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Crankshaft Failure and Why It May Happen Again

D.A. Moore, K.F. Packer, A.J. Jones, and D.M. Carlson

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This case study involves two continuously cast steel crankshaft failures. Three parties performed their own failure analyses: (1) the engine manufacturer responsible for component design, specification, and application; (2) the steel supplier and forging supplier responsible for making the steel, forging the shape, and preliminary heat treatment; and (3) a supplier that provided induction hardening, finish machining, and inspection. An independent fourth party engineering firm was subsequently involved, but because each party had their own agenda, there was no agreement on the metallurgical failure cause and therefore no continued analysis to pin-down and eliminate the root cause. A classic case showing how we may be doomed to repeat our failures because sound engineering was not allowed to proceed.

Keywords: crankshaft, continuous cast steel, segregation, woody fracture, MnS inclusions, fatigue, induction hardening

Failure analysis has long been a special field of study for metallurgical and materials engineers. Much of what a metallurgical engineer is taught is intended to develop his observational and reasoning skills so that he or she may understand the interrelationship between observable features and properties or performance. To many, the process of a metallurgical failure analysis is almost an art form since so much of the analysis may be based on the ability of the analyst to identify and recognize important features. The myth that failure analysis is an art rather than a science is seemingly supported when two failure analysts come up with differing conclusions about the same event.

Twenty-five years ago, the first paragraph of the text *Analysis of Metallurgical Failures* stated, "The primary reasons for conducting an analysis of a metallurgical failure are to determine and describe the factors responsible for the failure of the component or structure. This determination may be motivated by either sound engineering practice or by legal considerations."[1]

The first sentence of that paragraph very correctly states that the reason is to determine the *factors responsible for the failure*, but unfortunately the metallurgical engineer doesn't always have access to the information necessary to assess all the factors that may contribute to the failure. Additionally, the engineer may not have the knowledge and resources to analyze all the potential factors. This is particularly true for an independent heat treat supplier, but can also be true for captive heat treaters. So instead of performing a complete failure analysis to determine the factors responsible for failure, the engineer may simply determine if the material met the customer's specifications.

This approach has become even more understandable if you consider the current business environment where lawyers and insurance companies are involved at the slightest hint of a problem. In a perfect world, the second sentence of the aforementioned quote would not be true, but it is too often the case that the driving force behind a failure analysis is legal considerations instead of sound engineering practice. In the 25 years that have passed since that text was printed, it appears that finding out who is to blame for a failure has become more prevalent than sound engineering practice.

Even in cases where there is no adversarial, blaming environment looming over the analysis, it is important to remember that a metallurgical failure analysis is in many cases not enough to determine the root causes of a failure. The stages of a failure analysis as outlined in the *Metals Handbook*[2] are:

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- Collection of background data and selection of samples
- Preliminary examination of the failed part
- Nondestructive testing
- Mechanical testing
- Selection, identification, preservation, and/or cleaning of all specimens
- Macroscopic examination and analysis
- Microscopic examination and analysis
- Selection and preparation of metallographic sections
- Examination and analysis of metallographic sections
- Determination of failure mechanism
- Chemical analysis
- Analysis of fracture mechanics
- Testing under simulated service conditions
- Analysis of all the evidence, formulation of conclusions, and writing the report

Although following these steps will provide information to help determine the contributing factors in a failure, it is not comprehensive enough to address all the possible root causes. Depending on the complexity of the failed component or system, one must also consider evaluation of factors relating to the mechanical design, manufacturing processes, quality control, product evaluation, and application. Out of these areas can come critical knowledge, information, and abilities relating to such things as competitive intelligence, standards and regulations, stress analysis, process control, environmental effects, instructions and warnings, human factors, and others that are not always considered in a metallurgical failure analysis. Relegating issues like these to the "collection of background data" category is treating these other possible factors too lightly.

The key to a successful root cause failure analysis is to consider all these factors and their impact on the cause or causes of failure. Ideally, a team would work together to evaluate and analyze the critical factors in a non-threatening atmosphere of mutual trust and cooperation. This team would naturally also involve those with abilities to make change for the prevention of future failures. Practical considerations in today's world make this ideal difficult to achieve, but it is still incumbent upon the failure analyst to draw upon expertise and information from other scientific and engineering disciplines to perform a complete root cause failure analysis with recommendations for further failure prevention. A comprehensive failure analysis that goes beyond the metallurgical analysis more often results in a win-win situation for all the parties involved because everyone benefits from the knowledge and understanding gained through the process. Without a broad approach, all causal factors may not be properly addressed, and the result is often only partial understanding and placing blame.

