readings due to indenter contact with graphite nodules were discarded. The results in Figure 10 demonstrate that 50 HRC was achieved to a depth of 1.8 mm from the machined nose of the camshaft.

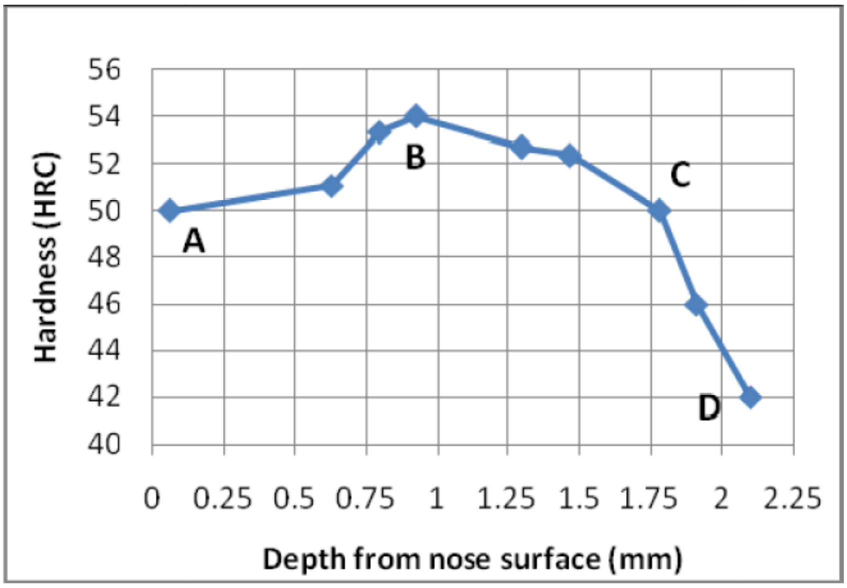
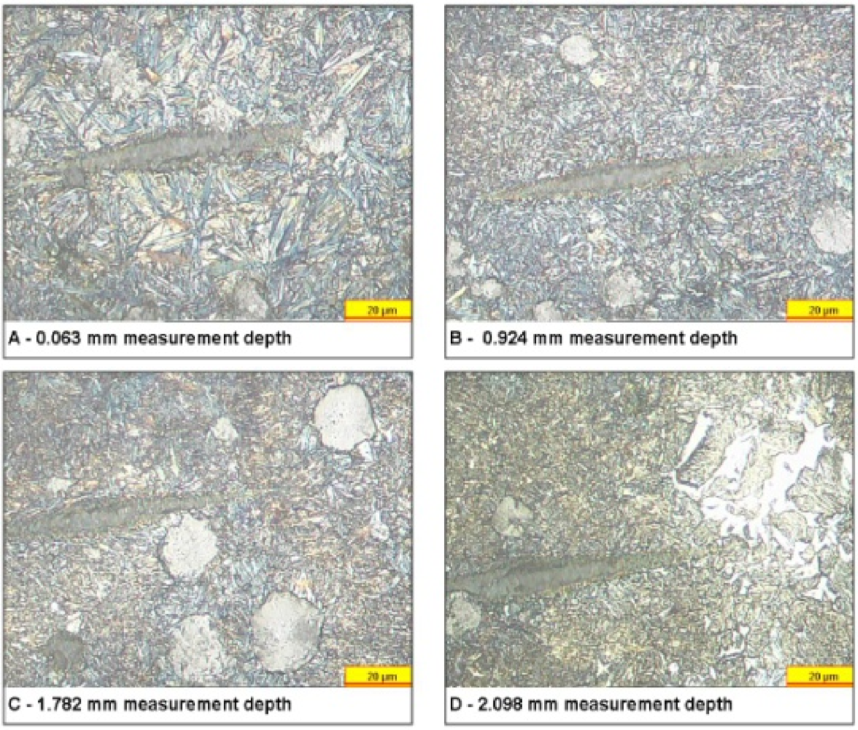


Figure 10: Hardness traverse results. Letters indicate the locations of photomicrographs pictured in Figure 11.

