A.J. Fuller, Jr., Introduction to Carburizing and Carbonitriding, *Steel Heat Treating Fundamentals and Processes*. Vol 4A, *ASM Handbook*, ASM International, 2013, p 505–521.

Introduction to Carburizing and Carbonitriding

General Process Description

The primary object of carburizing is to provide a hard, wear-resistant surface with surface residual compressive stresses that improve the useful life of components. The steel is austenitized and brought into contact with an environment of sufficient carbon potential to cause absorption of carbon at the surface and, by diffusion, to create a carbon concentration gradient between the surface and the interior of the metal. The objective is to increase the carbon content at the surface from that of the base alloy (typically 0.2%) to between 0.8 and 1.1%.

Two factors may control the rate of carburizing: the carbon-absorption reaction at the surface and the diffusion of carbon into the metal. Carburizing generally is done at temperatures in the range of 850 to 950 °C (1550 to 1750 °F). However, temperatures as low as 790 °C (1450 °F) and as high as 1100 °C (2010 °F) have been used. Although the carburizing rate can be greatly increased at temperatures above approximately 950 °C (1750 °F), the service life of most furnace equipment is degraded by operation at higher temperatures. This serves to limit the carburizing temperature at which processes can be operated economically.

Carbon Gradient. The gradient of carbon content between the surface and the center is the signature feature of a carburized component. The high-carbon layer at the surface is known as the case, and the low-carbon center is known as the core. The methods for the measurement of case depth are described later. A representative carbon concentration gradient for a carburized component appears in Fig. 1. Note how the hardness profile follows the carbon profile. The profile for a particular component will depend on the specific process parameters, including the desired surface carbon and the desired case depth.

