CS3.1 INTRODUCTION

After an accident in which a light pickup truck left the road and overturned, it was noted that one of the rear axles had failed at a point near the wheel mounting flange. This axle was made of a steel that contained approximately 0.3 wt% C. Furthermore, the other axle was intact and did not experience fracture. An investigation was carried out to determine whether the axle failure caused the accident or whether the failure occurred as a consequence of the accident.

Figure CS3.1 is a schematic diagram that shows the components of a rear axle assembly of the type used in this pickup truck. The fracture occurred next to the bearing lock nut, as noted in this schematic. A photograph of one end of the failed axle

Figure CS3.1 Schematic diagram showing typical components of a light truck axle and the fracture site for the failed axle of this case study. (Reproduced from MOTOR Auto Repair Manual, 39th edition, Copyright © 1975. By permission of the Hearst Corporation.)

Learning Objective

After studying this case study, you should be able to do the following:

1. Briefly describe the difference in surface features (as observed in scanning electron micrographs) for a steel alloy that (a) experienced a ductile fracture and (b) failed in a brittle manner.

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1 This case study was taken from Lawrence Kashar, “Effect of Strain Rate on the Failure Mode of a Rear Axle,” Handbook of Case Histories in Failure Analysis, Vol. 1, pp. 74–78, ASM International, Materials Park, OH, 1992.
shaft is presented in Figure CS3.2a, and Figure CS3.2b is an enlarged view of the other fractured piece that includes the wheel mounting flange and the stub end of the failed axle. Here (Figure CS3.2b) note that a keyway was present in the area of failure; furthermore, threads for the lock nut were also situated next to this keyway.

Upon examination of the fracture surface, it was noted that the region corresponding to the outside shaft perimeter [being approximately 6.4 mm (0.25 in.) wide] was very flat; furthermore, the center region was rough in appearance.

CS3.2 TESTING PROCEDURE AND RESULTS

Details of the fracture surface in the vicinity of the keyway are shown in the photograph of Figure CS3.3; note that the keyway appears at the bottom of the photograph. Both the flat outer perimeter and rough interior regions may be observed in the photograph. There are chevron patterns that emanate inward from the corners of and parallel to the sides of the keyway; these are barely discernible in the photograph but indicate the direction of crack propagation.

Figure CS3.3 Optical micrograph of failed section of axle that shows the keyway (bottom), as well as the flat outer-perimeter and rough core regions. [Reproduced with permission from Handbook of Case Histories in Failure Analysis, Vol. 1 (1992), ASM International, Materials Park, OH, 44073-0002.]
Figure CS3.4  Scanning electron micrograph of failed axle outer-perimeter region near the keyway, which shows cleavage features. 3500×.

Fractographic analyses were also conducted on the fracture surface. Figure CS3.4 shows a scanning electron micrograph taken near one of the keyway corners. Cleavage features may be noted in this micrograph, whereas any evidence of dimples and fatigue striations is absent. These results indicate that the mode of fracture within this outer periphery of the shaft was brittle.

An SEM micrograph taken of the rough central region (Figure CS3.5) revealed the presence of both brittle cleavage features and also dimples; thus, it is apparent that the failure mode in this central interior region was mixed; that is, it was a combination of both brittle and ductile fracture.

Figure CS3.5  Scanning electron micrograph of the failed axle rough core region, which is composed of mixed cleavage and dimpled regions. 570×.
Metallographic examinations were also performed. A transverse cross section of the failed axle was polished, etched, and photographed using the optical microscope. The microstructure of the outer periphery region, as shown in Figure CS3.6, consisted of tempered martensite.\(^2\) On the other hand, the microstructure in the central region was completely different per the photomicrograph of Figure CS3.7. It may be noted that the microconstituents are ferrite, pearlite, and possibly some bainite.\(^3\) In addition, transverse microhardness measurements were taken along the cross section; Figure CS3.8 is a plot of the resulting hardness profile. Here it may be noted that the maximum hardness of approximately 56 HRC occurred near the surface, and that hardness diminished with radial distance to a hardness of about 20 HRC near the center. On the basis of the

\(^2\)For a discussion of tempered martensite, see Section 10.8 of Introduction (Section 11.8 of Fundamentals).

\(^3\)Ferrite, pearlite, and bainite microconstituents are discussed in Sections 10.5 and 10.7 of Introduction (Sections 11.5 and 11.7 of Fundamentals).
With induction hardening, the surface of a piece of medium-carbon steel is rapidly heated using an induction furnace. The piece is then quickly quenched so as to produce an outer surface layer of martensite (which is subsequently tempered), with a mixture of ferrite and pearlite at interior regions.
SEM examinations. The following results from these tests/examinations would be expected if the core region of the axle were sensitive to the rate of straining:

- The failure of the core-region specimen to be impact (high strain rate) tested would not be totally ductile in nature.
- The core-region specimen to be tensile (low strain rate) tested would display at least a moderate degree of ductility.
- The outer-perimeter specimen to be impact tested would fail in a totally brittle manner.