The following case study involves an engine manufacturer responsible for the component design, specifications, and application; a steel supplier and forging supplier responsible for making the steel, forging the shape, and preliminary heat treatment; and a supplier that provided induction hardening, finish machining, and inspection. The information in the case study is based on an actual failure analysis, with names and certain facts omitted to protect the anonymity of the parties involved.

It is important to note that all three parties performed their own individual failure analyses prior to having this study performed. In simple terms, the engine manufacturer and induction hardening supplier concluded that the cause of the failure was defective steel, while the steel supplier and forging supplier believed that poor induction hardening caused the failure. Each party agreed to have an independent source analyze the failure to break the stalemate, but unfortunately not all the parties were willing to accept and act on the outcome.

What you will see in this case study is that a thorough metallurgical analysis was not able to definitively determine the root causes of failure, but could merely point to areas that needed to be addressed and studied by the parties responsible for the component. Unfortunately, the true problems were never solved because of the unwillingness of the parties to cooperate together with sound engineering in support of the metallurgical failure analysis.

Case Study

(This information is based on an actual failure analysis, with names and certain facts omitted to protect the anonymity of the parties involved.)

An engine manufacturer experienced two similar in-service crankshaft failures on separate engines (referred to as crank #1 and crank #2). Crank #1 completely fractured at the second pin journal, resulting in catastrophic failure of the engine. Crank #2 was also cracking through the second pin journal, but was caught before the crankshaft completely fractured. Each engine had been operating for only a relatively short time, and the engines were in totally different service environments.

The crankshaft was made from a proprietary alloy steel, similar to a modified SAE 1548 alloy. The steel was continuously cast by one supplier, hot forged, then austenized, quenched and tempered by a second supplier. A third supplier machined the journals, induction hardened and tempered the journal surfaces, finish machined, and balanced the crankshaft. The end product was to have a core hardness of 241-285 BHN and a surface hardness of 47-52 HRC to 2-5 mm depth.

Fig. 1 *Sectioned #2 pin journal from Crank #1*

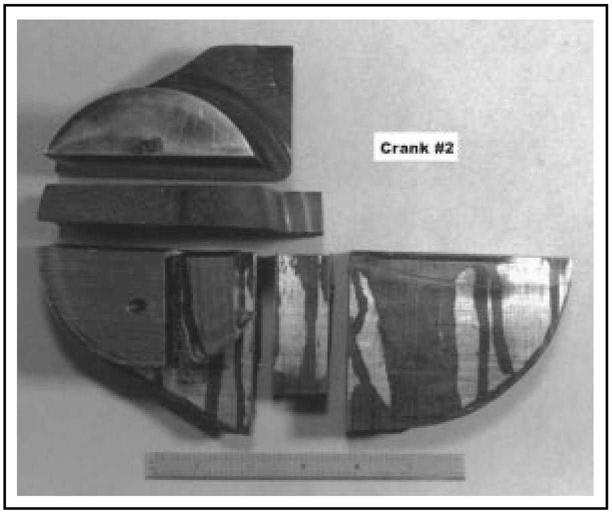

Fig. 2 *Sectioned #2 pin journal from Crank #2*

External Examination

When samples of the failed crankshafts were eventually received for independent analysis, evaluations had already been separately performed by the engine manufacturer and the suppliers. The #2 pin journals from both crankshafts had already been extensively sectioned prior to delivery to Packer Engineering. Some pieces had already been mounted for metallographic examination (Fig. 1 and 2).

Crank #1 exhibited cracking on the journal surface that is longitudinally oriented near the middle of the surface, becoming diagonal and then circumferential near each end of the journal. Circumferential abrasive wear patterns were present over the entire journal surface, with more severe areas located along the center and near an area of spalling along the cracks (Fig. 3). Several areas on the surface exhibited small, longitudinally oriented heat check cracks, particularly aligned with the wear near the area of spalling.

Crank #2 exhibited similar cracking patterns, although the cracking had not progressed as extensively around the pin journal circumference. The degree of abrasive wear was somewhat less than that observed on crank #1. A small amount of chipping was observed along the crack edges, but no large spalled area was observed as found on crank #1.

The remaining pin journals and main journals on both crankshafts did not contain cracks or evidence

Fig. 3 *Severe wear and spalling near the center journal surface on Crank #1*

of abnormal abrasive wear. Magnetic particle and contact ultrasound inspection of the remaining pin and main journals did not uncover further cracking or indications.

