Minimizing Gear Distortion During Heat Treating

Marcel Suliteanu

Graded hardening technology has proven over the years to yield very good results when used in the heat treating of carburized gears. It is especially advantageous for smaller companies, subject to higher competitive pressures. Unfortunately, despite the fact that graded hardening is a very well-known method, its use has been limited. We strongly recommend this technology to all of those who need to produce gears with high metallurgical quality.

A Few Well-Known Facts

The distortion of the gears made out of case-hardening steel is one of the biggest flaws in the carburizing-hardening process. This distortion causes great difficulties in the manufacturing process, complicates machine tool technology, calls for costly readjustment and straightening operations, prolongs the manufacturing cycle and drives up the costs.

When gear tooth distortions are so great that grinding cannot correct them, a reduction in the case quality follows. Among the results are

- the exaggerated grinding of the carburized layer,
- the removal of carbides out of the carburized layer,
- the decrease in the hardness of the carburized tooth surface,
- anomalies caused by rough grinding of the carburized layer.

In the broader sense of the word, distortion includes both the notion of "variations of dimensions" as well as the notion of "curving." The variation of dimensions caused by structural tensions is unavoidable, while curving is an avoidable distortion of the gear caused by inaccurate heat treatment, such as faulty heating and cooling, inappropriate placement of the gears, uneven carburization, single-side carburization, structural defects, etc.

The variation of dimensions is determined by several elements. One of the most important determining factors is the connection between the depth of the case and the thickness of the gear tooth. The case is dominant in gears with a layer of carburization that is more than half the thickness of the gear itself. Such gears will shrink in the largest dimension.

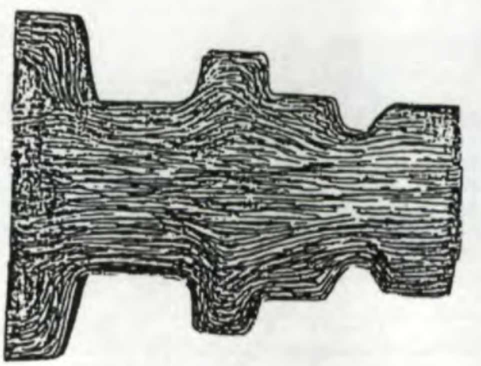

Fig. 1 — The correct distribution of fibers in a gear.

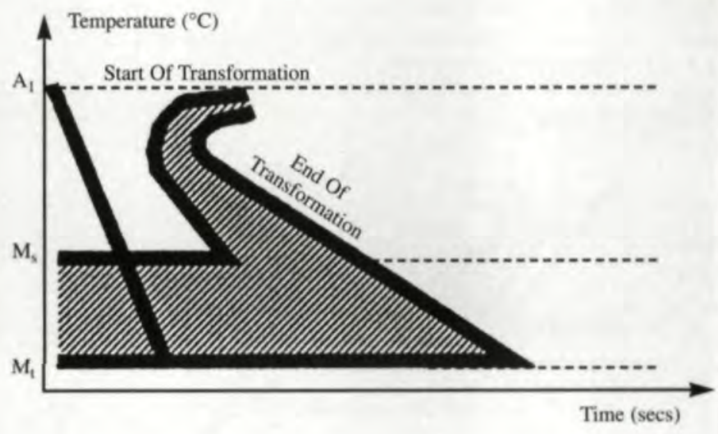

Fig. 2 — Cooling curve.

If, on the contrary, the case is small compared to the tooth section, the variation of dimensions is determined by the way the case responds to the transformation that produces a larger or smaller growth of the largest dimension, according to the type of gear and the quality of the steel. For example, we have noticed an increase in the spindle

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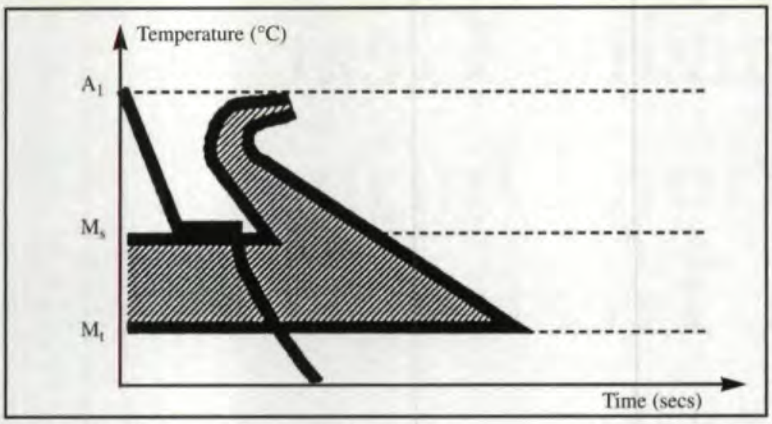

Fig. 3 — Cooling curve using graded hardening.

