Failures of Tools and Dies

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Failure Mechanisms in tool and die materials that are very important to nearly all manufacturing processes are discussed in this article. A wide variety of tool steel compositions are used. Properties and selection of tool steels are described in the Section “Tool Materials” in Volume 3 of the 9th Edition of Metals Handbook; microstructures and metallographic techniques for tool steels are detailed in the article “Tool Steels” in Volume 9 of the 9th Edition of Metals Handbook. This article is primarily devoted to failures of tool steels used in cold-working and hot-working applications.

Tool and Die Characteristics

Steels used for tools and dies differ from most other steels in several aspects. First, they are used in the manufacture of other products by a variety of forming processes (stamping, shearing, punching, rolling, bending, and so on) and machining processes (drilling, turning, milling, and so on). Second, tools and dies are generally used at higher hardnesses than most other steel products; 58 to 68 HRC is a typical range. Dies for plastic molding or hot working are usually used at lower hardnesses, typically from 30 to 55 HRC.

These high hardness requirements are needed to resist anticipated service stresses and to provide wear resistance. However, the steels must also be tough enough to accommodate service stresses and strains without cracking. Premature failure due to cracking must be avoided, or at least minimized, to maintain minimum manufacturing costs. Unexpected tool and die failure can shut down a manufacturing line and disrupt production scheduling. This leads to higher costs.

Tools and dies must also be produced with the proper size and shape after hardening so that excessive finishing work is not required. Heat-treatment distortion must be controlled, and surface chemistries must not be altered. Because of the careful balance that must be maintained in heat treatment, control of the heat-treatment process is one of the most critical steps in producing successful tools and dies. Heat treating of tool and die steels is discussed in the Section “Heat Treating of Tool Steels” in Volume 4 of the 9th Edition of Metals Handbook. In addition to controlling the heat-treatment process, tool and die design and steel selection are integral factors in achieving tool and die integrity.

Analytical Approach

Analysis of tool and die failures is substantially aided by knowledge of the manufacturing and service history of the failed part. In many instances, however, such information is sketchy, and the analyst must rely on experience and engineering judgment. The examples discussed in this article are typical of tool and die failures and illustrate many of the features specific to such failures. Additional information can be found in the Selected References that follow this article.

A basic approach can be followed for most tool and die failures that will maximize the likelihood of obtaining reasons for the failure. At times, however, no reason for failure can be discovered. In such cases, the failures are normally attributed to unknown service conditions.

Before beginning the investigation, a complete history of the manufacture and service life should be compiled. This is often difficult to accomplish. Next, the part should be carefully examined, measured, and photographed to document the extent and location of the damage. Relevant design features, as well as some machining problems, are generally apparent after this study. The origin of the failure, when due to fracture, will also usually be determined. Only after careful visual examination has been completed should any destructive work be considered. In certain cases, various nondestructive examination techniques—for example, ultrasonics, x-ray, or magnetic-particle inspection—should be implemented before cutting to obtain a more complete picture of the damage, either internal or external.

When this work is completed, several other phases of the study can begin. First, the composition of the component should be verified by a reliable method. Tool and die failures occasionally result from accidental use of the wrong grade of steel. While this work is underway, the analyst continues macroscopic examination of the fracture features by opening tight cracks (when present). Because quench cracking is a very common cause of failures, the fracture surfaces should always be checked for temper color. Scale on a crack wall would indicate that it was exposed to temperature higher than those used in tempering.

Visual inspection of the damage done to a tool and die is usually adequate to classify the type of tool and die failure, as illustrated by the examples in this article. High-magnification fractographic examination is required in only a small percentage of the cases. A simple stereomicroscope generally suffices.

Microstructural examination at and away from the damage and at the origin is imperative. This generally requires good edge-retention preparation, which is relatively easy for tool steels. A large percentage of tool and die failures are due to heat-treatment problems, as illustrated by the examples in this article; the value of proper metallographic procedures cannot be stressed enough.

Other techniques are also very important. Hardness testing is used to confirm the quality of the heat treatment and often reveals problems. Macrostructural examination, either by cold etching (more common) or hot etching, is very useful for detecting gross problems. Prior-austenite grain size is frequently evaluated by the Shepherd fracture grain size technique, a simple but accurate approach. X-ray diffraction can be used to determine the amount of retained austenite present.

In some cases, it is necessary to perform simulations or to conduct experimental heat treatments to determine if a part was tempered. Chemical analysis of millings or turnings from the surface will define variations in surface-carbon content. Electron metallographic devices using either wavelength- or energy-dispersive x-ray analysis can be used to identify inclusions or segregates. It is also helpful in some studies to compare the characteristics of good parts to those of failed parts.

When these data are compiled and analyzed, the analyst is ready to prepare a report that details the cause of failure with the supporting facts. In many such cases, it is also necessary to make recommendations regarding corrective action for future parts or for existing parts.
Causes of Tool and Die Failures

A number of factors are responsible for tool and die failures including:

- **Mechanical design:** Must be compatible with the steel grade selected, the procedures required to manufacture the tool or die, and the use of the tool or die.
- **Grade selection:** Must be compatible with the design chosen, the manufacturing processes used to produce the tool or die, and the intended service conditions and desired life.
- **Steel quality:** Must be macrostructurally sound, free of harmful inclusions to the degree required for the application, and free of harmful surface defects.
- **Machining processes:** Must not alter the surface microstructure or surface finish and must not produce excessive residual stresses that will promote heat-treatment problems or service failures.
- **Heat-treatment operation:** Must produce the desired microstructure, hardness, toughness, and hardenability at the surface and the interior.
- **Grinding and finishing operations:** Must not impair the surface integrity of the component.
- **Tool and die setup:** Alignment must be precise to avoid irregular, excessive stresses that will accelerate wear or cause cracking.
- **Tool and die operation:** Overloading must be avoided to ensure achievement of the desired component life.

The above classification of factors, while helpful in categorizing problems, will not necessarily deduce the cause of a particular failure. For example, a failure due to one of the above factors may have been caused by other problems earlier in the processing sequence. To illustrate, the majority of cracking problems attributed to abusive grinding practices are caused by failure to temper the part or are due to overaustenitization. Both of these problems will make a tool steel virtually impossible to grind without producing surface burning and cracking regardless of the care taken during grinding. Thus, the above factors are interdependent, much like the links of a chain. If one step is poorly executed, the tool or die will exhibit limited service life regardless of how carefully all of the other steps are conducted. This sensitivity to processing steps from the use of tools and dies at these very high hardnass levels, at which minor deficiencies in processing exert major influences on performance.

**Mechanical Testing of Tool Steels.** For the majority of tool steels, tensile tests at room temperature are not conducted because of the technical difficulties of obtaining valid results at these very high hardnesses. Also, because most tools and dies are subjected to high compressive stresses, it would be more useful to obtain compressive yield strength data to aid the designer. However, such tests are quite difficult to perform, and few useful data are available. Consequently, the simple indentation hardness tests, generally the Rockwell C test or the Vickers test, are used to define strength differences. Such data are simple to produce and are extremely useful. The lower carbon, high-strength hot-work tool steels can be tested in tension, and such data are available for both room temperature and elevated temperatures. Tension, compression, and hardness testing are discussed in separate articles in Volume 8 of the 9th Edition of Metals Handbook.