Examination of the connecting rod bearings from crank #1, pin #2 showed that substantial abrasive wear and heat had affected the bearings causing them to mushroom, craze crack, and generally deteriorate. Abrasive wear was present on both sides indicating the bearings were spinning within the connecting rod end. In one set of bearings, a very deep groove was worn through part of the bearing presumably from a trapped piece(s) of the fractured pin journal (Fig. 4 and 5).

Substantial bearing wear and damage was also observed in the connecting rod bearings from pin #2 on crank #2. These bearings also appeared to have been spinning within the connecting rod end. The remaining bearings from crank #2 were in good condition with no signs of poor lubrication or spinning within the connecting rods.

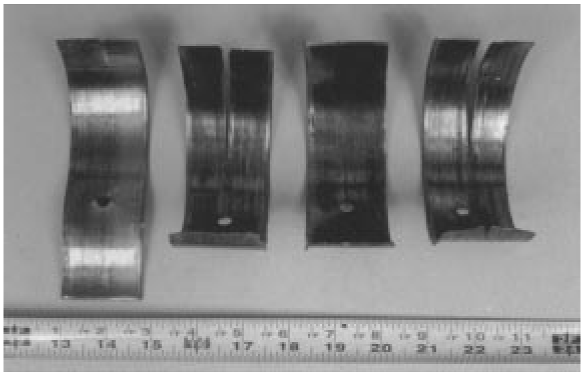

Fig. 4 *Connecting rod bearings from Crank #1, pin #2*

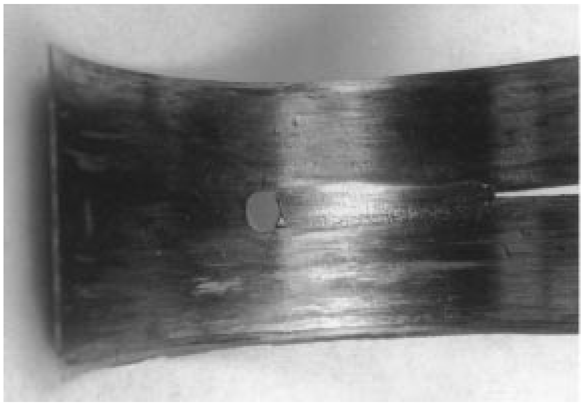

Fig. 5 *Connecting rod bearing from Crank #2, pin #2*

Fracture Examination

Both #2 pins were intentionally broken open to reveal the fracture surface features associated with the cracking.

Both #2 pins exhibited large, woody textured fracture planes oriented perpendicular to the plane between 12 and 6 o'clock on the pin (Fig. 6 and 7).

This fracture plane is about 2 ½ in. from the 12 o'clock position. Near the center of this woody plane, the fracture has a smoother and flatter appearance. Oblique lighting on the woody fracture area from crank #1 shows patterns in this smooth region indicating progression outward (Fig. 8). Woody texture is present along this plane, but does not progress out through the induction hardened layer to the surface. Crank #2 exhibits similar features though less obvious due to surface oxidation.

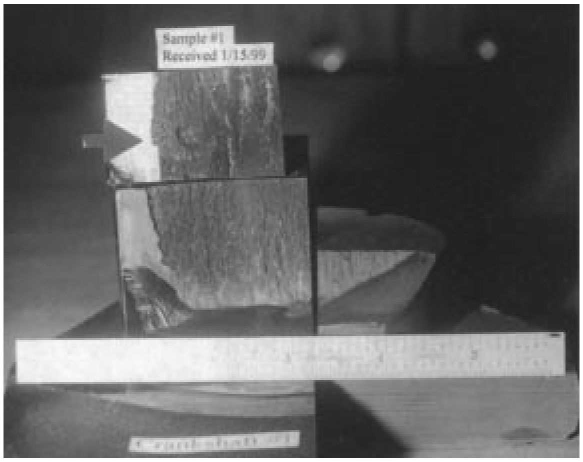

Fig. 6 *Woody textured fracture on Crank #1, pin #2*

Fig. 7 *Woody textured fracture on Crank #2, pin #2*

The woody textured fracture was covered with a black substance that prohibited identification of any fine fracture features. Some areas of woody textured fracture were damaged by cleaning and/or etching, so high magnification examination was unsuccessful. EDS analysis of areas on the woody fracture revealed the black layer contained many elements commonly found in oil additives (S, Zn, Ca, Si, P, Mg), so it was presumed that most of the black substance was oil residue.