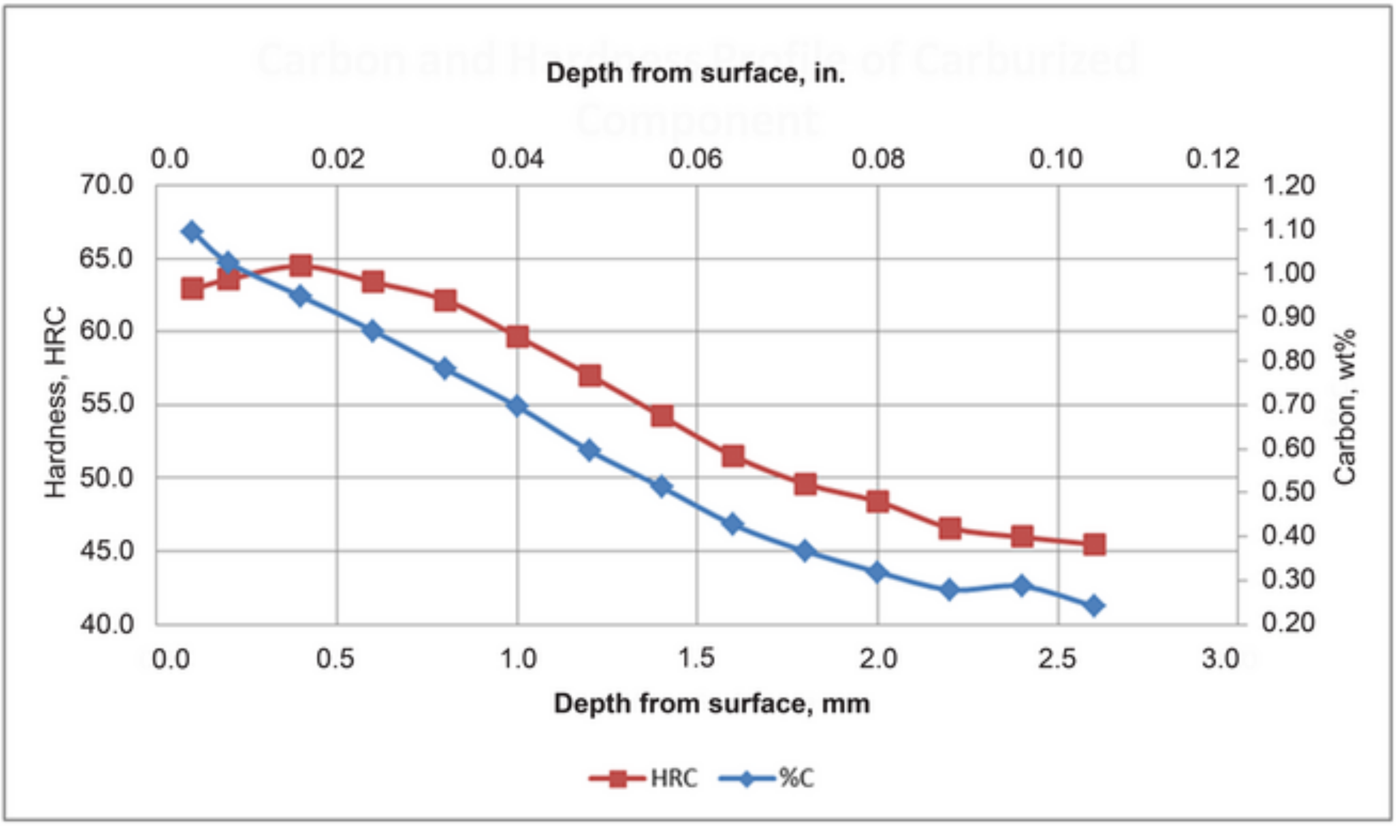

Fig. 1 Representative carbon profile on an AISI 8620 steel rod of approximately 25 mm (1 in.) diameter after carburizing at 950 °C (1750 °F) for 12 h in an enriched endothermic atmosphere. The rod was subsequently austenitized at 850 °C (1560 °F) and oil quenched, untempered. Courtesy of Amsted Rail Brenco

Martensite Start Temperature. Carbon content has a powerful effect on the martensite start (M_S) temperature of steel, and this in turn is a significant contributor to the unique properties of a carburized component. Figure 2 shows the effect of carbon content on the M_S temperature as well as the corresponding microstructure and retained austenite levels. The inverse relationship between carbon content and M_S temperature results in suppression of the M_S temperature at the surface of a carburized component.

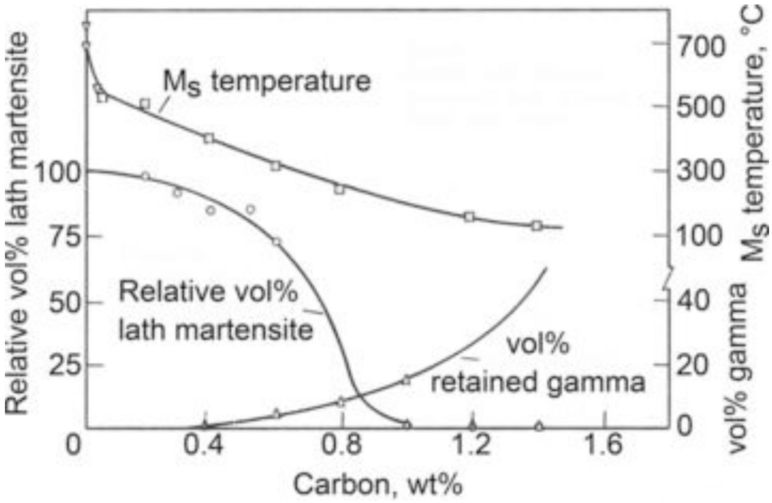

Fig. 2 Effect of carbon content in iron-carbon alloys on the martensite start (M_S) temperature, the relative proportions of lath and plate martensite, and the volume percent retained austenite. Source: Ref 1

In components made from through-hardened steels, the carbon content is uniform throughout the cross section. During quenching, the martensitic transformation begins at the surface and progresses inward as conduction reduces the temperature of successive layers. The center transforms last.

In a carburized component, the higher carbon content at the surface decreases the M_S temperature. During quenching, the surface begins cooling, but because of the lower M_S temperature, the surface does not begin to transform immediately. As heat flows out of the component by conduction, the temperature profile crosses the M_S temperature profile at a point below the surface, and martensite begins to form while the surface remains austenitic. The result is that the martensitic transformation does not begin at the surface, as one might expect, but rather at a depth below the surface. Soon thereafter, the surface drops below its M_S temperature and transforms to martensite. This "inside-out" hardening has a profound effect on the residual-stress profile of a carburized component.