The variation in hardness values in Figure 10 can be explained by microstructural differences across the heat treated zone (See Figures 11A-D). A coarse ausferrite is observed adjacent to the surface (Figure 11A) followed by a finer scale ausferrite (Figure 11B) and then finer scale ausferrite with increasing amounts of proeutectoid ferrite present (Figures 11C and D).



A - 0.063 mm measurement depth

B - 0.924 mm measurement depth

C - 1.782 mm measurement depth

D - 2.098 mm measurement depth

Figure 11: Photomicrographs from corresponding points labeled in Figure 10.

When the surface of an ADI component is deformed, the reacted austenite within the ausferrite will undergo a strain transform to martensite; resulting in a localized increase in hardness at the surface. The depth of this transformed layer has been shown by others to be on the order of 0.006 mm. [5] Post heat treatment processing such as grinding or polishing will cause this hardened surface layer to form. Furthermore, as the hardened layer is worn away during normal operation, the pressures of the roller lifter should generate a new hardened layer. This self generating wear surface will allow LADI to have wear properties comparable to quench and tempered steel at 60 HRC.

BENCH TESTING RESULTS

Bench testing of LADI camshaft lobes was completed per the test parameters listed in Table 2. The high spring pressure loads utilized for this bench test caused the hydraulic roller lifters to degrade every 30 hours. As a result, the roller lifters were changed at each 24 hour wear check in order to maintain test integrity.

Calculations provided by the OEM suggest that a 3400 N (764 lbf) load applied to the camshaft lobe would produce an 1850 MPa (268 kpsi) contact stress at the surface. Actual test parameters were 3447 N (775 lbf) implying that the tested lobes withstood a contact stress greater than 1850 MPa.

At the completion of bench testing, only minor scuffing marks were observed on the lobe surfaces. No signs of appreciable wear were noted.

IMPLICATIONS FROM THIS STUDY

MACHINING

While the LADI process will be applied to the lobes, the remainder of the camshaft will be ferritic ductile iron. This should increase the machining tool life in the unprocessed areas over comparable materials such as pearlitic ductile iron or quench and tempered steel. The austempered lobes of the camshaft can be ground and polished to final tolerances after heat treatment. In addition, grinding and polishing after heat treatment should induce a high normal force to initiate the strain transformation of austenite to martensite as previously described.

APPLICATIONS OF LADI TECHNOLOGY

The LADI process was initially designed for use as a camshaft material. During evaluation, other applications were discussed. Those could include:

- Ground engaging equipment
- Wear surfaces
- Gears
- Powertrain components
- Railroad components

SUMMARY/CONCLUSIONS

The LADI project was undertaken to produce a better, lower-cost method of producing a locally hardened ADI component. The results of this program indicate:

The use of fully ferritic ductile iron (65-45-12 or 450-12) as a base material allows the foundry to decrease initial alloy requirements. This reduces the cost of the raw casting.

Fully ferritic ductile iron machines better than free-machining (re-sulfurized) steel or other grades of ductile iron implying cost savings in product machining.

Full machining capabilities after heat treatment are possible when using the LADI process.

Fully machining a component (like a camshaft) after heat treatment reduces steps in the manufacturing process. This should remove the need for an initial stop at the machine shop for rough machining.

Bench testing of the LADI camshaft lobes proved that the process can produce a very robust wear surface that will compare favorably with current, commercially available processes and, perhaps, even with carburized and hardened steel in allowable contact stress.

LADI appears to be a viable process for producing components with localized areas of ADI.

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DEFINITIONS/ABBREVIATIONS

ADI - Austempered Ductile Iron

AP - Applied Process, Inc.

ATM - Ajax Tocco Magnethermic Corporation.

Ausferrite - A cast iron matrix microstructure, produced by a controlled thermal process, which consists of predominantly acicular ferrite and high carbon austenite.

LADI - Locally Austempered Ductile Iron

TKW - ThyssenKrupp Waupaca, Inc.

XRD - X-ray Diffraction