A Failure Analysis Conducted on a Fractured AISI 5160 Steel Blade Which Separated from an Agricultural Rotary Cutter.

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Abstract. One of the six blades of an agricultural rotary cutter used for cutting down small trees and bushes broke into two pieces while the blades were rotating. One piece was hurled from the cutter and struck a young farmer, who had been operating the machine, causing a near fatal leg injury.

In the ensuing litigation against the manufacturers and marketer of the machine each litigant retained a metallurgist and other experts. The metallurgists jointly directed laboratory work on the broken blade conducted at an independent laboratory according to a protocol which they developed and which was approved by the court.

As a result of the laboratory work the present authors, working for the Plaintiffs, concluded that failure of the blade occurred because it contained quench cracks introduced when it was manufactured. The Defendants’ metallurgists concluded that the blade had been misassembled onto the machine and, as a result, had failed by fatigue. Eventually, the case was set for a jury trial in a Circuit Court in rural Kentucky. The jury found for the Plaintiffs and awarded them $5.9 million in damages. Part of this judgement was later reversed by the Kentucky Court of Appeals and the case was then settled without a second trial under terms which were not revealed.

1. Introduction
On July 5th, 2002, a young farmer working on his farm in Adair County, Kentucky, was operating a piece of machinery known as a “Bush Hog” which is used to cut down bushes and small trees. He stepped off the machine leaving its engine running and the blades engaged and, at that moment, one of the machine’s six blades broke at the bolt hole where it was secured to the machine. The main length of the blade flew off the machine and struck the farmer causing a near fatal leg injury. The farmer and his wife filed suit against corporations involved in the manufacture and marketing of the machine. The suit was filed in Adair County Circuit Court [1].

The Plaintiff’s counsel retained the present authors as potential expert witnesses. The Defendant corporations each hired a metallurgist, or designated a staff metallurgist, to act as expert witnesses for
them. As is common in product liability cases in the United States, the metallurgists jointly drew up a protocol for work that needed to be carried out in conducting a failure analysis. They then agreed on an independent laboratory which would carry out this work but not be permitted to interpret it. The laboratory selected for this purpose was IMR Metallurgical Services of Louisville, Kentucky. The protocol was approved by the court and executed. It involved photographic documentation, dimensional measurements, quantitative spectrographic and combustion analysis, stereo-optical microscopy, scanning electron microscopy, metallography and microhardness measurements.

2. Examination of the Broken Blade

Because the blade broke at its bolt hole, one end of it remained in the machine and was removed after the accident. The two pieces are shown together in Figure (1). The overall length of the blade was found to be 62.2 cm, its width 10.2 cm and its thickness 1.1 cm. The bolt hole was found to have a diameter of 4.1 cm.

A chemical analysis was carried out on a specimen cut from a location away from the fracture. Combustion analysis was used for carbon and quantitative spectroscopy for all other elements. The results, which are shown in Table 1, show that the steel from which the blade was made comes close to meeting the AISI/SAE 5160 specification. That is, it is a low chromium steel with nominally 0.60 wt% carbon. The silicon content is slightly too high to meet the specification and the copper, nickel, niobium and molybdenum are not part of the specification. They probably were incorporated into the steel through the addition of scrap steel to the original melt. For all practical purposes the steel meets the AISI/SAE 5160 specification. This is a steel which is widely used for springs in automobiles and trucks because of its resistance to corrosion fatigue in salt water. It was an appropriate choice for the manufacture of blades for an agricultural rotary cutter.

A specimen was cut for metallography from a location near the fracture and it was prepared for examination using standard metallographic techniques. Examination in a metallograph showed that the specimen had a tempered martensite structure. Knoop microhardness measurements were made on the metallographic specimen. On conversion to the Rockwell C scale these came out to be in the range Rc37 to Rc40. This is about what one would expect for a quenched and tempered AISI/SAE 5160 steel. Some subsidiary cracks were observed and these ran roughly parallel to a fracture surface.