Beneficial Residual-Stress Profile. The key to the success of carburized components is the suppression of M_S, as discussed in the previous section. As the layer of steel beneath the surface transforms into martensite, it expands as a result of the crystallographic change associated with the austenite-to-martensite transformation. Martensite formation results in an increase of both hardness and strength. Moments later, when the surface (with its lower M_S) transforms, it similarly tries to expand. However, because the surface is constrained by the volume underneath that has already transformed, expansion is inhibited. This causes the surface to enter a state of residual compression. Because all static components must be in balance, the surface compressive residual stress is balanced by a tensile stress at the core of the component (Fig. 3a). If a bending load is applied to the component, the applied stresses will match the profile given in Fig. 3(b). Note that the greatest magnitude of applied stress is realized at the surface of the component, while the stress drops to zero at the center. If a component with a compressive residual stress such as that in Fig. 3(a) is loaded as in Fig. 3(b), then the resulting stress profile will look like that in Fig. 3(c).

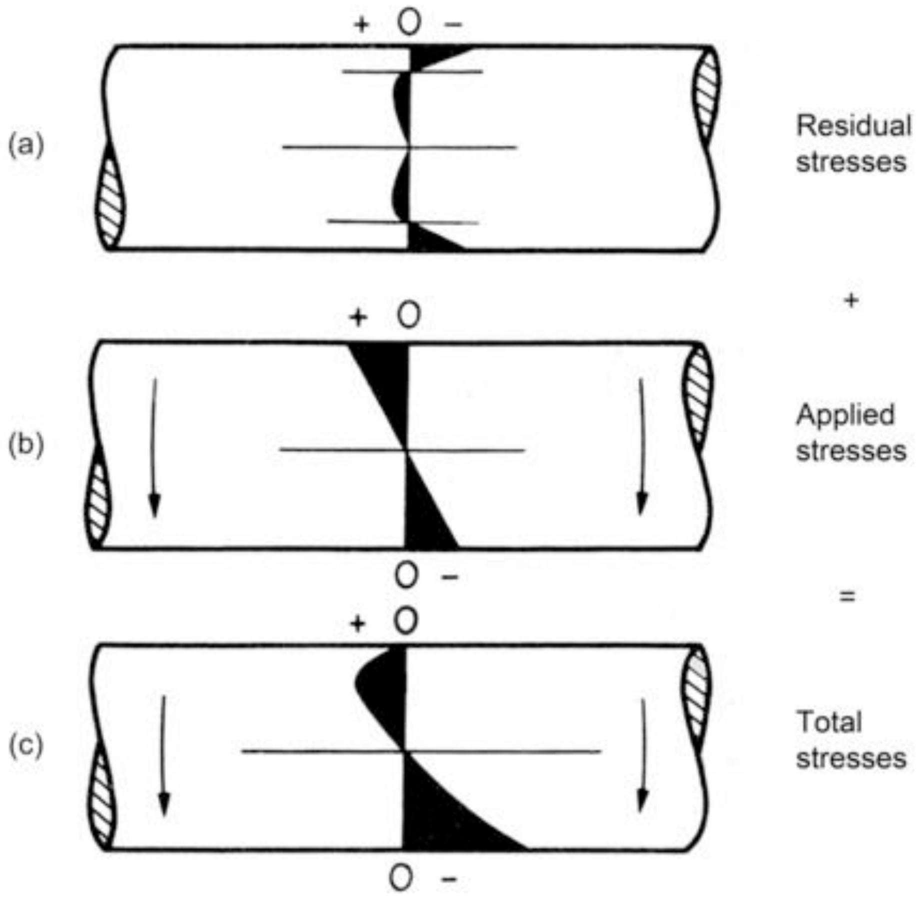

Fig. 3 Illustration showing how residual stresses associated with a carburized surface reduce the effect of surface stress due to an applied load. Source: Ref 1