As a class, tool steels are not noted for high toughness. Impact-type tests are commonly used, but most test specimens either are not notched or have a C-type notch rather than the more common V-notch. Use of the latter type of specimen is reserved for the higher-toughness grades or is used with low-blow fracturing devices. Fracture-toughness data are available for many tool steel grades, particularly the higher-toughness grades for which such data are useful. For most tool steels, plane-strain fracture toughness predicts very small critical flaw sizes, which emphasizes the need for minimizing stress concentrators and maintaining smoothly machined surfaces.
Fig. 3 AISI O1 tool steel die that cracked during oil quenching
Note the cracks emanating from the sharp corners. The four holes, which are close to the edge, also contributed to cracking. Temper color was observed on the crack walls.

Types of Failures. Tool and die failures due to breakage, which are generally catastrophic, are the most spectacular and draw the most attention from the failure analyst. Such failures are usually the easiest to diagnose, but the analyst should be cautioned not to halt the investigation when one obvious problem is observed. It is not uncommon to observe several factors that contribute to the failure in varying degrees. The goal of any failure analysis should be to provide a total picture of all the problems present so that complete corrective action, rather than partial corrective action, is taken on future parts.

Aside from cracking, a wide variety of problems can be encountered that cause limited tool or die life. These problems include, but are not limited to, distortion (during heat treatment, machining, or service), excessive wear, galling, pick-up, erosion, pitting, cosmetic problems, and corrosion problems.

Influence of Design

Any examination of tool or die failures must begin with a careful reexamination of the design to determine if shortcomings are present and if improvements can be made. Tools and dies that perform satisfactorily over the desired service life may not produce the same performance if a new manufacturing process is adopted, the grade is changed, or the service conditions are altered. Consequently, in the study of the existing design, it is imperative to obtain complete details on the history of the component relative to its past performance, manufacturing line-up, service conditions, and so on. All too often, however, such data are sketchy.

The importance of a good design cannot be overemphasized. Poor design can cause or promote heat-treatment failures before any service life is obtained or may reduce service life, sometimes dramatically. In designing a tool or die, a host of factors must be considered. In practice, it is difficult to separate the design stage from grade selection because the two steps are interdependent. The choice of a certain grade of steel, such as one that must be brine or water quenched, will have a very substantial bearing on all aspects of design and manufacture. In general, any steel grade that requires liquid quenching demands very conservative, careful design. Air-hardening grades tolerate some design and manufacturing aspects that could never be tolerated with a liquid-quenching grade. The design must also be compatible with the equipment available—for example, heat-treatment furnaces and surface-finishing devices.

Designing tools and dies is more difficult than designing components made from structural steels because of the difficulty in predicting the service stresses. Despite advances made in design procedures, much of the design work is still empirically based. Such experience is primarily based on past failures; therefore, it is important that the findings of the failure analyst be incorporated into future work. Despite the shortcomings of the empirical approach, there is a vast body of common sense engineering knowledge available for guidance (see the Selected References).

Effect of Sharp Corners and Section-Mass Changes. Analysis of many tool and die failures shows that two relatively simple design problems cause the most failures. These design shortcomings are the presence of sharp corners and the presence of extreme changes in section mass. A sharp corner concentrates and

Fig. 4 Fixture made from AISI O1 tool steel that cracked during oil quenching
This design is poor for liquid quenching. A nick in the fillet region helped to initiate cracking. 0.75 ×

Fig. 5 Threaded part made from AISI W2 tool steel that cracked during quenching at an undercut at the base of the threads
(a) The two pieces that separated during fracture. (b) Cold-etched (10% aqueous nitric acid) disk cut through the threaded portion showing the hardened surface zone, which is also visible on the fracture faces shown in (a)
Fig. 6 Punch made of AISI S7 tool steel that cracked during quenching
Temper color was observed on the crack walls. Cracking was promoted by and located by the very coarse machining marks. Magnetic particles have been used to emphasize the cracks. 0.5 x

Fig. 7 The surface of an AISI A4 primer cup plate showing spalling at one of the 3.2-mm (⅛-in.) diam holes made by EDM
The surface was etched with 10% aqueous nitric acid to bring out the influence of the EDM operation at the spall. 2.5 x

Magnifies applied stresses, stresses that arise in tool and die manufacturing (such as during quenching), or stresses that occur during service. In addition to promoting cracking during liquid quenching, sharp corners promote buildup of residual stresses that may not be fully relieved by tempering and can therefore reduce service life. The largest possible fillet should be used at all sharp corners. Air-quenching grades are more tolerant of sharp corners than liquid-quenching grades and are preferred when only minimal fillets can be used.

Changes in section size can locate premature failures. Figure 1 shows two AISI W1 carbon steel concrete roughers that failed after a few minutes of service. Cracking occurred at the change in section due to bending stresses. Although the section change has a smooth, filleted surface, it is still a very effective stress concentrator. Subsequent design changes involved a tapered change in section at the cracked location and later at the start of the wrench flats above the cracked region.

Holes placed too close to the edges of components are a common source of failure during heat treatment or in service. Figures 2(a) and (b) show an AISI O1 tool steel die that cracked during oil quenching. The die face contained numerous fine cracks. The left side of the die broke off during quenching. Figure 2(b) shows both sides of the fracture. Temper color (arrow), typical of the 205 °C (400 °F) temper used, is apparent. This indicates the depth of the crack produced during quenching that was open during tempering. Coarse machining marks and deep stamp marks were also present.

Sharp, unfilleted corners may also promote quench cracking. Figure 3 shows a 76- x 87- x 64-mm (3- x 3⅞- x 2½-in.) AISI O1 tool steel die that cracked during oil quenching. The crack pattern (emphasized using magnetic particles) that emanates from the sharp corners is visible. A few cracks are also associated with...
Fig. 9 Plastic mold die made from AISI S7 tool steel that was found to be cracked before use
A crack followed the lower recessed contour of the large gear teeth and had an average depth of 1.6 mm (1/16 in.). Smaller cracks were also observed on the flat surfaces. (a) Actual size. (b) Etching the surface with 10% aqueous nitric acid revealed a white-etching appearance at the teeth. 2 ×. (c) Micrograph showing a surface layer of as-quenched martensite (from the EDM operation) and an overaustenitized matrix structure (unstable retained austenite and coarse plate martensite). Etched with 3% nital. 420 ×.

Fig. 10 Grinding cracks caused by failure to temper a part
(a) Two dies made from AISI D2 tool steel that cracked after finish grinding (cracks accentuated with magnetic particles). (b) Macroetching (10% aqueous nitric acid) of the end faces revealed grinding scorch. These dies were not tempered after hardening.

the holes that are rather close to the edges. Temper color was observed on the crack surfaces, indicating that the cracks were present before tempering.