3. The Fracture Surfaces

The fracture occurred at the bolt hole and thus divided the blade into two unequal pieces. The fracture surfaces on the smaller piece were selected for study. Because of the presence of the bolt hole there are two parts to the fracture surface, the part contiguous to the leading edge and the part contiguous to the trailing edge. In Figure (1) the leading edge runs along the bottom of the photograph and the trailing edge is at the top.

The fracture surfaces were first documented with a macro-camera and a low power stereo-microscope and then with a scanning electron microscope. Figures (2a) and (2b) show the two fracture surfaces, i.e. the fracture surfaces contiguous to the leading and trailing edges. Also shown are the ten locations on each fracture surface where scanning electron microscopy was carried out. At each location micrographs were obtained at magnifications of X25, X250 and X1000, for a total of 60 micrographs.

Examination of these micrographs showed that they divided clearly into two groups. One group exhibited classic void initiated ductile fracture. An example is shown, at a magnification of about X1000, in Figure (3). This is the mode of fracture to be expected when the steel is subjected to tensile overload. The others had three features in common:

(i) “Leaves” protruding out of the fracture surface
(ii) Secondary cracking which had the appearance of being intergranular
(iii) Small pits in the fracture surface.

These features could be seen most clearly at the X1000 magnification and, at this magnification, all three features could be seen on careful examination of each micrograph. Two micrographs have been
chosen to illustrate these three features clearly. Figure (4) shows predominately “leaves,” and pits, and Figure (5) numerous secondary cracks.

In Figures (2a) and (2b) the locations where void initiated ductile fracture was observed have been labelled “ductile”. Locations which exhibited the second type of fracture, involving “leaves”, secondary cracks and pitting, have been labelled “intergranular” for lack of a more descriptive term. The three locations labelled “mixed” showed features of both types of fracture. There were also some micrographs which showed evidence of damage to the fracture surface through contact with some other body. These marks were in the vicinity of the mounting blade.

There was general agreement among the metallurgists that the regions of void initiated ductile fracture were where final separation occurred. Using the colour changes caused by surface roughness and topography, which are apparent in Figures (2a) and (2b), it was possible to delineate these areas on the fracture surfaces. They are shown in Figure (6a) and (6b).

4. Discussion

By the time that the laboratory work was completed it was apparent that to understand the cause of this accident we had first to understand the fractography of the “intergranular” regions of the fracture surfaces. A page by page search of the volume on fractography in the ASM Metals Handbook [2], the two volume ASM Handbook of Case Histories in Failure Analysis [3] and other sources did not turn up any fractographs similar to the ones obtained in the “intergranular” regions of the fracture surfaces of the broken blade. The other metallurgists working on the case apparently had a similar experience. This absence of similar fractographs in the published literature is perhaps not surprising since the use of scanning electron microscopy in failure analysis is relatively recent [4].

In attempting to develop an interpretation of this “intergranular” fracture the following points were considered:

(i) The “leaves” have a degree of directionality which might be taken as an indication of fatigue. No evidence for striations or beach marks was found, however, and the directionality did not appear consistent with the spreading of a fatigue crack.

(ii) The pervasive intergranular cracking observed would be unusual for fatigue but consistent with it being due to quench cracking. However, quench cracking usually produces a conventional faceted intergranular fracture surface which becomes coated in a black oxide if the steel is tempered.

(iii) The presence of pitting on the “intergranular” fracture surface indicates that it was heated in air after the fracture occurred.

(iv) The occurrence of contact marks on the “intergranular” fracture surface near the bolt hole suggests that the fracture occurred in the manufacturing plant before the blade was clamped in place in its mount.

Faced with this situation it became necessary to develop a theory capable of giving a plausible interpretation to these apparently disparate observations. We start by suggesting that when the blade was quenched during its final heat treatment cycle, the quench was too severe and it cracked. There are numerous factors which determine whether or not quench cracking will occur [5] and we do not know enough about the blade’s history to even guess what was done incorrectly. Normally, a product such as this blade might be heated to around 850°C and then quenched into oil at 100° to 150°C.