The resulting compressive residual stresses at the surface serve to arithmetically reduce the magnitude of an applied stress on the component. A component with a compressive residual stress at the surface can support a load higher than its material properties would otherwise allow. This phenomenon has the effect of increasing the practical load-carrying capacity of the component (Fig. 3c). The same principle of overcoming applied tensile stress with residual compression is used in prestressed concrete beams. Through-hardened steels do not readily produce this type of residual-stress profile. If a through-hardened component and a carburized component are compared in the same application and both have the same hardness, the carburized component will generally support a greater load before yielding. Alternatively, the use of carburization could allow a smaller, lighter component to replace a larger, heavier one made of through-hardening steel while supporting an equivalent load.

The benefit of surface compressive residual stresses applies not only to static loading but to fatigue loading. As can be seen in Fig. 4, the fatigue limit of rollers in pure rolling is much higher for the carburized steel than for the alternative processes. This is a direct result of the compressive residual-stress profile that carburizing produces.

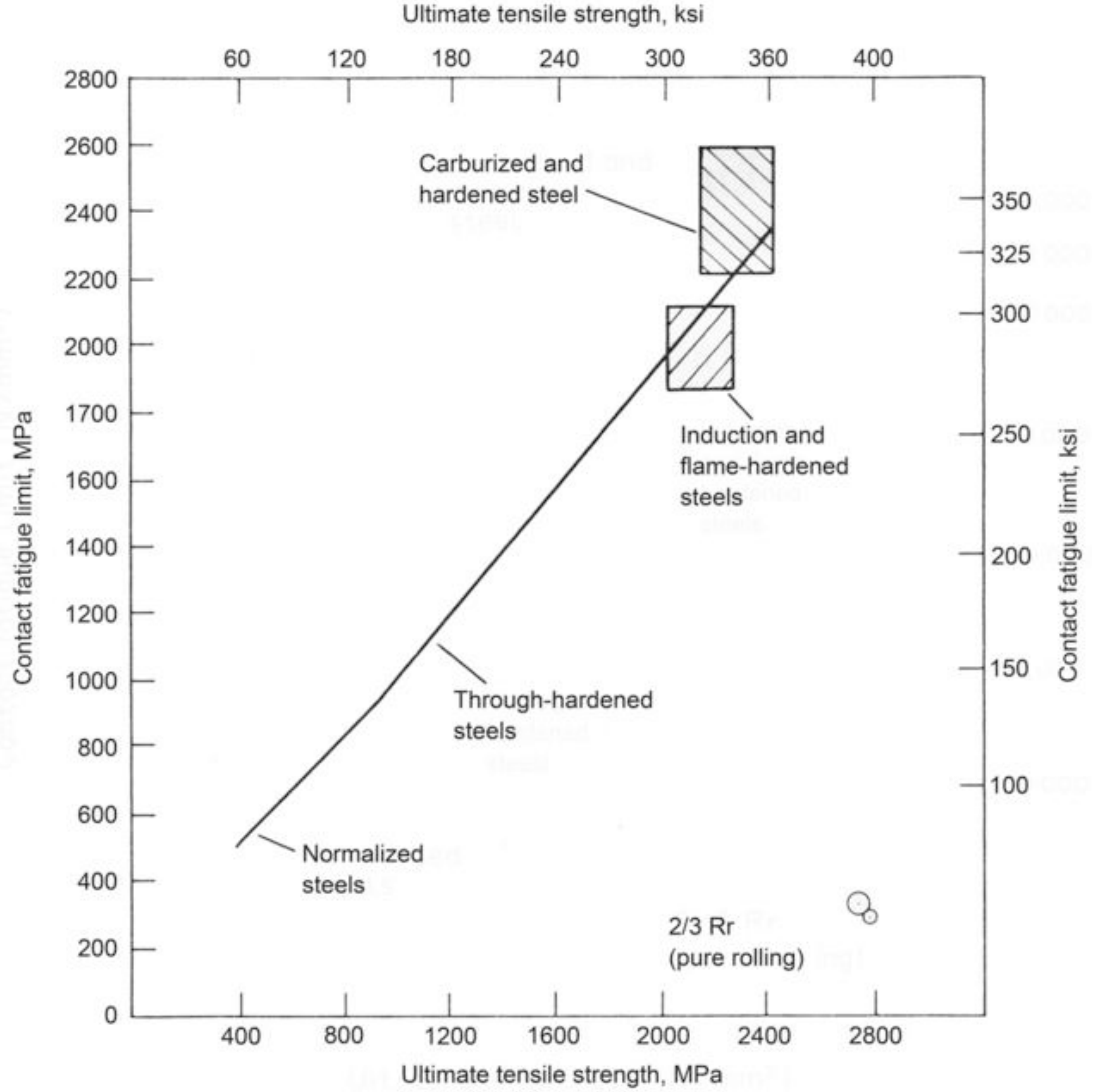

Fig. 4 Rolling contact fatigue test results. Test material run against a case-hardened surface. Deep cases used on all surface-hardened discs or rollers. Source: Ref 1

Strength and Hardness. While the carbon profile serves to create a beneficial residual-stress profile, it also serves to produce substantial changes in the mechanical properties. Figure 5 shows the relationship between carbon content and hardness for various microstructures. From this diagram, it can be seen that the hardness of martensite increases dramatically up to approximately 0.7% C, at which point the hardness begins to plateau. In a carburized component, the surface carbon is typically greater than 0.7%, so the hardness will be highest near the surface and then decrease with depth. The gradient in hardness is due to a combination of decreasing carbon content and cooling rates from the quench. The effective cooling rate at each position is determined by its distance from the surface, with positions closer to the surface seeing a more rapid quench and deeper positions seeing a progressively slower effective quench rate. The achieved strength and hardness at each point on the profile is a function of both position and carbon content.