Figure 4 shows another example of a quench crack initiated by a sharp corner. This fixture was also made of AISI O1 tool steel that was oil quenched. In this case, the corner was filleted, but there was a nick in the corner where cracking began. The shape of this fixture is also poor for a steel that must be oil quenched. The thinner outer regions cool more rapidly, forming martensite first, while the more massive central region cools at a slower rate. An air-hardenable steel would be a better choice for this part.

Another example of a poor design for liquid quenching is shown in Fig. 5. This 76-mm (3-in.) diam × 76-mm (3-in.) long threaded part made of AISI W2 carbon tool steel cracked in half at an undercut at the base of the threads. Figure 5 shows the two broken halves, along with a cold-etched disk taken from the hollow portion of the part. The hardened outer case can be seen in the fracture detail and in the cold-etched disk. Similar parts, without the undercut, were successfully hardened.

**Influence of Steel Grade**

Selection of the optimum grade for a given application is generally a compromise between toughness and wear resistance, although other factors may be more important in certain situations. Because most tools and dies operate under highly stressed conditions, toughness must be adequate to prevent brittle fracture. It is usually better for a tool or die to wear out than to break in service prematurely. Thus, in a new application, it is best to select a grade that will definitely have adequate toughness. When some experience is gained that shows freedom from breakage but perhaps excessive wear, a
different grade can be chosen that would provide better wear resistance but somewhat less toughness. As experience is gained, the best grade choice can be made by balancing the required toughness and wear resistance.

**Influence of Machining**

Machining problems are a common cause of tool and die failures. It is generally best to avoid machining directly to the finish size unless a prehardened die steel is used. It is difficult to obtain perfect control of surface chemistry and size during heat treatment. Thus, some final grinding is usually needed after heat treatment. The presence of decarburization is generally quite detrimental. Also, because stresses are high in heat treatment and in service, rough machining marks must be avoided. Identification stamp marks are another common source of failures in heat treatment and in service; they should be avoided.

**Quench-Crack Failures.** Two quench-crack failures promoted by machining problems have been illustrated. Quench cracking of the fixture shown in Fig. 4 was located by a nick in the fillet, while failure of the threaded part shown in Fig. 5 was due to an undercut at the base of the threaded region.

Fig. 11 Two views of an AISI S1 tool steel cutter die that cracked and spalled after regrinding
(a) The as-received condition. (b) The cracks have been accentuated by use of magnetic particles. Also note the grinding scorched pattern (the dark parallel lines perpendicular to the cracks).

Fig. 12(a) Two AISI A6 tool steel parts that shattered during finish (abusive) grinding
See also Fig. 12(b)

Fig. 12(b) Photomicrograph of the ground parts shown in Fig. 12(a)
A reaustenitized region (white) and a back-tempered zone (dark) at the ground surface are shown. Etched with 3% nital, 70 X

Rough machining marks are another common cause of quench cracking. Figure 6 shows a punch made of AISI S7 tool steel that cracked during quenching. Because of the section size,
Fig. 13(a) AISI S5 tool steel hammer head that cracked during heat treatment
The fracture was caused by quench cracking that was promoted by the decarburized surface (Fig. 13b) and deep stamp mark (arrows). Actual size

Fig. 14 A quench crack promoted by the presence of a deep, sharp stamp mark in a die made of AISI S7 tool steel
This die had not been tempered, or was ineffectively tempered, after hardening. 2 ×

Fig. 15 AISI W2 carbon tool steel (1.05% C) component that cracked during quenching due to the presence of soft spots (arrows) on the surface
These soft spots were revealed by cold etching the surface with 10% aqueous nitric acid. 0.4 ×

the punch was oil quenched to 540 °C (1000 °F), then air cooled. The crack pattern has been emphasized with magnetic particles. Temper color was observed on the crack walls.

Failures Due to Electrical Discharge Machining (EDM). Die cavities are often machined by EDM. The technique has many advantages, but failures have been frequently observed due to failure to remove the as-cast surface region and associated as-quenched martensitic layer. Cavity surfaces must be stoned or ground, then tempered to prevent such failures.

A classic example of a failure due to improper EDM technique is shown in Fig. 7 and 8. Figure 7 shows four 3.2-mm (⅛-in.) diam EDM holes in an AISI A4 tool steel primer cup plate. The holes were finished by jig-bore grinding, during which spalling was observed at many of the holes (see upper-right hole). The surface was swabbed with 10% aqueous nitric acid (HNO₃) to reveal regions affected by EDM. Figure 8 shows the microstructure of these regions. An as-cast region was present at the extreme edge (about 35.5 HRC). Beneath this layer was a region of as-quenched martensite (about 63.5 HRC). Next was a back-tempered region (about 56 HRC) and then the

Fig. 13(b) Macroetched disk cut from the head of the sledge hammer shown in Fig. 13(a)
The heavily decarburized surface is revealed by macroetching. Actual size

Fig. 16(a) AISI O1 tool steel ring forging that cracked during quenching
The forging was overaustenitized (unstable retained austenite was present) and was decarburized to a depth of about 0.5 mm (0.020 in.). Temper color was present on the crack walls. See also Fig. 16(b).

Fig. 16(b) Interior microstructure of the cracked ring forging shown in Fig. 16(a)
Unstable retained austenite (white) and coarse plate martensite (dark) can be seen. The amount of residual carbide was negligible compared to what should have been present. Etched with 3% nital. 700 ×
Fig. 17 AISI M2 roughing tool that cracked just after heat treatment
(a) Cracks (arrows) accentuated with magnetic particles. (b) Microstructural examination revealed a badly overaustenitized condition with a heavy grain-boundary carbide film, coarse plate martensite, and unstable retained austenite. Etched with 3% nital. 490 x

Fig. 18 AISI O6 graphitic tool steel punch machined from centerless-ground bar stock that cracked after limited service
(a) Cracks (arrows) accentuated with magnetic particles. (b) Microstructural examination revealed an overaustenitized structure consisting of appreciable retained austenite and coarse plate martensite. Etched with 3% nital. 700 x.

Fig. 19 AISI P20 mold made from prehardened stock that was carburized and rehardened
After heat treatment, it was found to be cracked (arrow). See also Fig. 20.

base, unaffected interior (59 to 61 HRC). The brittle nature of the outer layers and the associated residual-stress pattern caused the spalling.

In many EDM-related failures, the as-cast layer is not observed, because of the technique used or because of subsequent machining. In these failures, however, an outer layer of brittle as-quenched (white-etching) martensite is present. Such a failure is shown in Fig. 9. This failure occurred in a plastic-mold die made from AISI S7 tool steel. The crack followed the lower, recessed contour of the larger-diameter gear teeth and extended to a depth of about 1.6 mm (5/64 in.). Etching of the surface revealed a light-etching rim around the teeth. Microstructural examination revealed an as-quenched martensite surface layer (thin, white layer), while the internal structure was grossly overaustenitized (note the retained austenite, white, and coarse plate martensite). Both factors lead to cracking. If the EDM surface layer was not present, poor service life would have resulted anyway due to the poor microstructural condition.