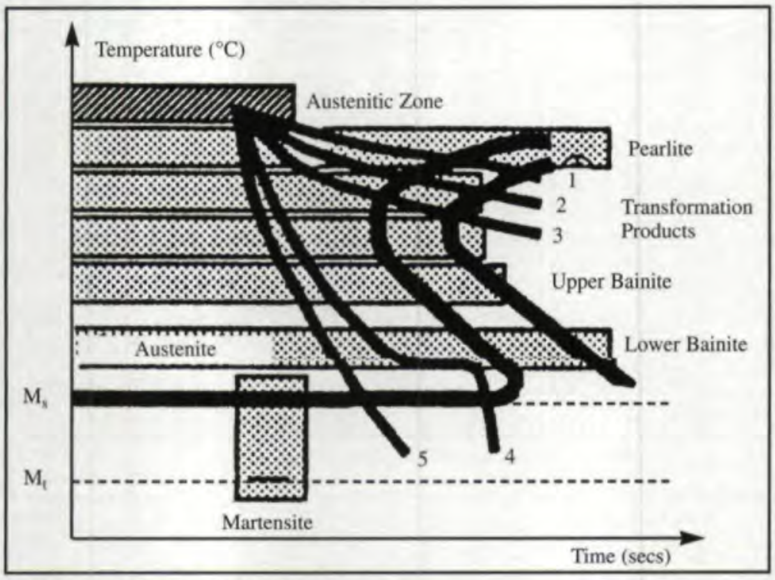

Fig. 4 — Lengthening the holding time.

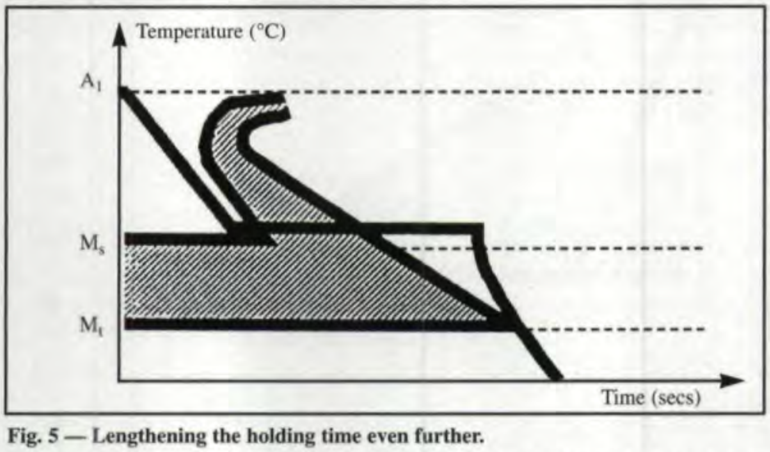

Fig. 5 — Lengthening the holding time even further.

dimension for spindles and shafts, but an increase in the radial dimension of gears, dials and flanges. The higher the hardenability of the steel, the larger the increase in spindle or radial dimensions.

In addition, the gear fibers impact the variation of dimension, which is known to be larger in the direction of the fibers. Fig. 1 shows the correct distribution of the fibers of a gear.

Most gear manufacturers receive relatively small orders, in the range of one to 300 gears. They manufacture the gears by cutting them out of rolled bars and send them to the heat treatment shop for preliminary hardening and tempering. Unfortunately, this type of heat treatment cannot guarantee the desired results. Instead, only isothermal annealing can yield results such as

- a pearlitic ferrite suitable for machining and finishing,
- a structural homogeneity in both the thick and thin areas of the gear, which also helps the dimensional stability after machining at cold temperatures),
- smaller distortions in later heat treatments as shown in Fig. 1 (Refs. 2–3).

It is true that to implement the isothermal annealing technology, one needs to invest in an appropriate furnace, and that such equipment is expensive for the small heat treating shop. However, the gains in quality often more than offset the expenditures.

The Technology

Most gear manufacturers use up-to-date machine tools and quality control technologies, but the high precision employed in machining the gears is often destroyed by the distortions occurring during heat treatment. Some of these distortions can be eliminated through grinding, but it often causes defects in the metallurgical quality of the rectified surfaces.

