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Some Needed Precautions When Induction and Flame Hardening

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Surface hardening after carburizing produces parts with residual compressive stresses at the surface — a very desirable condition to enhance fatigue resistance against alternating loads in bending or torsion. Flame hardening produces lower surface compressions, and an underlying layer in tension dangerous to fatigue resistance. Induction hardening acts in a similar way, but the extent of this zone in tension can be limited by controlling frequency and power input.

THE METALLURGIST or the engineer who specifies induction hardening or flame hardening for highly stressed machine parts may find himself in trouble with fatigue failures. This risk of weakening machine parts by these localized surface hardening processes is due to trapped tension stresses in the hardened layer and to reduced hardness of the adjacent non-hardened material. These effects are the natural result of the highly localized heating and cooling operations and they will be serious fatigue hazards so long as the quality is judged solely by surface hardness.

We have ample evidence that surface hardening by flame heating and by induction heating merits the serious consideration that it is receiving for many new production items. It therefore seems appropriate that we critically analyze these hardening processes to discover, if possible, the results that may be expected from the several types of hardening equipment that are being offered. The data now at hand are too meager for complete evaluation of induction and flame hardening equipment and processes and, therefore, the discussion that follows is based upon studies of these processes as now practiced together with studies of other heat treating processes that most nearly resemble them.

Surface hardening is applied to machine parts for the purpose of

1. Resisting destruction of the surfaces as by wear, scoring or corrosion.
2. Increasing the fatigue strength of highly stressed machine members.
3. Combinations of wear or corrosion resistance and increased fatigue strength.

The following discussion will be concerned only with the effect of superficial quench-hardening on the fatigue strength of the part.

Fatigue strength of machine parts of any hardness is increased when the regions that are stressed in tension by the operating loads are residually stressed in compression. This increase in strength is obtained because

1. The surface of any specimen is more vulnerable to fatigue fracture than underlying layers.
2. Fatigue failures result only from tension stresses.

We may, therefore, greatly increase the durability to alternating loads (endurance) by inducing residual compressive stress in regions that are stressed in tension by the operating loads, since we thereby reduce the stress (tension) that causes fatigue failure. This is particularly true for parts that are loaded in bending or in torsion;

we can profit less by compressive pre-stressing for members stressed in direct tension.

Intentional introduction of residual stress to increase the fatigue strength of machine parts has been practiced for a very long time but the processor has rarely understood that the added strength was due to favorable internal stresses. To most of us residual stresses are undesirable because we only know that they cause warpage and occasional fractures during heat treatment and premature fatigue failures of parts in service. It can be shown, however, that residual stresses are not bad; it is only our failure to understand them and to use them properly that makes them seem bad. Like the sailor who has learned to use "adverse" winds to his own advantage, so must we learn to use residual stresses to the advantage of our structural materials.

In modern practice, compressive pre-stress is obtained by mechanical manipulation and by heat treating. Thus, springs are "pre-set", meaning that they are stressed beyond the yield strength a few cycles; because of yield, this induces residual stresses in the springs when the external load is removed. This is done because of the known improvement in fatigue durability that results. Similarly, springs, gears and other parts are improved by shot blasting, tumbling, and sometimes by straightening because these operations induce compressive residual stresses to counteract tension stresses in operation.

Compressive residual stresses in the surface layers are also obtainable by carburizing, nitriding, induction hardening, flame hardening and by severe quenching. The well-known improvement in fatigue strength that results from these treatments, when they are properly applied, is largely a matter of the residual stress pattern that is obtained. However, it is also possible to obtain the *wrong* distribution of residual stress, in which case the fatigue strength of the part is decreased. Rather than issue blanket condemnations of all residual stress in applying processes in which the wrong distribution can be obtained, we must surround the operation with suitable safeguards so that we encourage good practices and avoid bad ones.