Failures Due to Finish Grinding. Cracking due to the stresses and microstructural alterations caused by grinding is a relatively common problem. In many cases, the grinding technique is not at fault, because the microstructure of the part rendered it sensitive to grinding damage due to failure to temper the part or because the part was overaustenitized and contained substantial unstable retained austenite.

Figure 10 shows an example of grinding cracks due to failure to temper the part. Two AISI D2 tool steel dies, which measured 57 x 60 x 29 mm or 51 mm thick (2 1/4 x 2 1/8 x 1 1/4 in. or 2 in. thick), were observed to be cracked after finish grinding. The cracks are emphasized with magnetic particles. Macroteching of the surfaces revealed the classic scorch pattern indicative of abusive grinding. The failure, however, was not due to poor grinding practice, but was caused by failure to temper the dies. The interior hardness was 63 to 64 HRC, typical for as-quenched D2. The scorched surface was back tempered to 55 to 58 HRC. It is difficult to grind as-quenched high-hardness tool steels without damaging the surface.

Grinding damage can also occur in parts that have been properly heat treated, but such cases are less common. Figure 11 shows two views of a 32- x 152- x 381-mm (1 1/4- x 6- x 15- in.) AISI S1 tool steel cutter die that cracked extensively during regrinding after an initial service period. The as-received surface is
Fig. 20 Metallographic section from the AISI P20 mold shown in Fig. 19
(a) Top part of a macroetched (10% aqueous nitric acid) disk cut from the mold revealing a heavily carburized case. Actual size. (b) Micrograph showing gross carbide buildup at the surface with an underlying region having a continuous grain-boundary carbide network. Etched with 3% nital. 100 ×

shown in Fig. 11(a); the crack pattern is vividly revealed by magnetic particles (Fig. 11b). The grinding scorch pattern is also visible. This die had been carburized and the surface hardness was 62 to 64 HRC.

Figure 12(a) shows two AISI A6 tool steel parts that shattered during finish grinding. These parts were properly hardened (57 HRC), and cracking was due to the grinding practice. The parts have been etched to show the scorch pattern (Fig. 12b). The surface hardness was erratic, varying between 48 and 56 HRC. The photomicrograph shows a typical surface region affected by the grinding heat. Spots, such as the white-etching martensitic region shown, were about 0.08 mm (0.003 in.) deep. The backtempered region beneath the as-quenched martensite extended to a depth of about 0.38 mm (0.015 in.). Cracking is often present in these rehardened zones.

Fig. 21 Failed AISI S7 jewelry striking die
(a) Crack (arrows) that formed shortly after the die was placed in service. (b) and (c) Microstructural examination revealed that the surface was slightly carburized and that the die had been overaustenitized. Note the coarse plate martensite and unstable retained austenite in the carburized surface region and the coarse martensitic matrix structure beneath this layer. (b) 75 ×. (c) 530 ×. Both etched with 3% nital.

Influence of Heat Treatment
Improper heat-treatment procedures are the single largest source of failures during heat treatment, in subsequent processing steps, or in service. Each tool steel grade has a recommended austenitizing temperature range (generally rather narrow), a recommended quench medium, and recommended tempering temperatures and times for optimum properties. Some grades are more forgiving than others regarding these parameters.

Handling of Samples. One of the most common sources of problems arises in the handling of samples between the quench and the temper. As soon as the part reaches a temperature of about 65 ºC (150 ºF), it should be quickly transferred to the tempering furnace. The heat treater will sometimes check the hardness of the part after quenching and avoid the tempering treatment if the as-quenched hardness equals the desired hardness. This is a very poor practice for two reasons. First, tool steels must always be tempered to reduce the quenching stresses to an acceptable level and to improve the toughness of the steel. Untempered tools and dies nearly always fail prematurely in service. Second, the as-quenched hardness may be low due to testing on a decarburized surface. If a spot is ground on an as-quenched surface, cracking may result. Double and triple tempering is required for the more highly alloyed grades to stabilize the microstructure.

Quench Cracking. Numerous heat-treatment problems can promote quench cracking. Figure 13(a) shows a 41-mm (1.6-in.) square, 1.4-kg (3-lb) AISI S7 tool steel sledge-hammer head that cracked during quenching. A disk cut from the head was macroetched, revealing a heavily decarburized surface (Fig. 13b). Such a condition promotes quench cracking, particu-
Fig. 22 AISI 57 punch that had a low surface hardness after heat treatment and was given a second carburizing treatment, then rehardened

Cracking was observed after this treatment (the cracks have been accentuated with magnetic particles). Coarse circumferential machining marks were present on the lower portion of the punch. See also Fig. 23 and 24.

Fig. 23 Crack pattern on the bottom of the punch shown in Fig. 22

Many of the cracks are located by the deep stamp marks (the cracks have been accentuated with magnetic particles). Actual size

larly in liquid-quenching grades such as S5 (oil quenched), due to differential surface stresses. A deep stamp mark also helped promote cracking.

Stamp marks, such as that shown in Fig. 14, commonly promote quench cracks. This was present on an air-quenched die made from AISI S7 tool steel. In this case, the die was not tempered, another prime cause of quench cracking. The hardness of the die was 61.5 to 62 HRC. The surface was slightly decarburized; the hardness was 59 to 60 HRC at the surface.

Quench cracking of water- or brine-quenched tool steels can be promoted by soft spots on the surface of the part. These soft regions may be due to the fixture used to hold the part during quenching, or from tongs, or may be caused by vapor pockets during quenching due to inadequate agitation or contamination of the quench.

Figure 33 shows a component made from AISI W2 tool steel that quench cracked due to soft spots (unhardened regions). The surface of the part was macroetched, revealing these zones. The hardness numbers reveal the difference in hardness between the case and the soft spots.

Failures Due to Overaustenitizing. Another very common heat-treatment problem is the use of an excessively high austenitizing temperature. This may be due to improper furnace-temperature control or the combining of several parts made of different grades in one furnace batch using an austenitizing temperature chosen as a compromise between the recommended temperatures for the grades. Excessively high austenitizing temperatures promote grain growth and excessive retained austenite. Most tool steel grades have high carbon contents and rely on the undissolved portion of the carbides to control grain growth. An excessive austenitizing temperature puts more carbon in solution, thus permitting grain growth as well as excess retained austenite due to suppression of the martensite start, Mₐ, and finish, Mₐ, temperatures.

Tool steel parts that have been overaustenitized, producing coarse plate martensite and unstable retained austenite, often fail by quench cracking. Figure 16(a) shows a 44-cm (17½-in.) OD x 33-cm (13-in.) ID x 5-cm (2-in.) thick ring forging made of AISI O1 tool steel that cracked during quenching. Temper color was present on the crack surface. The interior microstructure (Fig. 16b) revealed an overaustenitized condition, coarse plate martensite, and retained austenite (white). The hardness was 61 to 62 HRC. A section was cooled in liquid nitrogen, which transformed much of the retained austenite to martensite and increased the hardness to 64 to 65 HRC. The surface was decarburized with a hardness of 55 to 57 HRC, which did not change after refrigeration.