Fig. 2 shows the well-known cooling curve. This transformation curve is not a particularly useful reference for cooling gears in a quenching medium such as oil because of both the gear thickness and the sectional variations (the thicker the gear, the slower the cooling of its core). Cooling along such a curve yields a high residual stress. This is caused by the difference between the austenite transformations in the material's core and in its outer layers. Another reason is the volume contractions that take place at the edges of the gear while the core is still hot and dilated.

The accumulated residual stresses lead, in turn, to plastic distortions. When the value of these distortions exceeds the yield point and the rate of breaking resistance, cracks occur. We can successfully avoid such mishaps with gears made out of carburized steel by employing a graded hardening method. This works because the cooling of the gear now takes place above the martensite superior point M_S, thus maintaining this temperature for as long as it is necessary to establish an even temperature within the entire mass of the gear (see Fig. 3).

This holding time is calculated so that the conversion of the austenite does not begin in the carburized layer. After the prescribed holding time, the cooling continues in open air, and the austenite begins its conversion to martensite.

If the holding time is lengthened so that the cooling curve intersects the TTT curve (curve 4 in Fig. 4), the result is a heterogeneous structure made out of several structural constituents.

If the holding time is lengthened enough so the cooling curve goes beyond the TTT curve for the end of transformation (as shown in Fig. 5), the result is an isothermal-bainitic hardening, not a martensitic one.

Note in Fig. 5 that the curve first stops at about point M_S; it is maintained at that level without *touching the TTT curve for the beginning* of transformation and then finally continues with the open air cooling. When the part is taken out of the salt bath where the first phase cooling takes place, the martensitic transformation of the carburized layer hasn't yet begun. This explains why the part is still somewhat plastic. The martensitic transformation takes place only during the later cooling in ambient air.

This kind of heat treatment yields a martensitic structure. This is the same as in the standard hardening in oil, except that the crossing of the martensitic interval from a temperature corresponding to the M_S point down to the ambient temperature is done steadily and evenly for all sections on the hardened part. It is very important to know with some precision the point of martensitic transformation M_S, that is, the temperature at which the steel acquires a martensitic structure. It is at this point where the steel acquires the hardness produced by the treatment. This temperature is important because it determines the ideal conditions in which to do the martensitic hardening.

Application to Gear Manufacturing

Graded and isothermal hardening is commonly applied to structural steel. However, its application to carburized steel in the manufacturing of gears seems to be largely unknown and is perceived as difficult.

A gear or any carburized part is made out of several layers, with a decreased ratio towards the core. To simplify the discussion, we shall disregard the variations of the M_S point due to varying percentages of carbon. We shall consider only two temperatures corresponding to the M_S point: one for the core and the other for the case.

The core of the gear will have a martensitic point M_S higher than the corresponding M_S point for the case. This fact leads to the core undergoing the phase transformation inside the cooling bath first, followed by structural transformation of the case outside the cooling bath that is in the ambient air. The structural transformation of the core, involving a corresponding increase in volume, takes place before the case has undergone the phase transformation. Thus it remains in a plastic state.

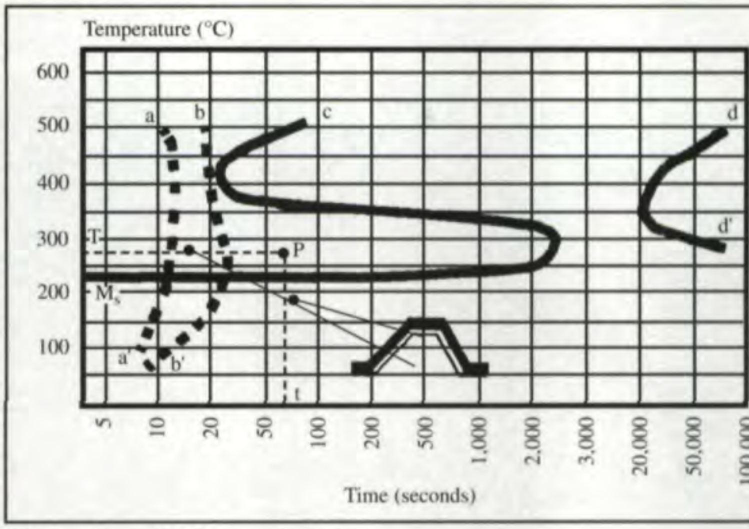

Fig. 6 — Example for a sample steel.