Fig. 1 — Top Is Side View of ½-In. Square Carburized on Two Opposite Faces Only, and Below Is Same Bar After Splitting Longitudinally. Bow is caused by compressive stresses trapped in carburized surfaces by carburizing and hardening

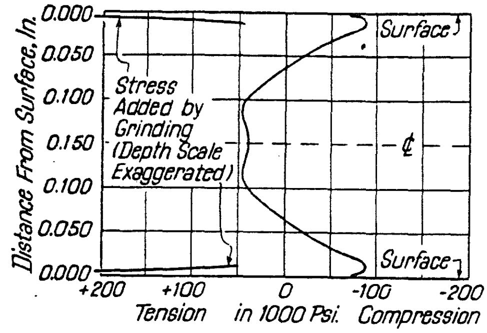


Fig. 2 — Residual Stresses Actually Measured in Hardened Gear Tooth (Carburized) Approach 100,000 Psi. Compression at Surfaces, and Can Be Increased 50% by Shot Peening

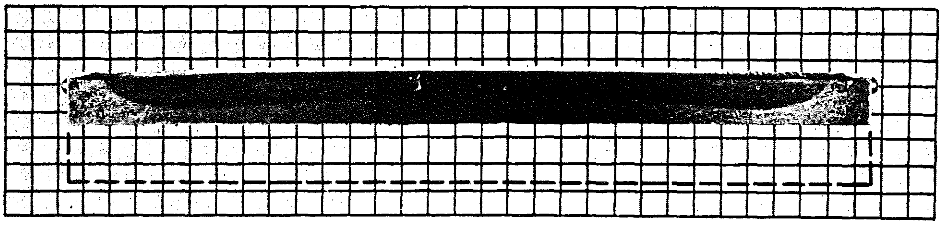


Fig. 3 — Compressive Stress of About 40,000 Psi. Causes a Small Segment Cut From an Induction Hardened Journal Bearing 6 In. Long to Take an Upward Bow. Original thickness shown by dotted line

The point can perhaps best be clarified by reference to our common experiences. Carburized parts are fatigue resistant because, through increased hardness, the strength of the outer carburized layer is increased and also because the carburized layer is highly stressed in compression. The compressive stress in the carburized layer is the result of thermal contraction of the outside layers upon quenching, and the increased volume of the hardened layer.

Let us see how this comes about:

When a cylindrical heated part is quenched, the contraction of the outer layers stresses the still plastic inner material beyond its yield strength and this inner material is, therefore, "upset". As the cooling proceeds, the inner material also contracts, drawing down upon the outer shell which compressively stresses these outer layers with corresponding tension stress in the inner material. Also, because of the increased carbon content of the carburized layer, this layer is transformed during the quench to a material (martensite) of *greater volume* which augments the surface compressive stress that was obtained by the thermal contraction.

The residual stress in a carburized bar is graphically illustrated in Fig. 1, showing at left a ½-in. square bar that is carburized on two opposite faces, carburization of the other two faces being stopped off by copper plating. The same bar, split with a saw after hardening, is shown at right. The curving of the two halves of the bar is the result of compressive residual stress in the outer layers and the balancing tension residual stress in the core material.