At the edges of the woody textured fracture plane, fatigue fracture planes were observed with striations and river patterns that indicated progression outwards to the journal surface (Fig. 9).

Additionally, larger fatigue fracture surfaces were observed that originated from the edge of the woody textured region and propagated diagonally and circumferentially through the journal (Fig. 10 and 11). River patterns and beach markings on these larger fatigue fracture surfaces indicate that the crack front was altered by intersection with the induction hardened case and the center of the woody fracture. In these areas, the crack front was slowed and was essentially turned so that the crack progressed in a radial fashion through the induction hardened case.

The largest fatigue fracture areas on both crankshafts were bounded by the woody textured zone and did not propagate across the woody fracture. The woody textured fracture extends beyond the larger, diagonal/circumferential oriented fatigue fracture planes. The shape of the fatigue beach markings near the woody texture surface indicates that the woody textured surface was a free surface when the fatigue fracture was formed. One area on crank #2 exhibited fatigue cracking that intersected the woody textured region near the oil hole, but the woody texture was not altered by the presence of the fatigue crack (Fig. 12), suggesting the woody textured fracture preceded the fatigue crack.

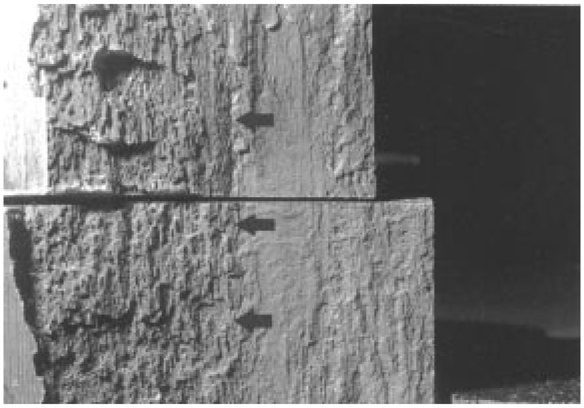

Fig. 8 *Woody textured fracture on Crank #1*

Fig. 9 *Fatigue crack progression outwards from the woody texture of fracture towards the journal surface*

Fig. 10 *Diagonal/circumferential fatigue fracture adjacent to the woody textured fracture*

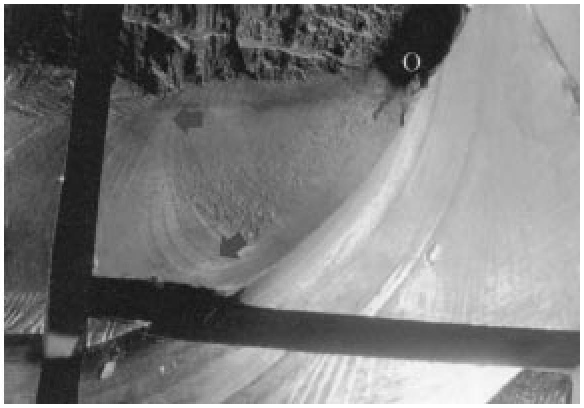

Fig. 11 *Diagonal/circumferential fatigue fracture adjacent to the woody textured fracture*

Careful examination of the oil hole present in crank #2 showed that longitudinal tool markings were present, some of which were altered at their intersection with the woody textured fracture plane (Fig. 12 and 13), suggesting the woody fracture was present when the hole was made. A similar area in crank #1 was not observed because that section of the woody textured fracture was not provided.

Microstructure Examination

Transverse sections through the #2 pin revealed that the core microstructure was primarily pearlite and ferrite, except along the central, smoother portion of the woody textured fracture region. In this area, bands of fine tempered martensite were observed surrounding a higher concentration of MnS inclusions and stringers (Fig. 14). Microhardness measurements confirmed that these microstructural bands exhibited higher hardness (as high as 37 HRC) than the surrounding core (20 to 30 HRC).

Sections through the woody textured fracture also showed secondary cracking and tearing that is roughly parallel to the woody textured fracture surface. Aligned MnS inclusions surrounded by thin bands of martensitic structure can also be observed parallel to and beneath the woody fracture (Fig. 15).