Figure 17(a) shows an AISI M2 roughing tool that cracked during hardening (the cracks were accentuated with magnetic particles). Microstructural examination revealed an overaustenitized condition with a heavy grain-boundary film, coarse plate martensite, and unstable retained austenite (Fig. 17b). The Snyder-Graff intercept grain size was 4.5 (ASTM 7), which is quite coarse for this grade.

Improper control of the austenitizing temperature is a common problem. Figure 18(a) shows an AISI O6 graphic tool steel punch that cracked after limited service. Examination of the microstructure revealed an overaustenitized condition (Fig. 18b). All of the carbide has been dissolved; only martensite and retained
austenite are observed. The hardness of the punch was 59 to 60 HRC at the surface and 60 to 62 HRC in the interior. Cooling in liquid nitrogen raised the hardnesses to 63 to 64 and 63 to 65 HRC, respectively.

**Excessive Carburization.** While many tool steels have high carbon contents, a few low-carbon P-type mold steels are carburized before heat treatment. Control of the carburizing cycle, as well as subsequent heat treatment, is required to obtain good results. Figure 19 shows a mold made of AISI P20 prehardened tool steel measuring 20.3 × 20.3 × 3.5 cm (8 × 8 × 1¾ in.) that cracked sometime after a carburizing/heat-treatment procedure. Figure 20(a) shows a disk cut from the mold that was cold etched to reveal a dark-etching surface case about 3.2 mm (¼-in.) thick. Microstructural examination revealed that the cracks (arrow, Fig. 19) on the outside diameter and the inside diameter of the mold were 1.8 and 2.9 mm (0.070 and 0.113 in.) deep. The external surfaces were carburized to a depth of at least 2.5 mm (0.10 in.). Figure 20(b) reveals the heavy concentration of carbide at the surface and the extensive grain-boundary carbide networks. Analysis of millings taken from the surface revealed that the carbon content of the outer 0.25 mm (0.010 in.) was 1.96 wt%. This is far too high, thus rendering the surface layer extremely brittle. Coarse machining marks were also present on the mold surface in the cracked region.

Furnace atmospheres are sometimes not properly controlled during heat treatment, and either decarburization or carburization results. The latter is less common, but when it occurs, failure may result. Some tool steel grades can tolerate minor, unintentional carburization better than others. Figure 21(a) shows a 64- × 56- × 81-mm (2½- × 2½- × 3½-in.) jewelry striking die made from AISI S7 tool steel that cracked shortly after being placed in service. Cracking occurred in the die cavity and extended along a recessed groove and down the side. The hardness of the die surface varied between 50 and 55 HRC, while the interior was 56 to 57 HRC. Cooling of a section in liquid nitrogen increased the surface hardness to 62 to 65 HRC, indicating the presence of substantial retained austenite at the surface. The interior hardness did not change. Examination of the microstructure (Fig. 21b and c) revealed extensive retained austenite (white) at the surface, while the interior microstructure was coarse, indicating that the austenitizing temperature was excessive. The excess retained austenite at the surface indicated that carburization had occurred during hardening. Chemical analysis of milling from the outer 0.13 mm (0.005 in.) revealed a carbon content of 0.79 wt% as opposed to an interior carbon content of 0.53 wt%. The carburized case was about 0.51 mm (0.020 in.) deep.

Another example of the detrimental influence of excessive carburization is shown in Fig. 22 to 24. This was a punch made from AISI S7 tool steel that was used in the first stage of cold forming of 105-mm shells that cracked after a second heat treatment. The desired hardness was not achieved with the initial treatment. The punch was supposed to be lightly carburized to produce a surface hardness of 62 HRC (higher than the usual hardness of 58 HRC for non-carburized S7).

Figure 22 shows the extensive crack pattern (accentuated with magnetic particles) on the outer surface of the punch. Coarse circumferential machining marks were also present. Figure 23 shows the bottom of the punch, which is also extensively cracked. The deep stamp marks promoted cracking. The hardness of the punch varied from the surface inward. At the extreme surface it was 63 to 64 HRC. The hardness decreased gradually to 55 HRC 25 mm (1 in.) below the surface and was 53 HRC at the center. Cooling in liquid nitrogen raised the subsurface hardness substantially, indicating the presence of unstable retained austenite. The fracture grain size was very coarse—equivalent to ASTM 4.5—which indicates overaustenitization.

Microstructural examination revealed a deeply carburized condition with a very high surface-carbon content and a coarse martensitic structure below the region of massive carbide content. Figure 24 shows the microstructure at the surface (Fig. 24a) and at three different levels below the surface (Fig. 24 b to d). The structure shown in Fig. 24(d) is very coarse and is undesirable. Chemical analysis of incremental turnings revealed that the carbon content between the surface and a depth of 0.13 mm (0.005 in.) was 2.94 wt%. The total depth of decarburization exceeded 2.5 mm (0.10 in.).

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**Fig. 24 Microstructure of the heavily carburized cracked punch shown in Fig. 22 and 23**

(a) Massive carbide enrichment at the surface. (b) Excess carbides at the base of the crack, about 0.7 mm (0.0275 in.) deep. (c) Structure at about 1.08-mm (0.0425-in.) depth. (d) Coarse overaustenitized structure about 19 mm (0.75 in.) below the surface. All etched with 3% nital. All 700×.
Fig. 25 Failed chromium-plated blanking die made from AISI A2 tool steel
(a) Cracking (arrows) that occurred shortly after the die was placed in service. (b) Cold-etched (10% aqueous nitric acid) disk cut from the blanking die (outlined area) revealing a light-etching layer. Actual size. (c) Micrograph showing the decarburized layer that was unable to support the more brittle, hard chromium plating. Etched with 3% nitric. 60 x

Thus, AISI S7 was not a good choice for this application. It is difficult to carburize this grade lightly unless a liquid-carburizing treatment is used.

Decarburization may also occur at the surface of components during heat treatment, and it will affect service life. Figure 25(a) shows a chromium-plated blanking die made from AISI A2 tool steel that cracked after limited service. Cold etching of a disk cut from the blanking die revealed a light-etching layer that is particularly prominent at the working face and along the adjacent sides (Fig. 25b). Microscopic examination (Fig. 25c) revealed that the surface at the working face was decarburized to a depth of about 0.05 mm (0.002 in.). The soft zone beneath the hard chromium plating permitted the plating to flex under the influence of the blanking stresses, thus cracking the plating and surface region.