As an example, we shall use a steel containing nickel and chrome that has been carburized. We will use this steel to analyze these two thermic phenomena, that make up the graded hardening of the case-hardened steels.

Fig. 6 shows in semilogarithmic coordinates the beginning (a–a') and ending (b–b') curves of the isothermal transformations of the core (C = .18%) in dotted lines. The same figure shows with a continuous line the beginning (c–c') and ending (d–d') curves of the isothermal transformation of the case (C = 1.00%).

To compute the M_S point for a specific stock of steel, we employ the following formula (Ref. 3):

$$M_S = 539 - 423C - 30.4Mn - 17.7Ni - 12.1Cr - 7.5Mo$$

Thus, for the steel used in our example, after performing the operation of austenitization at approximately 850°C (1,560°F), followed by cooling in a salt bath, we notice that

- the non-carburized core of the gear is transformed into lower bainite, because the curve of transformation of the uncarburized layer is on the left side of the transformation curve for the case,
- the case remains austenitic.

The temperature T (See Fig. 6) must be higher than the martensitic temperature so that the martensitic transformation is avoided during the cooling of the gears in the salt bath.

Note in Fig. 6 that the core is liable to undergo an isothermal transformation—the area between the b–b' and the c–c' curves. Here we obtained a greater cohesiveness and toughness in the core of the gear. Although the bainite is less hard than the martensite by a few Rockwell units, this does not affect the bending resistance of the gear tooth. Often, the appearance of bainite needles is also joined by a martensitic structure.

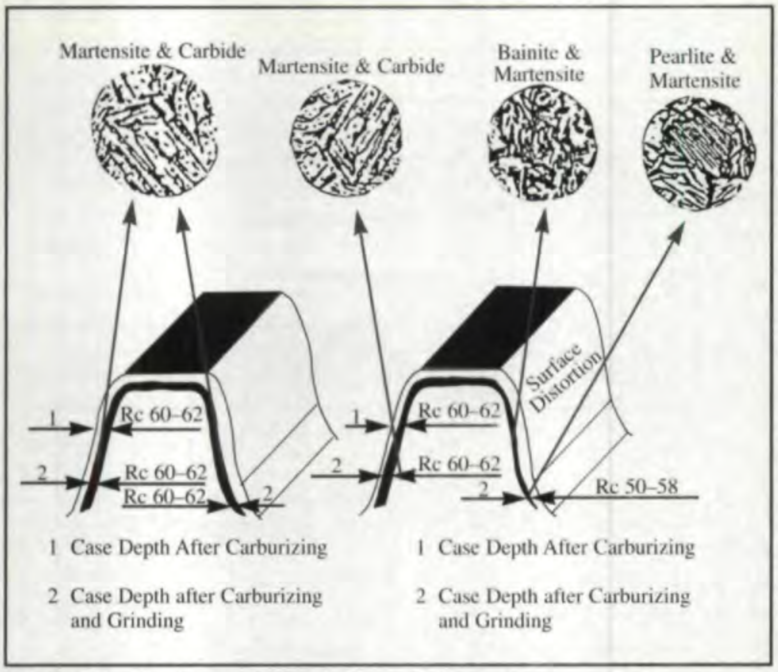

Fig. 7 — Results after graded hardening and oil quenching.