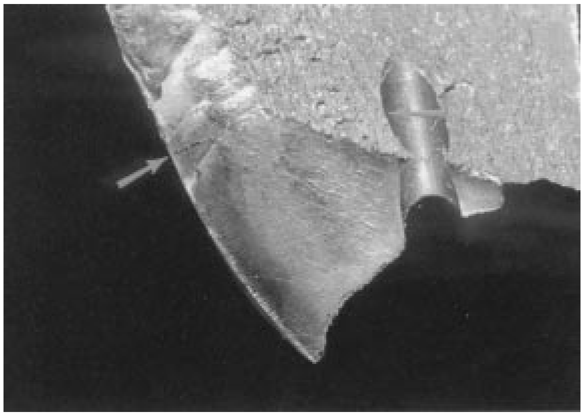

Fig. 12 *Fatigue crack that intersected the woody fracture*

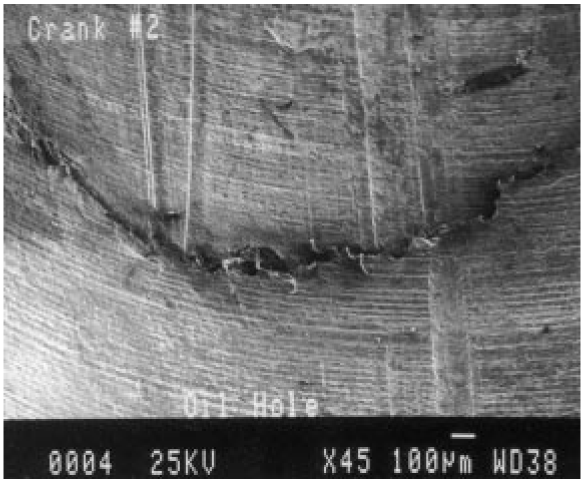

Fig. 13 *A drilled hole with tool marking that was altered by the woody textured fracture plane*

Fig. 14 *A band of martensite found at the woody textured fracture edge*

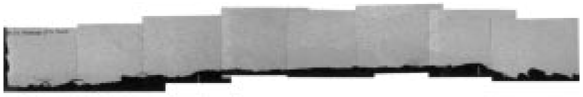

Fig. 15 *Microstructure at the woody fracture surface exhibiting MnS inclusions, bands of martensite, and secondary cracking*

Fig. 16 *Cracking, deformation, and a white hardened layer at the journal surface of Crank #1*

At the location of spalling in crank #1, a high concentration of MnS inclusions and some oxides were observed just beneath the surface of the journal.

At various locations around the journal surface, the induction hardened layer exhibited variations in microstructure. In areas near the spalling on crank #1, cracking, deformation, and a white hardened layer were observed at the journal surface indicating frictional heating (Fig. 16).

Other areas exhibited similar signs of friction damage, although not as pronounced. The most severely damaged areas exhibited a 1 to 2 mm thick layer of transformed structure at the surface with tempered martensite beneath (Fig. 17, 18, 19, and 20). Hardness measurements reflect the changes in microstructure with the white layer being as hard as 66 HRC, and the layers beneath having hardness variations from 25 to 40 HRC. Areas exhibiting tempered martensite can be found with hardness in the 47 to 52 HRC required range.

Some areas of the pin #2 journals on both cranks, however, exhibited rather uniform microstructures in the induction hardened zone of ferrite and pearlite, with some bainite. These microstructures were found throughout the induction layer, and there was no distinct line of demarcation between that structure and the underlying core microstructure. Hardness in these areas was typically 25 to 40 HRC depending on the area.

Longitudinal sections through pin #2 on both crankshafts show the woody fracture extends beyond the journal, following the forging grain flow. The longitudinal section also shows the microstructural variation at the radius edge of the pin #2 surface. At