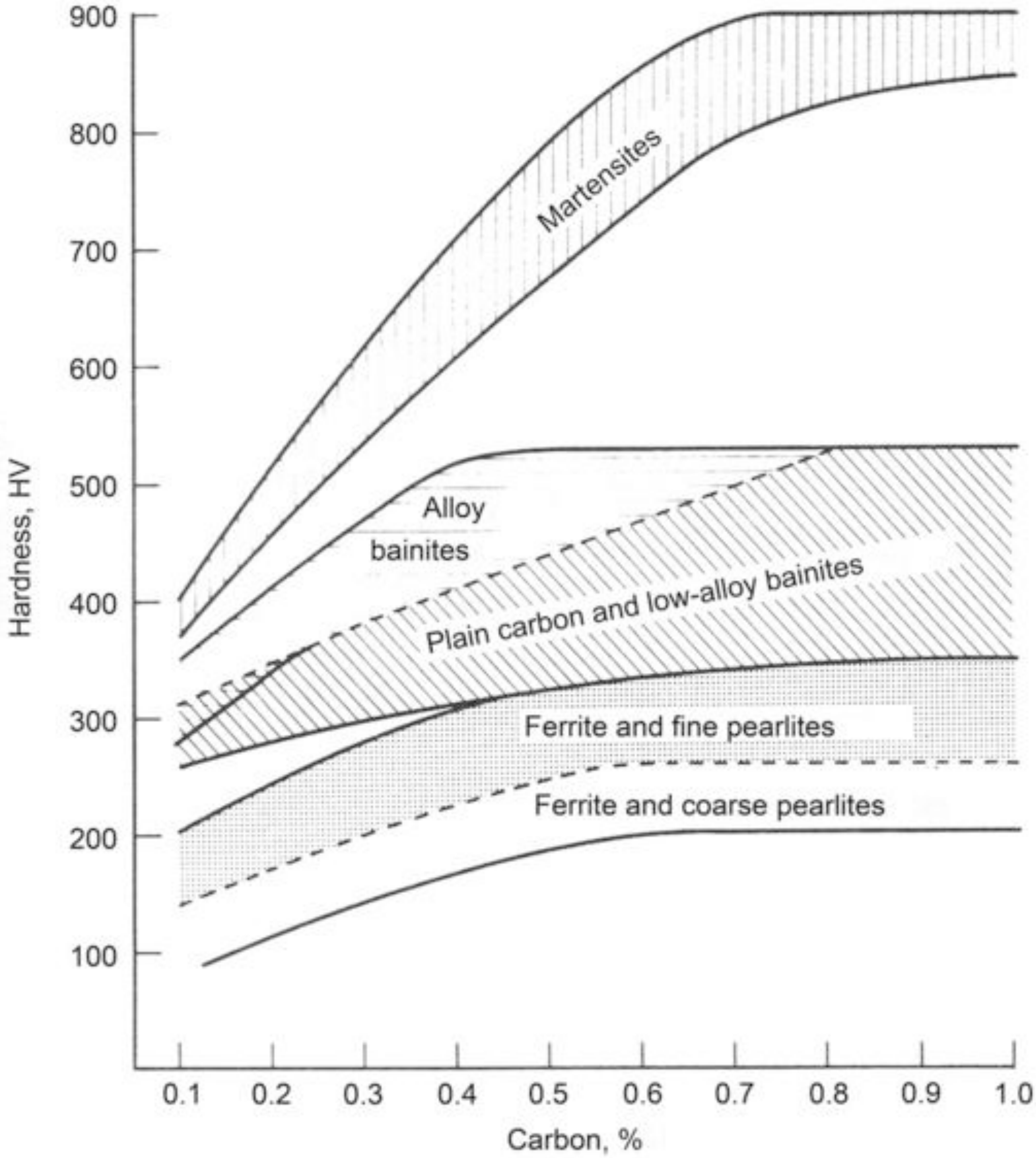

Fig. 5 Effect of carbon on the hardness of various microstructures observed in plain carbon and low-alloy steels. Source: Ref 1

It is worth noting that the highest hardness in a carburized component is often just below the surface (Fig. 1). This seemingly contradictory behavior is typically due to the influence of higher carbon and thus higher retained austenite levels at the surface. Austenite is softer than martensite, so when it is present in sufficient proportions, it has the effect of reducing the overall hardness. This effect tends to be rather shallow.

The relationship between tensile strength and bending fatigue is illustrated in Fig. 6. Because of the relationship between hardness and tensile strength, it can be seen that the bending fatigue strength of a carburized component will be highest at the surface, where fatigue cracks usually initiate. Carburized components match the strength and hardness of through-hardened steels, so they would be expected to exhibit similar fatigue life. However, while both carburized and through-hardened components benefit from the relationship between hardness and tensile strength, carburized components are unique in that they derive additional fatigue strength from the presence of compressive residual stresses at the surface.