After quenching, the blade would have been tempered in the vicinity of 550°C. The presence of the pits indicates that it was tempered in air and so it would have oxidized extensively [6]. At 550°C iron forms two layers of oxide. The inner layer is of magnetite (Fe₃O₄), and the outer layer hematite (Fe₂O₃). Above 570°C a layer of wüstite (non-stoichiometric FeO) also forms next to the metal, but this probably did not occur unless the tempering temperature was slightly higher than normal [7].

A quench crack is always intergranular [6] and has secondary intergranular cracks associated with it. In the case of steel, the oxides formed during tempering tend to spill. Pilling and Bedworth [8] have shown that if the ratio of the specific volume of the oxide divided by the specific volume of the metal from which it formed approaches 2, the oxide is not adherent. For the three oxides formed on
iron, the Pilling-Bedworth ratios are 1.77 for FeO, 2.09 for Fe$_3$O$_4$ and 2.14 for Fe$_2$O$_3$. Thus, spalling is to be expected.

In a study of the oxidation and combustion of finned steel tubing, Johnson, von Fraunhofer and Jannett have shown that oxidation at the sharp edge of a fin results in repeated spalling events and a substantial change in the configuration of the fin [9]. It is suggested that the tempering of a blade with quench cracks in it can result in comparable changes in the “intergranular” fracture surface of a quench crack. Such a surface starts with exposed sharp grain edges and corners which would be expected to spawn successive spalling events which would change the configuration of the fracture surface. We believe that this process can result in a fracture surface such as can be seen in Figures (4) and (5).

5. The Outcome of the Case
A nine day jury trial was held in Adair County Circuit Court in the heart of rural Kentucky. One of the present authors (A.A.J.) testified for the Plaintiffs that he believed that the blade which caused the accident failed because it contained quench cracks created during the manufacture of the blade. Metallurgists retained by the Defendants testified that they believed that the blade failed by fatigue caused by wobbling of the blade as the result of incorrect assembly. The jury found for the Plaintiffs and awarded them $5.9 million in compensatory and punitive damages.

The decision was appealed to the Kentucky Court of Appeals by the manufacturer of the blade and the Appeals Court reversed and remanded the part of the judgement (50%) against them. The grounds for the reversal were:

(i) The trial judge denied them permission to bring in the person who had assembled the blades onto the machine as a third party defendant.
(ii) The Plaintiffs were allowed to use evidence of prior warranty claims which were irrelevant to the case.
(iii) The Plaintiffs’ counsel had failed to give up in discovery photographs taken by the individual who assembled the blades just after the accident.
(iv) The punitive damage award arose from unfairly prejudicial evidence which should not have been admitted.

The case did not result in a second trial because the litigants settled out of court for an undisclosed sum.

References
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Table I - The chemical composition of the blade and the AISI-SAE 5160 specification.

| Element       | Amount in wt.% | Blade | AISI-SAE 5160 |
|---------------|----------------|-------|---------------|
| Carbon        | 0.63           | 0.54 – 0.65 |
| Manganese     | 0.95           | 0.70 – 1.00 |
| Silicon       | 0.32           | 0.15 – 0.30 |
| Chromium      | 0.77           | 0.60 – 0.90 |
| Molybdenum    | 0.02           | --     |
| Nickel        | 0.09           | --     |
| Copper        | 0.21           | --     |
| Niobium       | 0.03           | --     |
| Sulphur       | 0.02           | --     |

Figure (1). The two pieces of the broken blade.
Figure (2). The location at which scanning electron microscopy micrographs were obtained on (a) the leading edge, and (b) the trailing edge.
Figure (3). A scanning electron micrograph illustrating void initiated ductile fractures (x1000).

Figure (4). A scanning electron micrograph illustrating “leaves” and pits (x1000).
Figure (5). A scanning electron micrograph illustrating secondary cracking (x1000).
Figure (6). The areas over which final separation occurred on
(a) the leading edge, and (b) the trailing edge.