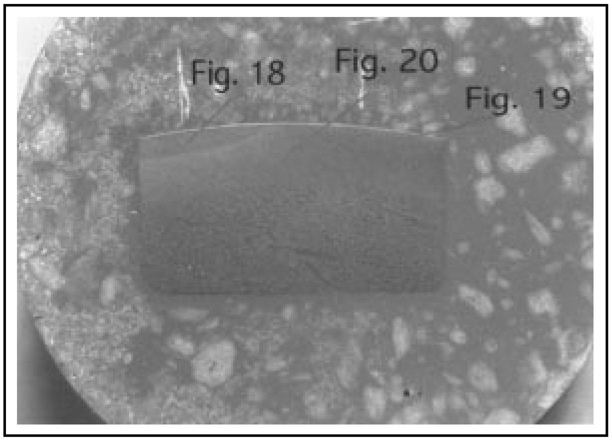

Fig. 17 *Macro view of metallographic cross section through the journal surface*

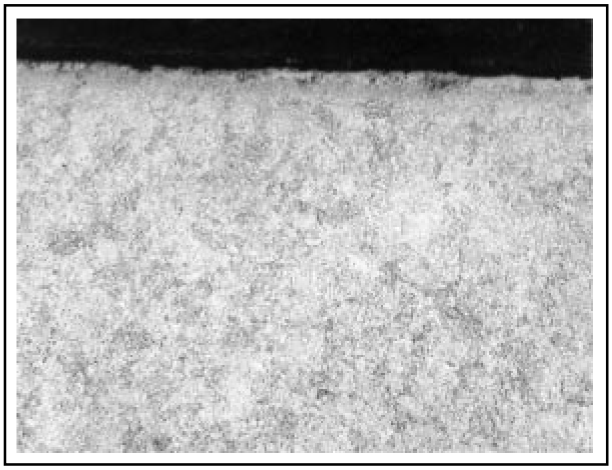

Fig. 19 *Surface away from severe friction damage*

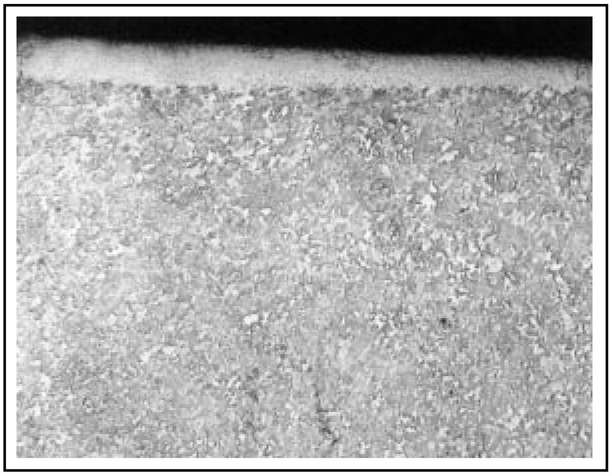

Fig. 18 *Frictional heating at surface*

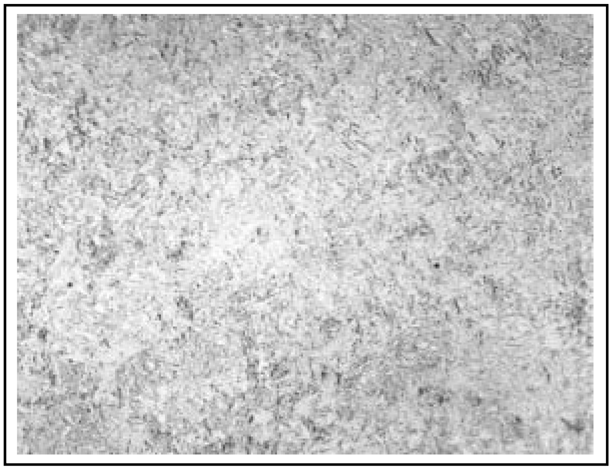

Fig. 20 *Microstructure just below surface layer*

the journal surface, the microstructure is primarily ferrite and pearlite with some very thin surface white layer present. Around the radius, just off the journal surface and on the cheek, there is tempered martensite with hardness levels near 50 HRC.

A macro-etched transverse section through crank #1 and crank #2 showed a distinctly recognizable area of non-uniform induction case. The macro-etched pattern is similarly oriented on both cranks, although the effects are more pronounced in crank #1.

Transverse sections through the #1, #3, and #5 pins from crank #1 revealed that each had uniform, tempered martensite induction layers with hardness of about 50 HRC at the surface. The core microstructures were primarily ferrite and pearlite, but bands of tempered martensite and MnS inclusions were observed similar to that observed in fractured #2 pins (Fig. 21). The location of this microstructural feature was near the surface in pin #1, and nearer the center of the core in pin #5 (Fig. 22). Similar to the bands in crank #2, the bands found in other pins also exhibited higher hardness than the surrounding core.

Chemical Analysis

EDS analyses was performed in several areas on fracture surfaces, as well as within the secondary cracks and metal near the fractures. On the fractures, manganese sulfides, iron oxides, and elements such as calcium, phosphorous, magnesium, silicon, and zinc were detected. Some of these elements are known oil additives. It should be noted that the condition of the present artifacts indicate some oxides present, apparently from chemical attack (cleaning, etching) after failure.