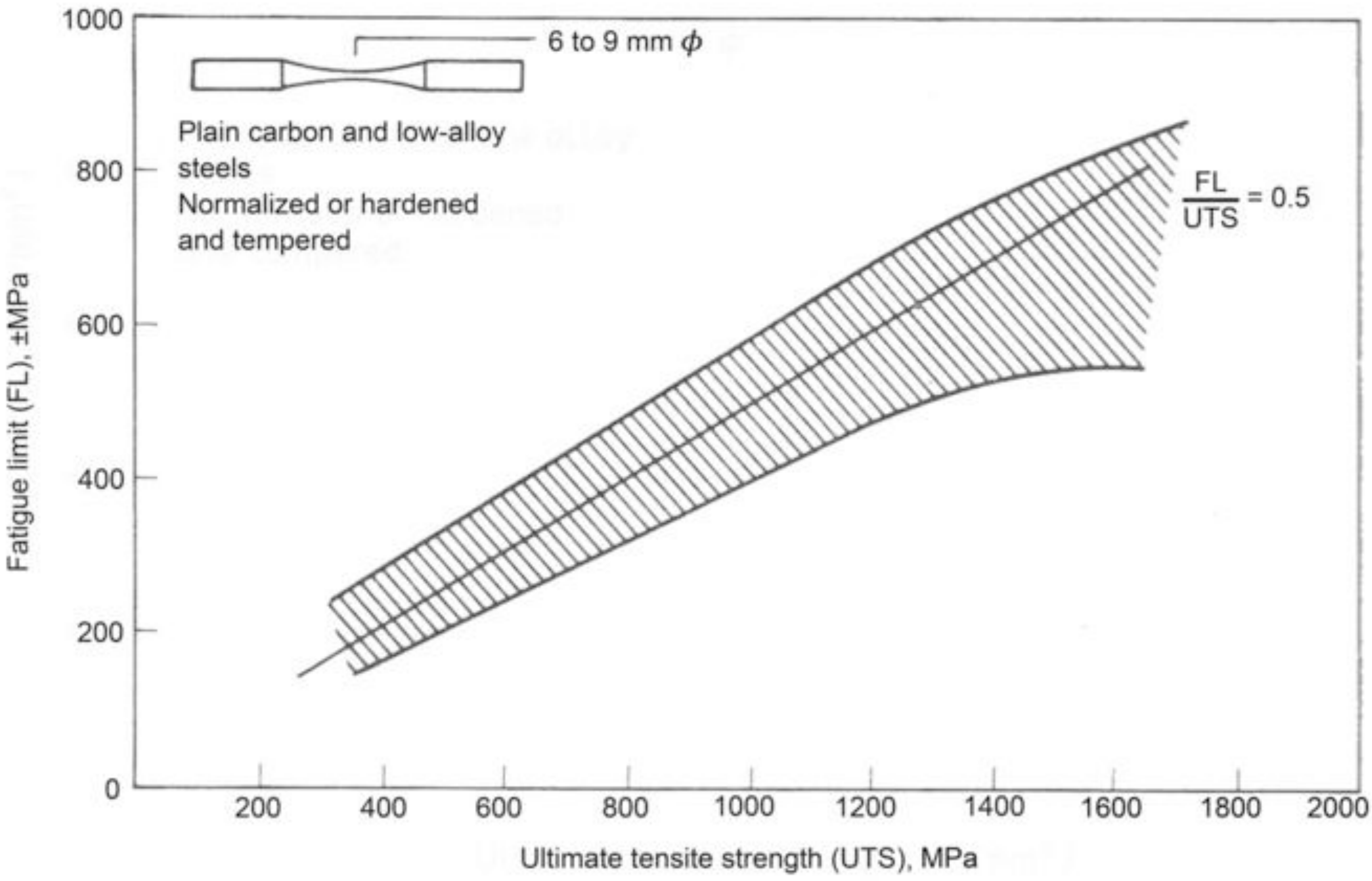

Fig. 6 Relationship between rotating-bending fatigue limit and tensile strength for through-hardened steels. Source: Ref 1

Design Considerations. When designing a carburized component, there are numerous variables that can be controlled to suit a particular application. Such variables include surface carbon content, surface hardness, case microstructure, case depth (either effective or total), core strength, and hardness. Some applications may even specify the level of surface retained austenite and residual stress.

The most important consideration is what case depth is required. The case depth has implications both for the cost of the component (due to energy consumption and processing time) and the load-carrying capacity of the finished part. The choice of what case depth to use is often based on experience with similar applications. However, such a method is subject to error because it could either specify a deeper case than necessary, wasting resources and increasing cost, or it could fail to account for differing operating conditions and loads, which could result in a case too shallow to adequately support the required loads. A thorough design approach must consider the loads that are anticipated in service and then match the case depth to these loads. Table 1 provides a general comparison of case depths for different application conditions.

Table 1 Typical range of case depths for carburized parts in general areas of applications

Application	Case depth	
	μm	in.
High wear resistance, low-to-moderate loading. Small and delicate machine parts subject to wear	≤500	≤0.020
High wear resistance, moderate-to-heavy loading. Light industrial gearing	500–1000	0.020–0.040
High wear resistance, heavy loading, crushing loads, or high-magnitude alternating bending stresses. Heavy-duty industrial gearing	1000–1500	0.040–0.060
Bearing surfaces, mill gearing, and rollers	1500–6350	0.060–0.250

Source: Ref 2

It is important to remember that the ultimate tensile strength of the carburized case changes with the hardness at each depth on the carbon profile. This gives the designer a unique opportunity to customize the strength of the component to the application.