As another example of the influence of decarburization on service life, Fig. 26 shows a fractured pin (16 mm or ⅝ in. in diameter) and gripping cam (19 mm, or ¾ in., thick), both made of AISI S5 tool steel, that were used in plate-lifting clamps that broke after limited service. The rough chamfered edges of the hole of cam No. 2 are visible. The pin surface was heavily decarburized, as shown by the cold-etched longitudinal section through the pin (Fig. 26b). The flat surfaces of the cam were also heavily decarburized. Measurement of the parts indicated that the mill bark present on the surfaces of the stock used to make these parts was not removed. The standard machining allowances for hot-rolled bars were not taken.

Decarb-free stock would have been a better choice for the material for these parts.

Failures of Nitrided Parts. Although not used as commonly as carburizing, nitriding is occasionally used to improve the surface properties of tool steel parts. As with any process, the conditions must be properly controlled to produce good results. Failure of nitrided components can arise if the nitriding operation produces a heavy, white-etching nitride surface layer. Figure 27(a) shows an AISI 4150 alloy steel chuck jaw that broke due to the presence of such a detrimental surface layer. A section from a broken tooth of the chuck jaw is shown in Fig. 27(b). The nitride layer is present as a grain-boundary film beneath the surface layer. This is a very brittle condition.

Failures Due to Improper Quenching. Carbon tool steels are widely used in many tool and die applications. For best results, the hardened case must be properly developed. Figure 28 shows the striking face of a 38-mm (1.5-in.) diam × 64-mm (2.5-in.) long header die made from AISI W1 (1.0% C) tool steel that failed early in service due to chipping at the striking surface. Macroteching of a disk cut longitudinally through the die at the broken region revealed that the case around the striking face region was quite shallow and unable to support the working stresses. The flash-quenching procedure used to harden the striking face and bore did not produce adequate case depth at the striking face. The sharp corners of the striking-face cavity act as a stress concentrator; even a minor fillet at the corner would be helpful.

Figure 29 shows another example of a failure of a carbon tool steel (AISI W1) component due to improper quenching. This part, which measured 38 mm (1.5 in.) at the base, 21 mm (⅞ in.) at the top, 22 mm (¾ in.) thick, and 92 mm (3½ in.) long, was a wire-forming die that broke prematurely in service. Macroteching of a disk cut behind the fracture (Fig. 29b) revealed that the bore of the die was not hardened. Only a region along the corner of the die (the dull gray region on the macroetch disk) was hardened, and this only superficially (35 to 38 HRC in this region). The balance of the disk was at 29 to 30 HRC. A hardened chill zone should have been present at the bore surface (working surface of the die) if it had been properly quenched.

Failures Due to Improper Furnace-Atmosphere Control. Other surface-related problems may occasionally be encountered in tool and die failures. Figure 30(a) shows the mottled surface of a moil point, made from AISI W1 (0.80% C) tool steel, that was detected after the surface was sand blasted following heat treatment. This surface condition was due to excessive scaling (oxidation) resulting from improper furnace-atmosphere control. Figure 30(b) shows that the surface case was poorly developed, probably due to the influence of the scaled surface.
Fig. 26 Fractured pin and gripping cam made from AISI 55 tool steel
(a) These fractures occurred when the plate-lifting clamps containing these parts failed early in service. (b) As shown by this macroetched (10% aqueous nitric acid) pin, both the cam and the pin were heavily decarburized. (c) The chamfered cam holes were quite rough. 6.5×. The as-rolled surface decarburization had not been removed before heat treatment, and the surfaces were not cleaned up after heat treatment.

Failures Due to Burning and Melting.
Temperature-control problems can cause difficulties other than overaustenitization: burning or incipient melting can also occur in extreme cases. Figure 31(a) shows an end view of a powder metallurgy die component made from AISI D2 tool steel that melted and deformed due to highly excessive localized temperatures during heat treatment. The microstructure in this region (Fig. 31b) shows the melted region, heat-affected zone, and base microstructure.

High-speed steel components are particularly susceptible to burning/localized-melting problems due to heat-treatment irregularities because the austenitizing temperatures required are very high, much higher than for other tool steel grades. Figure 32(a) shows a part made from AISI M2 tool steel whose surface exhibited a rippled appearance after hardening. This condition was usually observed on the top of these parts, sometimes on the sides, but not on the bottoms. Examination of the top surface of the die on a transverse section (Fig. 32b) revealed a remelted surface layer. Beneath this zone was a layer containing as-quenched mar-

Fig. 27(a) AISI 4150 alloy steel chuck jaw that broke because of the presence of a brittle white-etching nitride surface layer
The part was hardened and tempered before nitriding. A micrograph of a broken tooth (arrows) of this chuck jaw is shown in Fig. 27(b).

Fig. 27(b) Surface of a broken tooth from the chuck jaw shown in Fig. 27(a)
The white layer at the surface is brittle iron nitride, which is also present as a grain-boundary film surrounding many of the grains near the surface. Note that the crack (arrows) follows the brittle white-etching nitride that formed in the prior-austenite grain boundaries. Etched with 2% nital. 290×
tensile and retained austenite. The outer 0.13 mm (0.005 in.) of the top surface was found to be enriched in carbon (1.28%). Immediately below this zone, the carbon content was normal for the grade. The higher carbon content lowered the melting point of the surface. The as-quenched martensite beneath the remelted zone probably formed due to conversion of some of the retained austenite at the surface during the tempering operations. The interior microstructure was tempered martensite.

Brittle Fracture of Rehardened High-Speed Steels. If high-speed steels must be rehardened, they must be annealed first. If they are not, fracture generally occurs. Such fractures have a fish-scale appearance due to the shiny, coarse-grain facets on their fracture surfaces. This is due to production of a coarse grain structure, which leads to a very brittle condition. Figure 33 shows the duplex, coarse-grain structure that results when a high-speed steel is rehardened without an intermediate anneal. Resistance to grain growth is provided by the presence of many fine carbides in the structure that are produced by the anneal but are not present after hardening. Thus, a second hardening treatment, without annealing, produces rapid grain growth at the very high austenitizing temperatures required for hardening high-speed steels.

Influence of Steel Quality

Despite the care taken in the manufacture and inspection of tool steels, faulty materials occasionally cause tool and die failures. However, the incidence of such problems is low. The most common of these defects are voids from secondary pipe, hydrogen flask, surface cracks (such as seams or laps), porosity or microvoids, cooling cracks, segregation, and poor carbide distributions. Improper control of annealing may also produce nonuniform carbide distributions or carbide networks that may influence heat-treatment uniformity, lower ductility, or impair machinability.

Failures Due to Seams or Laps. Figure 34 shows a coil spring made from AISI H12 tool steel bar stock. Although the bar was centerless ground before cooling and heat treatment, a tight seam (arrows) that was still present opened during quenching. Figure 35 shows part of a ring forging made of AISI A8 tool steel that measured 46 cm (18 in.) OD × 32 cm (12 in.) ID × 3.8 cm (1½ in.) thick. As shown in Fig. 35, cracks were found after forging and annealing. Scale was present on the crack wall, showing that the crack was open during forging. Figure 36(a) shows a macroetched disk cut transverse to the ring, illustrating the crack depth and decarburization around the cracks. Alkaline chromate etching (Fig. 36b) shows oxygen enrichment around the crack, verifying that it was open during high-temperature exposure. Figure 37(a) shows another example of a forging lap. This 3.6-kg (8-lb) sledge-hammer head, which measured 16.8 × 6 × 5.7 cm (6½ × 2½ × 2¼ in.), cracked shortly after being placed in service. The crack surface was oxidized, and the alkaline chromate etch (Fig. 37b) revealed oxygen enrichment. These two forging laps were caused by the forging operation and were not present in the original forging billet.