**Impact Tests**

For the impact tests, small (~2.5-mm- (0.1-in.-) wide] Charpy V-notch test specimens were prepared from both outer-perimeter and interior areas. Because the hardened outer region was very thin (6.4 mm thick), careful machining of these specimens was required. Impact tests were conducted at room temperature, and the energy absorbed by the surface specimen was significantly lower than for the core specimen [4 J (3 ft-lb) versus 11 J (8 ft-lb)]. Furthermore, the appearances of the fracture surfaces for the two specimens were dissimilar. Very little, if any, deformation was observed for the outer-perimeter specimen (Figure CS3.9); conversely, the core specimen deformed significantly (Figure CS3.10).

Fracture surfaces of these impact specimens were then subjected to examination using the SEM. Figure CS3.11, a micrograph of the outer-perimeter specimen that was impact tested, reveals the presence of cleavage features, which indicates that this was a brittle fracture. Furthermore, the morphology of this fracture surface is similar to that of the actual failed axle (Figure CS3.4).

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**Figure CS3.9** Fracture surface of the Charpy impact specimen that was taken from the outer-perimeter region.


**Figure CS3.10** Fracture surface of the Charpy impact specimen that was taken from the core region.

For the impact specimen taken from the core region, the fracture surface had a much different appearance; Figures CS3.12a and CS3.12b show micrographs for this specimen, which were taken at relatively low and high magnifications, respectively. These micrographs reveal the details of this surface to be composed of interspersed cleavage features and shallow dimples, being similar to the failed axle, as shown in

Figure CS3.11  Scanning electron micrograph of the fracture surface for the impact specimen prepared from the outer-perimeter region of the failed axle. 3000×. [Reproduced with permission from *Handbook of Case Histories in Failure Analysis*, Vol. 1 (1992), ASM International, Materials Park, OH, 44073-0002.]

Figure CS3.12  (a) Scanning electron micrograph of the fracture surface for the impact specimen prepared from the core region of the failed axle. 120×. (b) Scanning electron micrograph of the fracture surface for the impact specimen prepared from the core region of the failed axle taken at a higher magnification than (a); interspersed cleavage and dimpled features may be noted. 3000×. [Reproduced with permission from *Handbook of Case Histories in Failure Analysis*, Vol. 1 (1992), ASM International, Materials Park, OH, 44073-0002.]
Thus, the fracture of this specimen was of the mixed-mode type, having both ductile and brittle components.

**Tensile Tests**

A tensile specimen taken from the core region was pulled in tension to failure. The fractured specimen displayed the cup-and-cone configuration, which indicated at least a moderate level of ductility. A fracture surface was examined using the SEM, and its morphology is presented in the micrograph of Figure CS3.13. The surface was composed entirely of dimples, which confirms that this material was at least moderately ductile and that there was no evidence of brittle fracture. Thus, although this core material exhibited mixed-mode fracture under impact loading conditions, when the load was applied at a relatively slow rate (as with the tensile test), failure was highly ductile in nature.

A summary of these impact and tensile tests is presented in Table CS3.2.

**CS3.3 DISCUSSION**

In light of the previous discussion, it was supposed that the truck rollover was responsible for the axle failure (i.e., scenario 1 was valid). Reasons for this supposition are as follows (see Tables CS3.1 and CS3.2):

1. The outer-perimeter region of the failed axle shaft failed in a brittle manner, as did also the specimen taken from this region that was impact tested. This conclusion
was based on the fact that both fracture surfaces were very flat and that SEM micrographs revealed the presence of cleavage facets.

2. The fracture behavior of the core region was strain-rate sensitive and indicated that axle failure was due to a single high-strain-rate incident. Fracture surface features for both the failed axle and impact-tested (i.e., high-strain-rate tested) specimens taken from this core region were similar: SEM micrographs revealed the presence of features (cleavage features and dimples) that are characteristic of mixed-mode (brittle and ductile) fracture.

In spite of evidence supporting the validity of the accident-caused-axle-failure scenario, the plausibility of the other (axle-failure-caused-the-accident) scenario (scenario 2) was also explored. This latter scenario assumes that a fatigue crack or some other slow-crack propagation mechanism initiated the sequence of events that caused the accident. In this case it is important to consider the mechanical characteristics of the portion of the specimen that was last to fail—in this instance, the core region. If failure was due to fatigue, then any increase in loading level of this core region would have occurred relatively slowly, not rapidly as with impact loading conditions. During this gradually increasing load level, fatigue crack propagation would have continued until a critical length was achieved (i.e., until the remaining intact axle cross section was no longer capable of sustaining the applied load); at this time, final failure would have occurred.

On the basis of the tensile tests (i.e., slow strain-rate tests) performed on this core region, the appearance of the axle fracture surface would be entirely ductile (i.e., dimpled, as per the SEM micrograph of Figure CS3.13). Inasmuch as this core region of the failed shaft exhibited mixed-mode (ductile and brittle) fracture features (both cleavage features and dimples, Figure CS3.5) and not exclusively dimples, the axle-failure-caused-the-accident scenario was rejected.

**SUMMARY**

This case study was devoted to a failure analysis, which detailed an investigation conducted on a failed rear axle of a light pickup truck that had overturned; the problem was to determine whether the accident resulted from this failure or vice versa. Impact and tensile specimens were fabricated from outer-perimeter and interior regions of the axle, which were subsequently tested. On the basis of scanning electron and metallographic examinations of the actual failed axle surface, as well as the surfaces of these test specimens, it was concluded that the accident caused the axle failure.

**REFERENCE**