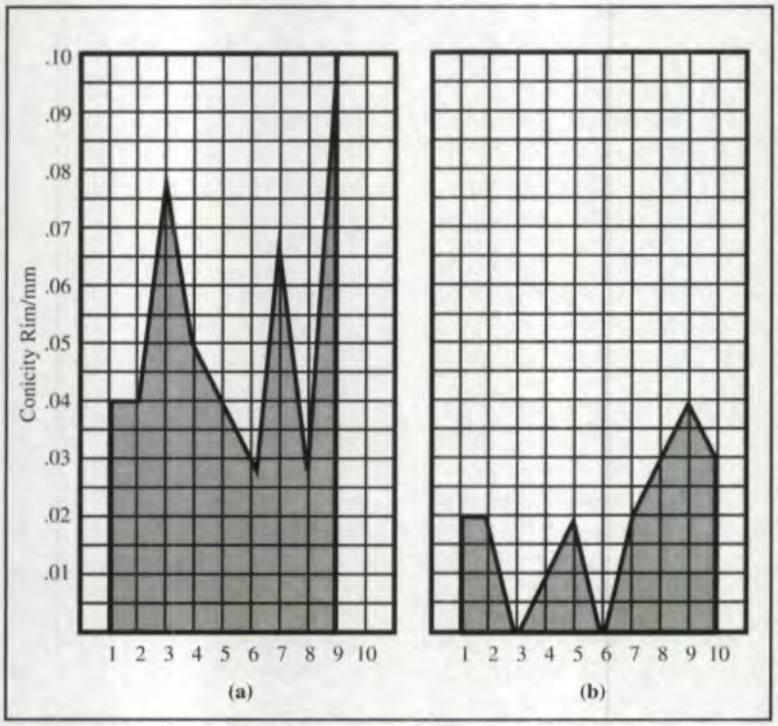

Fig. 8 — Conicity distortion in (a) hardening in oil vs. (b) graded hardening.

The transformation of the core of the carburized gear into a bainitic-martensitic structure is made without important contractions. During this time, the case remains unchanged austenitically.

The martensitic transformation of the case takes place during the cooling in ambient air.

The martensite structure of the case leads to an increase in the specific volume. This in turn leads to compression stress, and therefore the resulting distortions will be very small and within allowed tolerances. This compression stress in the case brings about a higher resistance to fatigue, making the case less sensitive to external potential stretching strains.

To determine the holding time T (see Fig. 6) one must take into account the geometrical shape and weight of the part. The determination is done through a series of tests.

Analysis

The advantage of using graded hardening technology comes from the fact that the martensitic transformation in the case occurs after the transformations have taken place in the core of the gear. While holding the gear in the salt bath, the temperatures in different sections of the gear become even, leading to simultaneous transformations during the subsequent cooling in ambient air. This avoids the distortions and cracks often resulting from the hardening operation.

The TTT curves used in carrying out these heat treatments provide only general hints as to what the transformation temperature may be. They do not help in determining the duration of the transformations because the gear weight sometimes requires modifications of the holding time. In actual practice, the gear weight does sometimes require adjustments of the temperature of the salt bath as well.

Thus one must use the austenite isothermal distortion curve very carefully. For example, a different rate for one of the alloy elements yields a change of the temperature of the M_s point.

Different hardness results may also be obtained for different holding times in the salt bath and different temperatures.

This dependence is useful in the hardening of gears with thick walls, where the danger of reduced hardness is higher. Thus, a lower bainitic structure may yield a hardness of $R_c = 57$, while a superior bainitic structure may yield a hardness of $R_c = 43$ (Ref. 6).

This advantage of being able to get a lower hardness in the gear core is successfully used for gears that must undergo large bending efforts. Examples include the gears used in tank gearboxes, gears for heavy vans, gears used in machine tools, etc. It is worth mentioning that bainite offers a very good quality to the finishing surface, both for low and high machinability speeds.

The holding time in the graded hardening bath is relatively short—approximately five times the duration of the standard hardening in oil. This holding time varies with the gear size.

The salt baths used to cool the gear are somewhat different than ordinary baths: They must guarantee an even temperature during the entire holding time (See Fig. 7).

This technology yields case hardness around $R_c = 58–64$. The hardness in the gear core can be determined from the gear shape.

Conclusions

The advantages introduced by the graded hardening of gears made out of case-hardening steels compared to the standard technology of hardening in oil come from the chronological inversion of the cooling transformations in the case vs. the core. A second basis for these advantages is the fact that the temperature across the part's section is kept even throughout the isothermal holding time.

The graded hardening approach yields reductions in the gear distortions of over 55%, when compared to the distortions measured on gears hardened using the standard method of quenching in oil (Refs. 4–5).

Fig. 8 shows the difference in conicity distortions for the standard hardening in oil (a) vs. the graded hardening technique (b).

Fig. 9. illustrates the ovalness distortions for the same two technologies. The two curves show the values for numbers of gears between 1 and 10 (See Figs. 10–11).

Taking into account the uncertainty and practical difficulties we face when employing the standard hardening in oil, we strongly recommend the graded hardening technology in all cases when small distortions in the heat treated gears are desired. ○