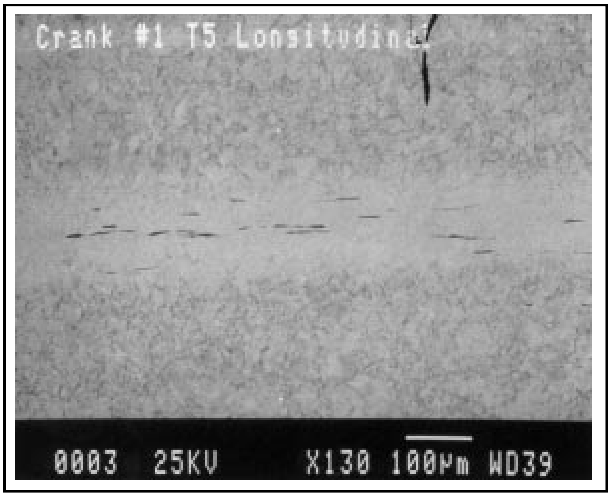

Fig. 21 SEM backscatter electron image of MnS inclusions surrounded by tempered martensite in Crank #1, pin #5

The steel supplier showed using high resolution Wavelength Dispersive Microanalysis (WDS) that the carbon level in the matrix surrounding the sulfide inclusions was as high as 0.7% in an area examined on crank #1, pin #1. They did not examine the fractured area using this method. The engine manufacturer analyzed a segregated area in a non-fractured spot using a Leco Glow Discharge Spectrograph (LECO Corporation, St. Joseph, MI) and found carbon levels as high as 1%, although the accuracy of this method is questionable because the equipment was reportedly not calibrated at that high carbon level.

Discussion

Several items observed in this evaluation demonstrate the woody fracture to be the initial area of fracture and that it was formed at a region of microstructural segregation. This woody fracture was followed by fatigue crack origination and propagation during service.

1. Patterns on the smooth section near the center of the woody fracture indicate an outward direction of crack growth.
2. At the edges of the woody fracture, numerous fatigue crack planes originate and propagate away from the woody surface.
3. The larger fatigue fractures intersect with the plane of the woody fracture, but do not cross the

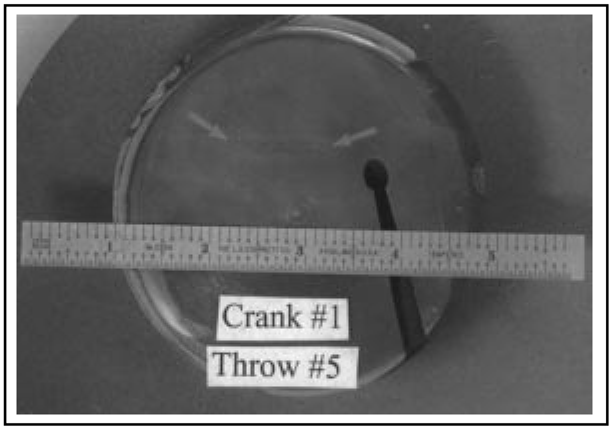

Fig. 22 Macro-etched cross section through Crank #1, pin #5

woody fracture and do not cause the woody fracture to change texture or direction.

4. Beach markings and river patterns on the fatigue fractures show that the woody fracture plane was a free surface when the fatigue fracture formed.

5. Tool withdrawal markings observed in the oil hole in crank #2 were altered at the intersection with the woody fracture, showing it was present during drilling of the hole, prior to service.

6. The non-uniform pattern of induction hardening observed was limited to pin #2 in both crankshafts and may be due to bearing damage; otherwise the induction currents, temperatures, and resulting microstructures could have been influenced by the presence of the open axial crack that was present during induction hardening.

The nature of the woody fracture region and the tool marks seen in the crank #2 oil hole indicate the flaw was of a kind that could have been detected during machining and heat treating subsequent to forging and prior to service.

The woody fracture coincides with microstructural segregation, particularly at the center where there are higher concentrations of sulfides surrounded by a higher carbon matrix. These higher carbon regions have higher hardenability than the surrounding core and therefore transformed into martensite during the quench after austenitizing while the surrounding core formed ferrite and pearlite. This is centerline casting segregation where the location, direction, and nature of the segregation is further altered by the metal flow and distribution during forging.

The steel supplier has claimed that this microstructural segregation containing a high carbon matrix and sulfides is typical of continuous cast material they supply. Others think that the centerline segregation in both crankshafts is greater than that which might be acceptable in commercial quality steel. Furthermore, the nature of the segregation noted can be expected to increase the susceptibility of the steel to forging anomalies detrimental to the life of the crank shafts in service. This is particularly true if the steel is heated to temperatures approaching the formation of delta ferrite and under some conditions of metal flow during pressing.