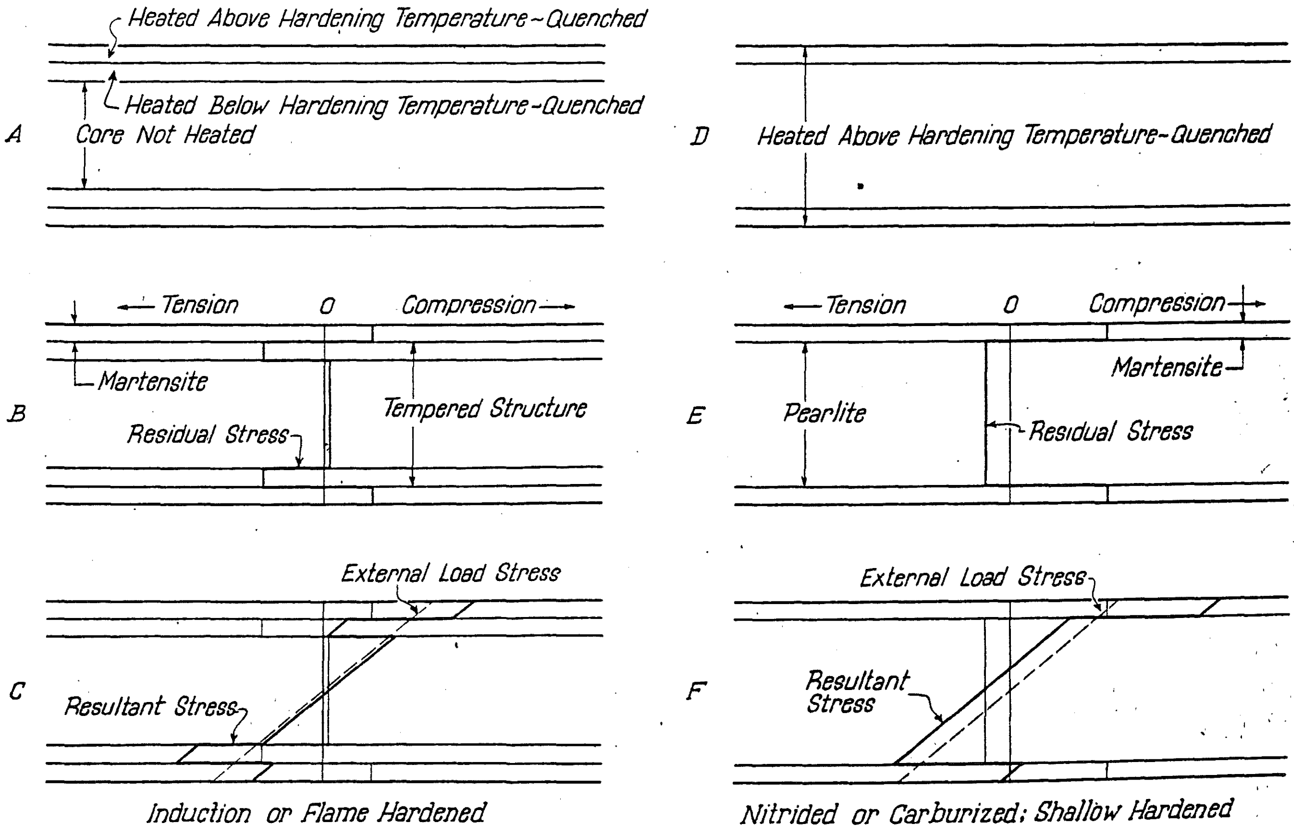
Figure 2 shows a diagram of the actual residual stress that existed in a carburized gear tooth. Here we see that the carburized layer is stressed in compression to approximately 90,000 psi. and the core is stressed in tension to approximately 50,000 psi. The stress in this gear tooth was measured by removing successive layers and measuring the change in length and in curvature of the remaining material as each layer was removed. Note the tendency for stress reversal toward tension at the surfaces. The reason for this reversal may be the result of retained austenite, decarburization, or similar influences. The great improvement in fatigue durability that is obtainable by shot peening carburized gears is due to the increase of the compressive stress in the outermost layers from less than 90,000 psi. to something like 150,000 psi.

In flame heating and induction heating processes, the sequence of events is reversed from that of carburizing and, therefore, the stress in the surface material, due to thermal contraction, is tension instead of compression. In such surface heating, the outer material becomes plastic while the inner material is cool and rigid. The hot outer layer wants to expand but, being restrained by the cold inner material, this hot layer is plastically deformed. Upon cooling, the thermal contraction of the deformed outer layer on the cool unyielding inner core results in tension of this layer and the part is, therefore, weak in fatigue as ordinarily understood.

However, when hardenable steel is quenched from above the hardening temperature it experiences a phase change upon cooling to a material (martensite) of greater volume. This volume increase, by itself, produces compressive stress in the transformed layer.

It follows that the net surface residual stress in surface hardened steel is the algebraic sum of the tension stress produced by the thermal contraction and the compression stress produced by the transformation. In specimens that have been measured, it has been found that the surface was compressively stressed to about 30,000 to 40,000

Fig. 4 — Diagram of Surface and Sub-Surface Stresses in Round Bar Resulting From Surface Hardening (A, B and C at Left) and From Carburizing or Nitriding to an Equally Shallow Depth (D, E and F at Right)



psi. Figure 3 on page 1264, for example, shows a section of an induction hardened crankshaft in which the stress has been analyzed in the same manner that was described for the gear tooth of Fig. 2. Note that this induction hardened specimen is curved convex on its upper surface, indicating a desirable compressive stress in the hardened layer.

We have described the several events that take place in the hardened layer of a surface hardened part as a result of heating and quenching (no carburizing). We must now consider what happens to the material immediately below that which was heated above the hardening temperature. We may imagine three zones as is shown in Fig. 4-A, an outer layer that is heated above the hardening temperature, a second layer that is heated below the hardening temperature, and the core material that is not heated at all.