Hydrogen flaking is a potential problem for carbon tool steels and for some of the medium-carbon low-alloy steels, such as those used as prehardened plastic-mold alloys. Vacuum degassing is commonly used for such grades to reduce the hydrogen content to a safe level. Figure 38(a) shows a die made from AISI O1 tool steel that was found to be cracked after heat treatment. When opened (Fig. 38b), these cracks exhibited a coarse, shiny, faceted appearance. The cracks in this part were longitudinally oriented and were confined to the center of the section. Flakes are not observed in the outer region of sections because there is apparently more time for the hydrogen in the outer region to diffuse to a safe level. Flakes that
Fig. 29 Failure caused by improper quenching
(a) AISI W1 tool steel wire-forming die that broke prematurely during service. (b) Cold etching (10% aqueous nitric acid) of a disk cut behind the fracture revealed that the bore-working surface was not hardened; only the dull gray region was partially hardened.

Fig. 30(a) Moil point made of AISI W1 tool steel that exhibited a rough, scaled surface after heat treatment
The actual size of the moil point is shown at left. An enlarged view (3 X ) at the surface condition, which resulted in erratic surface hardness, is shown at right. See also Fig. 30(b).

Fig. 30(b) Cold-etched (10% aqueous nitric acid) disk cut from the moil point shown in Fig. 30(a)
A nonuniform chill is evident; the dark areas are hardened. 2 X

were close to the surface of the die exhibited temper color, but some of the deeper flakes did not. The temper-colored flakes apparently opened during quenching.

Failures Due to Overheating During Hot Working. Heating for hot working must be carefully controlled to prevent overheating, burning, or incipient melting problems. Overheating involves higher-than-tolerable hot-working temperatures such that most or all of the sulfides are put into solution and grain growth is excessive. Heavy hot reduction can repair most of the damage due to overheating, but if hot reduction is limited, ductility suffers. Figure 39 shows some of the typical characteristics of overheating. Tensile testing of an AISI H12 tool steel forged liner revealed poor tensile ductility. The coarse nature of the tensile fracture is apparent in Fig. 39(b). A section cut from the liner was notched and fractured, re-
revealing similar, coarse fracture features (Fig. 39a). The microstructure was also coarse, with a grain size coarser than ASTM 1.

**Failures Due to Unconsolidated Interiors.** It is possible, particularly with large section sizes that receive limited hot reduction, to experience failures due to material with an unconsolidated interior. A study of failures conducted over a 20-year period revealed three such failures, one of which is illustrated in Fig. 40(a) and (b). Figure 40(a) shows a fractured section from part of an AISI W2 die insert that cracked during rehardening. This die insert was made from a 15 × 25-cm (6 × 10-in.) billet. The horizontal arrow in Fig. 40(a) indicates the origin of the fracture, which was near the center of the section. A disk was cut through the part shown in Fig. 40(a) and hot acid etched. This revealed an unconsolidated region along the centerline (Fig. 40b).

**Failures Due to Carbide Segregation and Poor Carbide Morphology.** Large sections of high-alloy tool steels may exhibit very fine porosity or microvoids, which are often associated with carbide segregation and poor carbide distribution and morphology. These conditions reduce ductility and may lead to failures, depending on the application. Figure 41(a) shows a roll made from a 23-cm (9-in.) diam bar of AISI D2 tool steel. The flange edge of the roll that chipped off during initial use was due to poor carbide morphology (Fig. 41b).

Figure 42(a) shows a 7-cm (2½-in.) diam scoring die made from AISI A2 tool steel. The scoring edge near the center of the die spalled during either the stoning or grinding step after heat treatment. Microscopic examination at the spalled region revealed a band of carbides running down the center of the profile of the scoring die (Fig. 42b). Such carbide bands are not unusual for AISI A2: a different grade of steel should be used for such an application.

**Influence of Service Conditions**

Tools and dies, although made from the correct grade, well designed, and properly machined and heat treated, can fail after limited service due to improper operation or mechanical problems. In such cases, the failure analyst may spend considerable effort evaluating the design, grade selection, machining, and heat treatment without uncovering any abnormalities. In many cases, the analyst has little information concerning the use of the tool and die and can only conclude that service problems were responsible for the failure. In some cases, there may be evidence of the mechanical or service problem.

Mechanical factors that may cause premature failures include overloading, overstressing, or alignment/clearance problems. Excessive temperature may be a factor in hot-working die failures, perhaps due to inadequate cooling between operations. Failures have also occurred during assembly—for example, during shrink fitting of one part onto another. Stamp
Fig. 33 Examples of the microstructure of AISI M2 high-speed steel
(a) Desired quenched-and-tempered condition: 1200 °C (2200 °F) for 5 min in salt, oil quench, double temper at 595 °C (1100 °F). Etched with 3% nital. 500 ×. (b) Grain growth caused by reaustenitizing without annealing: 1220 °C (2225 °F) for 5 min in salt, oil quench, 1175 °C (2150 °F) for 5 min in salt, oil quench (not tempered). Etched with 10% nital. 400 ×. (c) Overaustenitization and onset of grain-boundary melting: 1260 °C (2300 °F) for 5 min in salt, oil quench, double temper at 540 °C (1000 °F). Arrows indicate regions of grain-boundary melting. Etched with 3% nital/Villella’s reagent. 1000 ×.

Fig. 34 Coil spring made from AISI H12 tool steel that cracked after heat treatment
A tight seam that was not removed by centerless grinding before heat treatment opened during hardening (arrows). 0.3 ×

Fig. 35 Portion of an AISI A8 ring forging that cracked (arrows) after forging and annealing.
Scale was present on the crack walls to a depth of 13 mm (1/2 in.) beneath the surface. Note the area that was ground to probe the crack depth.

Fig. 36 Metallographic samples from the ring forging shown in Fig. 35
(a) Macroetching (10% aqueous nitric acid) of a disk cut through the ring forging revealed decarburization around the cracks. 0.75 ×. (b) Etching of a polished section with a hot alkaline chromate solution revealed oxygen enrichment indicative of a defect open during forging. 80 ×
marks, in addition to causing heat-treatment failures, can cause service failures due to stress concentration. Alignment problems are a common cause of failure of tools used in shearing operations. While most tools and dies fail in a brittle manner, fatigue failures are sometimes encountered. In most cases, the fatigue failure is located at a change in section size, at a sharp corner, or at stamp marks.