As an example of how to design a component for a specific application, consider a component intended for a contact application such as a gear or roller bearing. For contact applications, it has been proposed that the principal failure mode occurs where the shear stresses experienced by a component exceed the shear fatigue limit at any given depth below the surface of the component (Fig. 7).

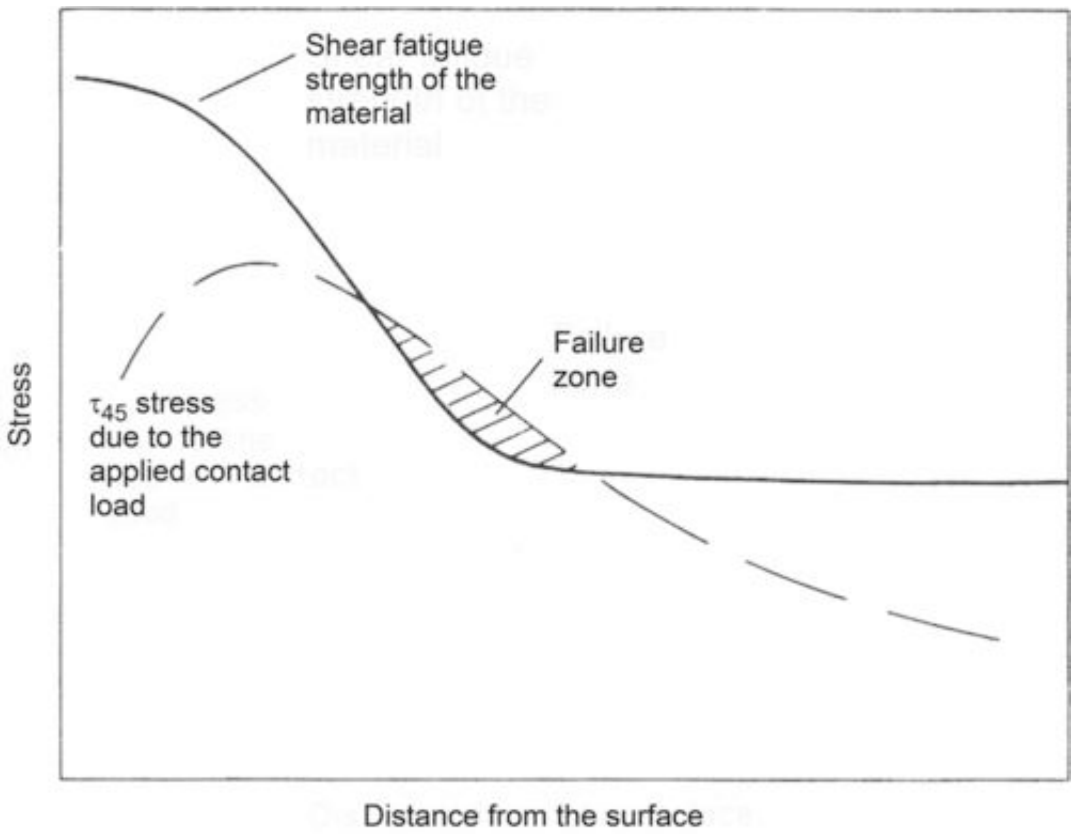

Fig. 7 Strength versus stress considerations for the crushing of a carburized case. Based on Sharma et al.'s explanation. Source: Ref 1

The first step is to determine the shear stress profile that the component will experience under the anticipated service loads. This can be done with mathematical models such as those proposed by Hertz and Stribeck. Computer models such as finite-element analysis have also been used to estimate the maximum shear stresses for certain applications. Once the shear stress profile is known, it is then possible to work backward to the desired hardness profile by determining the shear fatigue strength required to counter the applied shear stress at each point along the stress profile. Then, by using the relationship between shear fatigue strength, ultimate tensile strength (shear fatigue strength ≈ 0.31 × Ultimate tensile strength), and hardness, it is possible to translate the applied shear stresses into a hardness value necessary to match that stress. By employing an appropriate factor of safety, the necessary hardness profile (and therefore case depth) to adequately support the applied shear stress can be determined.

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