The outer layer, which is quenched from a temperature above that required for hardening, is compressively stressed as is shown in Fig. 4-B by virtue of the transformation that occurred upon hardening. However, the second layer does not experience this transformation, although it was hot enough to be effectively annealed and thereby weakened. Upon cooling, it experiences only the thermal contraction and this layer will be stressed in tension, as is also shown in Fig. 4-B.

When such a specimen is stressed by an external load, as is shown in Fig. 4-C, the second layer is very highly stressed in tension since the stress in this zone is the sum of the tension stress from the external load and the residual tension that resulted from the thermal contraction. Since fatigue failures result only from tension stresses, this second zone is vulnerable to fatigue, particularly if it emerges to the surface as at the end of a hardened zone or at the overlap of two passes of a hardening flame. When this highly stressed layer is exposed, it is doubly vulnerable because it then is subject to the added stress raisers of surface irregularities. The emergence of the second zone to the surface occurs when local areas are hardened, as on crankshaft journals, or gear tooth flanks, or when a previously heated area is reheated — that is, when the surface is too large to be heated at one time or when it cannot be continuously heated in one direction.

The loss of fatigue strength of an induction hardened crankshaft is shown in the S-N chart in Fig. 5. Fatigue failure occurred by bending stress in the vicinity of the fillet where the second zone emerged to the surface of the journal.

Contrast these surface heating conditions with the conditions that prevail in specimens hardened by nitriding, carburizing, or severely quenched shallow hardening steel as is shown in the charts of Fig. 4-D, E and F. There is no "second zone effect" because the direction of heat flow is opposite to the heat flow in induction and flame hardened parts. The resultant operating tension stress, which normally causes fatigue failure, is therefore much lower. Also there is no annealed material below the hardened layer, and this underlying material is stronger than the annealed material in induction or flame hardened specimens.

Whereas flame hardening and induction hardening may be harmful to fatigue strength, we should look for means to reduce this effect or to eliminate it altogether. For example, in Fig. 6 are etched sections of two gears that have been hardened so as to obtain widely different effects. The gear at the left was heated at a low rate and by relatively low frequency current. The outer

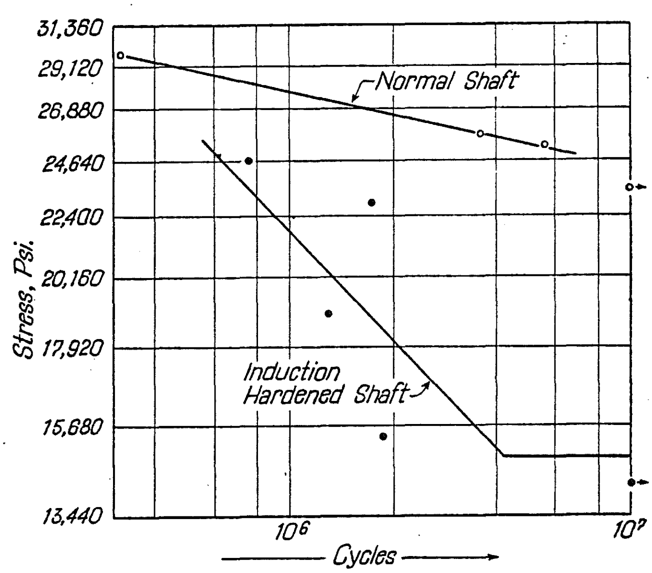


Fig. 5 — Endurance Tests on Crankshafts; "Normal" Was Carburized and Quenched. (Williams and Brown, Engineering, Vol. 154)

(hardened) zone includes practically all of the tooth and the second zone is prominent near the root. This gear would probably be satisfactory where strength is not needed but only resistance to wear or corrosion. Its fatigue strength would presumably be low because the high residual tension stress in the second zone would combine with operating bending tension stresses, as shown in Fig. 4-C. Remember also that this high resultant tension stress is acting on annealed material and not on the stronger hardened material.