Tools used in hot-working applications generally fail due to development of a craze-crack network referred to as heat checks. These result due to thermal stresses from alternate heating and cooling. Certain hot-working grades are particularly susceptible to heat checking if rapid cooling—for example, water cooling—is used.

As an example of a severe-wear condition that caused premature failure of a proprietary air-hardening die steel, Fig. 43 shows a die measuring 92 mm (3½ in.) max OD × 90 mm (3½ in.) high whose surface exhibits a crazed and eroded condition. The vertical scratch marks indicate inadequate clearance. The severe rubbing action reaustenitized a portion of the surface, resulting in a layer of brittle air-quenched martensite, a commonly observed condition in such failures. This die was properly machined and heat treated with no apparent problems other than service abuse.

Shear knives operate under particularly difficult service conditions. Figure 44 shows two AISI H13 shear knives used to grip bars after hot rolling so that they can be separated. Bar temperatures were typically from 815 to 980 °C (1500 to 1800 °F). Heat from contact and friction was excessive enough to reaustenitize the gripping edge, and this promoted spalling. Figure 45 shows the as-quenched martensite produced in this manner at the tip of one of the knives.

The heat pattern produced by service conditions can generally be revealed by macroetching. Figure 46 shows the face of a 12.7-cm (5 in.) wide AISI S7 cutter blade that was cold etched (10% aqueous nitric acid) after resharpening. The heat pattern is visible along the working edge and at the clamping locations.

Surface-chemistry changes can also occur during service. For example, Fig. 47 shows a cold-etched disk (10% aqueous nitric acid) from a 13.5-cm (5/4-in.) diam AISI H13 mandrel that was used to pierce and extrude brass. The mandrel cracked after about 30% of its anticipated service life. Cracking was due to heavy decarburization that occurred during service.

**Fig. 37 Failure caused by a forging lap in a sledge-hammer head**
(a) Cracks on the striking face soon after the hammer was first used. (b) A hot alkaline chromate etch revealed oxygen enrichment (white region) adjacent to the crack. 65 ×

**Fig. 38 Die made from AISI O1 tool steel that was found to be cracked after heat treatment**
(a) Longitudinal cracks after the surface was swabbed with 5% nital. (b) One of the cracks opened, revealing features typical of hydrogen flakes. 6.5 ×

**Fig. 39 Microstructural characteristics of overheating**
(a) Test fracture and (b) tensile-bar fracture from an overheated forged liner made from AISI H12 tool steel. Both 2 ×. (c) Micrograph illustrating the very coarse martensitic grain structure due to overheating during forging. Etched with 3% nital. 75 ×
Fig. 40(a) Fractured section of an AISI W2 die insert that cracked during rehardening

The horizontal arrow shows the origin of the failure, which corresponds to the center of the billet used to make the insert. 0.3 ×

Fig. 40(b) Disk that was cut through the origin of the insert section shown in Fig. 40(a)

Hot-acid etching (50% aqueous hydrochloric acid at 70 °C, or 160 °F) revealed an unsound center condition that promoted the fracture.

Die-casting dies usually fail by erosion of the die cavity, runners, and gates or by heat checking of the die cavity. Zinc die-casting dies are particularly prone to erosion-related problems. Heat checking is less of a problem because service temperatures are lower than for magnesium or aluminum die casting. Figure 50(a) shows an AISI H13 nozzle used in zinc die casting that failed due to erosion. A furrow about 7.6 cm (3 in.) long in the longitudinal direction by about 1.6 mm (1/16 in.) wide was present from the base of the nozzle to the outside diameter surface. Intrusion of the zinc into the crack was apparent. Figure 50(b) shows a longitudinal section through the nozzle, revealing rough machining marks and a misalignment of the bore.

Aluminum die casting places severe demands on hot-work die steels. The type of damage that results during such service is illustrated by the hot-work die steel runner block shown in Fig. 48. This part was used to produce over 100,000 aluminum transmission case covers. Areas 1 and 2, illustrating heat checking and wash-out, respectively, are shown at higher magnifications in Fig. 49.

Fig. 41(a) The flange edge of a roll made from AISI D2 tool steel that chipped off during its initial use

Failure was due to poor carbide distribution and morphology, which embrittled the material. See also Fig. 41(b).

Fig. 41(b) Micrograph showing the poor carbide distribution and morphology in the roll shown in Fig. 41(a)

The grain size, ASTM 6.75, was coarser than desired. Etched with 3% nital. 700 ×

Fig. 42 Failure due to a band of carbides

(a) AISI A2 scoring die splattered at the cutting edge during either the stoning or final grinding step after heat treatment. (b) Sectioning through the splattered region revealed a band of carbides intersecting the edge profile that promoted cracking. Etched with 3% nital. 180 ×

Figure 51 shows an AISI H26 exhaust-valve punch that split longitudinally due to fatigue after producing 1007 parts. The progressive nature of the crack growth is evident on the fracture faces. Heat checking on the working face initiated the fatigue failure. The punch surfaces were nitried after heat treatment. No material or manufacturing abnormalities were detected. Heat checking was promoted by the service conditions.

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Fig. 43 Die failure caused by severe wear
(a) Die made from air-hardening tool steel that exhibited a crazed and eroded condition. Areas A and B are shown in (b) and (c), respectively. Both 10 × . (d) Microstructural examination of area B revealing a layer of as-quenched martensite at the surface and a back-tempered region beneath it caused by frictional heat. Etched with 3% nital. 295 ×

Fig. 44 Two shear knives made from AISI H13 tool steel
The knives were used to grip hot-rolled bars after rolling so that they could be separated. The knives failed by spalling of the gripping edge after normal service life.

Fig. 45 A typical example of freshly formed martensite at the tip of a failed shear blade
The hardness was 59 to 60 HRC. Etched with 3% nital. 50 ×

Fig. 46 Macroetched (10% aqueous nitric acid) face of a cutter blade made from AISI S7 steel
Macroetching reveals the influence of frictional heat from service (dark-etching areas) that produce localized back-tempering (softening).
Fig. 47 AISI H13 mandrel used to pierce and extrude brass that failed after 298 pushes, about 30% of its expected life
The disk shown below, cut from the mandrel, was macroetched (10% aqueous nitric acid), revealing a heavily decarburized surface. The decarburization occurred during service.

Fig. 48 Runner block made from a proprietary hot-work tool steel that was used to die cast aluminum transmission case covers
Macrograph shows the worn out surface of the die. 0.25 x. Close-up views of areas 1 and 2 are shown in Fig. 49.

Fig. 49 Close-up views of areas 1 and 2 shown in Fig. 48
(a) Area 1 reveals heat checking on the working surface. 6 x. (b) Area 2 illustrates a washed-out area. 3 x

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**Fig. 50(a)** Erosion damage from the bore to just below the outside-diameter surface of an AISI H13 nozzle from a zinc die-casting die

![Image](image.png)

Fig. 50(b) Erosion damage and misaligned bore of the AISI H13 tool steel zinc die-casting nozzle shown in Fig. 50(a) after longitudinal splitting

![Image](image.png)

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Die-Casting Dies


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