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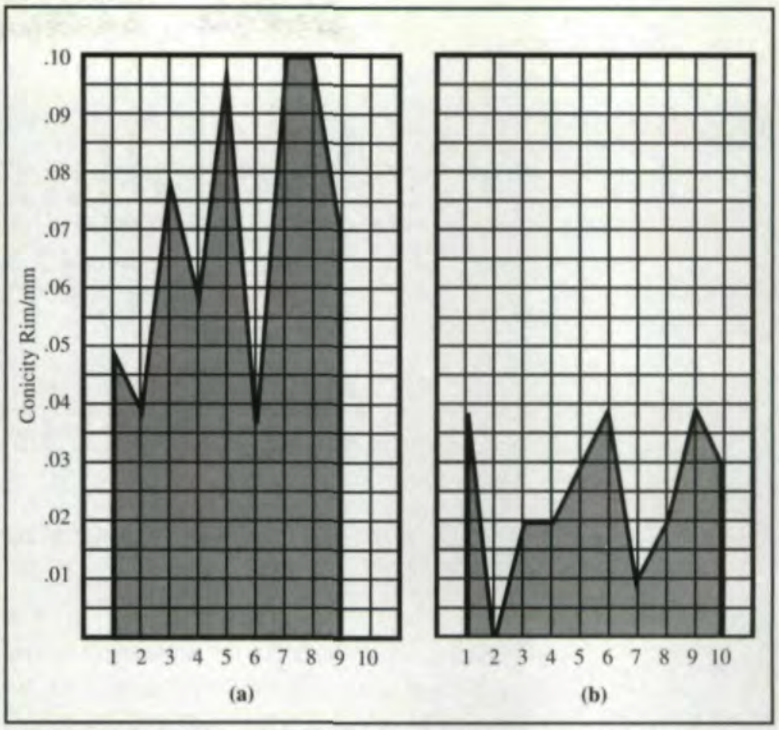

Fig. 9 — Ovalness distortion in (a) hardening in oil vs. (b) graded hardening.

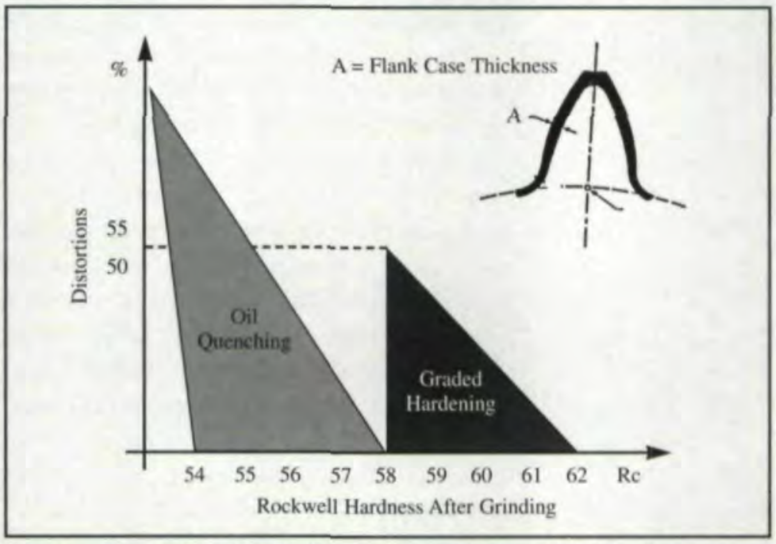

Fig. 10 — Comparison of graded hardening and oil quenching distortions.

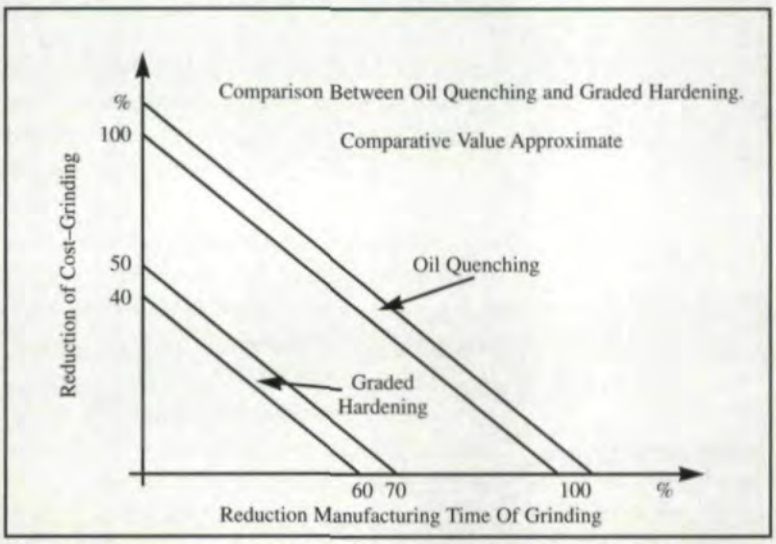

Fig. 11 — Comparison of costs and manufacturing times of graded hardening and oil quenching.