At the right in Fig. 6 is shown another induction hardened gear in which the frequency was so high as to successfully heat the root area

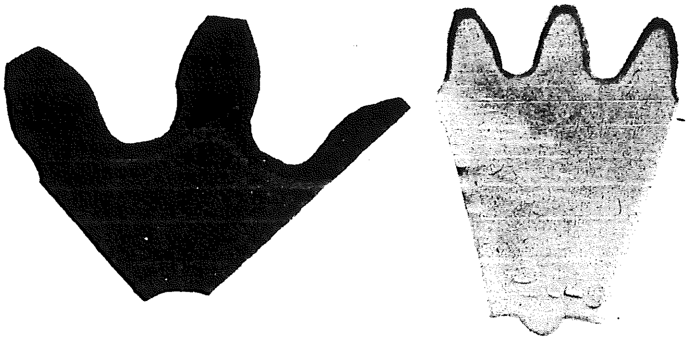


Fig. 6 — Widely Varied Hardness Patterns of Gears Hardened by Induction

5 in.	Diameter	4 in.
	Width	¾ in.
2 in.	Pitch	8½ in.
153,000	Frequency	450,000
28 kw	Input	58 kw.

while affecting the flanks and tips of the teeth much the same as is produced by carburizing. Also the rate of heat input was great enough to reduce the second zone to very small proportions. Note that similar effects are produced on the spline at the center of the gear. This gear would be equal to the gear shown at the left in resistance to wear and corrosion and would, presumably, be very much stronger in bending fatigue because of the reduced second zone effect.

Many gears are flame hardened on the side, from root to edge of tooth only, somewhat as is shown in Fig. 7. This hardness pattern is more detrimental to fatigue strength than the one shown at the left of Fig. 6 because the second zone comes to the surface at the root of the tooth where the bending stress is greatest.

These illustrations, Fig. 6 and 7, indicate that we should not install surface hardening equipment until we have determined the effects that are desired and how they may be obtained. If highly loaded gears are to be hardened by induced electrical currents we should presumably use very high frequency equipment with a high power input. The high frequency is necessary to produce a satisfactorily hardened case at the root of the tooth. High power is necessary to increase the heat gradient and thereby decrease the thickness of the second zone, a tension stressed layer.

For small gears the equipment should be capable of heating the *entire* toothed periphery, because if the gear is heated in sections it would be necessary to form one or more junctions between the previously heated and the newly heated sections. When this junction is formed at the root of the tooth there will be a severe disturbance of the previously heated material with a loss of surface compression and, therefore, fatigue strength. If this junction is made at the tip of the tooth a similar disturbance will occur but this will be in a region of low stress and, therefore, not harmful unless it affects the hardness at the tooth tip (in which case the scoring resistance of the tooth will be adversely affected).

The danger of "second zone fatigue vulnerability" is by no means confined to gear teeth and crankshafts. It is present in all highly loaded machine parts where the bending or torsion loads are high and the hardened layer is relatively shallow. It is particularly harmful where the hardening is localized so as to bring the second zone to the surface, as occurs in local induction hardened journals or when flame or induction heat is applied to hard surfaces to soften local areas. Likewise it is an effect that has long been known to the makers of case carburized parts (gears and roller bearings) and is guarded against by proper mutual adjustment of depth of case and strength of underlying core to the loads that must be carried by the machine part.

In flame hardening the temperature gradient is lower than can be obtained by induction heating and, as a consequence, the second zone effect cannot be reduced to the same extent as is possible by high frequency induction hardening. The harmful second zone effect can, of course, be avoided by heating to such depth, whether it be by flame, by resistance, or by induction, as to approach heating all the way through — as is done in the ordinary furnace. This method of heat treating has considerable merit as a means of quick heating to avoid decarburization, but it is not in the class of surface hardening treatments discussed in this article.

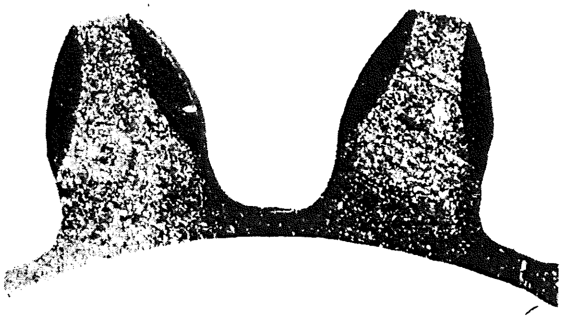


Fig. 7 — Frequent Pattern of Flame Hardened Metal on Faces of Teeth (No Hardening at Root)