Manganese steels like an SAE 1548 steel have a greater tendency to form areas of sulfide and microstructural segregation. This is due to the high carbon levels and presence of additional manganese to boost the hardenability of the steel. Current steels with less susceptibility to this segregation are available.

There are local areas on both crankshafts that experienced enough friction and heat from journal and bearing damage to cause hard, white layers to form at the surface, and to temper the underlying case microstructure. In some areas, though, the case microstructure exhibits ferrite grains that appear similar to the ferrite grains in the nearby core microstructure. These areas also do not exhibit large surface damage, white layer formation, or distinct transition between the core and case microstructure. It appears that these areas of the case were not completely austenitized during the induction hardening process. Both the induction hardening supplier and engine manufacturer suggest that the microstructures indicate the case has been transformed due to the temperature experienced during the failure. Clearly, some distinct areas experienced severe frictional heating, but the prevalence of ferrite in the case microstructure in areas that do not show other signs of severe heating supports the conclusion that not all the case was thoroughly heated for induction hardening.

Because this case microstructural variation was only observed in pin #2 and not in any other pins that experience the same induction hardening process, it seems unlikely that the induction hardening process itself is the cause of the microstructures seen. It is more likely that something unique is happening at pin #2 either in process or in service. It appears that the induction currents and resulting microstructure were influenced by the presence of an open axial crack that was present during induction hardening, thus causing variations in the induction currents and temperature profiles at certain portions of the journal surface.

Regardless of the cause of induction hardened case microstructure variations, they are not a cause of this failure. Even with a soft case, in a crankshaft free of internal flaws one would still expect a bending or torsional fatigue crack to initiate at the pin surface, radius, or at the surface of an oil hole. A crankshaft fracture like that observed in this investigation has not been seen before by any of the parties involved in analyzing this failure.

Conclusions

1. Fracture initiated in a segregated region near the neutral bending axis of pin #2 and produced a woody fracture plane perpendicular to the direction of imposed piston loading. This woody fracture existed prior to machining and induction hardening. The woody fracture location, orientation, and size is similar in both crankshafts.

2. The large woody fracture region was produced by stresses that acted in a cross planar direction as evidenced by the orientation of secondary cracking.

3. The woody fracture pre-existed final machining and heat treatment, as evidenced by the disruption of tool withdrawal markings in the oil hole on crank #2. (A similar determination was not possible on crank #1 because the material containing the oil hole and woody fracture intersection was not available.)

4. Regions of segregated material, including MnS inclusions and higher carbon, tempered martensite bands, existed throughout the crankshaft with some segregated areas extending to or near the journal surface.

5. Cracking continued from the edges of the woody fracture plane through the hardened case to the journal surface in service by low cycle fatigue.

6. Fatigue propagation was by combined bending and torsional stresses. The actual level of these stresses as compared to design or expected stress levels in this engine is unknown.

7. When the fracture reached the bearing interface, spalling and localized seizure caused bearing failure and engine outage. Lubrication conditions appeared nominal as evidenced by bearing, piston, and oil examination.

Final Thoughts

Although much good work was done in this case study, and many good conclusions were drawn, none of these conclusions definitively determine the true causes of failure in such a manner that the source of the problem could be identified and addressed. This would require the input of each of the parties who should be the real experts in their own processes. For example, the steel and forging suppliers could begin constructive work to isolate the reasons behind the fracture initiation location at the center of pin #2. The induction hardening and final machining supplier could analyze their inspection practices to determine if they are able to detect such flaws in the crankshaft. The engine manufacturer could analyze the possibility of selecting a more forgiving steel chemistry and could develop a program of condition monitoring to assess the performance of their product in service.

The parties in this case study performed their own metallurgical analysis without knowing all the facts, and their conclusions had a sense of bias and protection of their own position. This approach is similar to the behavior of a lawyer protecting his client – not an engineer or scientist in search of the truth. It will only lead to a loss of trust, confidence, and competitive position and prevent true understanding of the root causes of failure.

The scenario played out in this case study is too often true in the everyday process of metallurgical failure analysis. Some customers and suppliers give no thought to what is really necessary to determine the root causes of failure, and they wrongly assume that the metallurgical failure analysis performed in a virtual vacuum should answer all those questions.

The metallurgical engineer, being a source of metallurgical engineering knowledge and also an important part of the component processing chain, often finds himself in the middle of these types of scenarios. In the interest of sound engineering practice and with a sense of obligation to the communities we serve, failure analysis would be done without a thought about who's to blame, and a metallurgical failure analysis would not always be relied upon as the sole source of information from which to draw conclusions about the root causes of a failure.

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