METALLURGY FOR BLACKSMITHS

Steel and Its Heat Treatment

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Bainite & Martensite

Figure 1–24 Example of bainite in low-alloy steel. Magnified 1000 times.

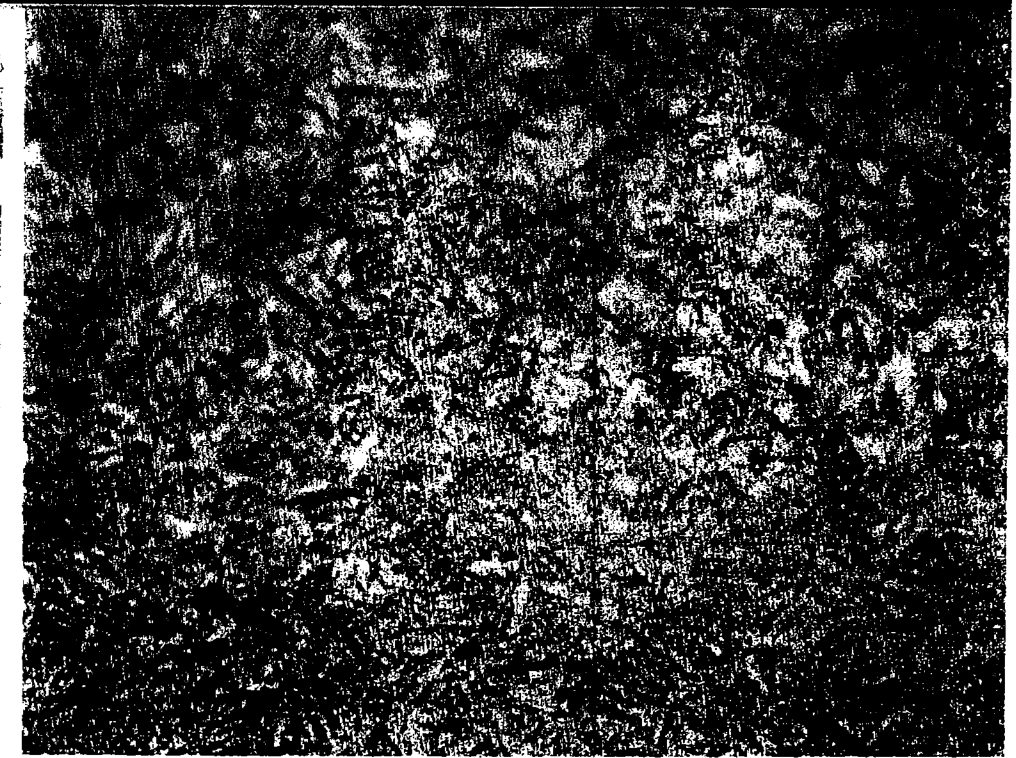


Figure 1–25 AISI 4130 low-alloy steel water-quenched from 1,600°F. Etched to show the fine martensite laths.

Tempered Martensite 300°C & 700°C

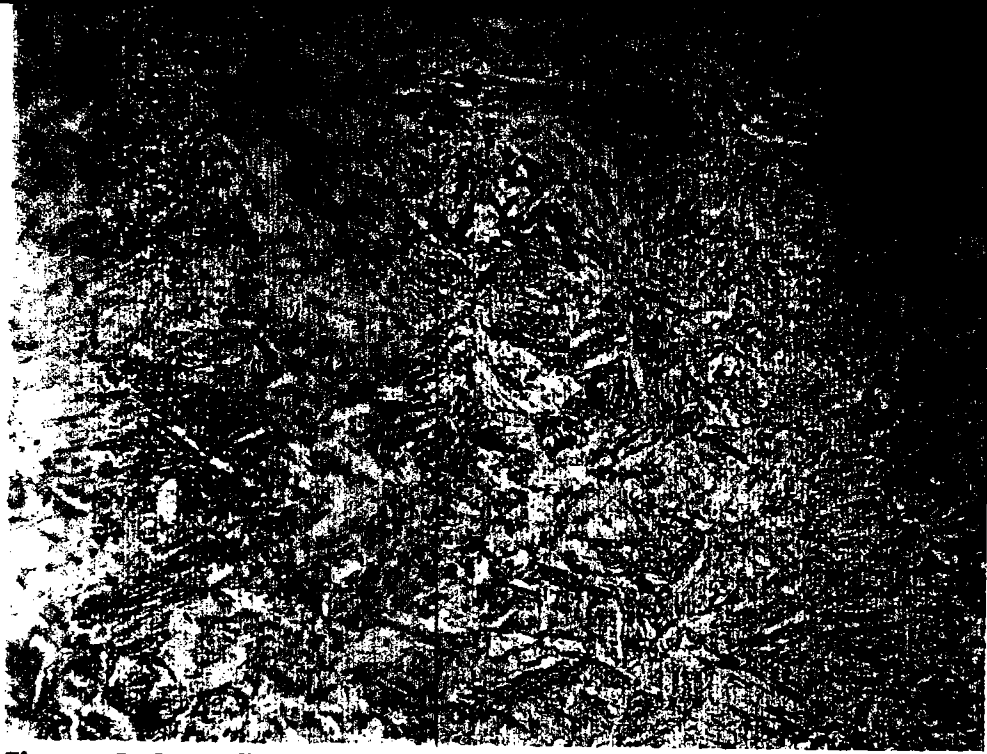
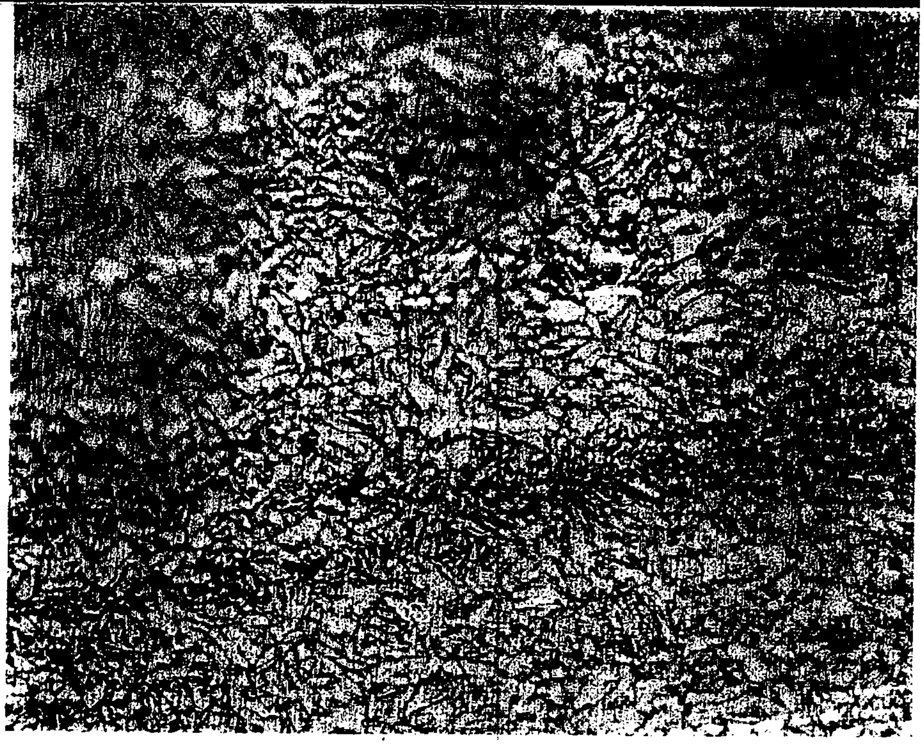
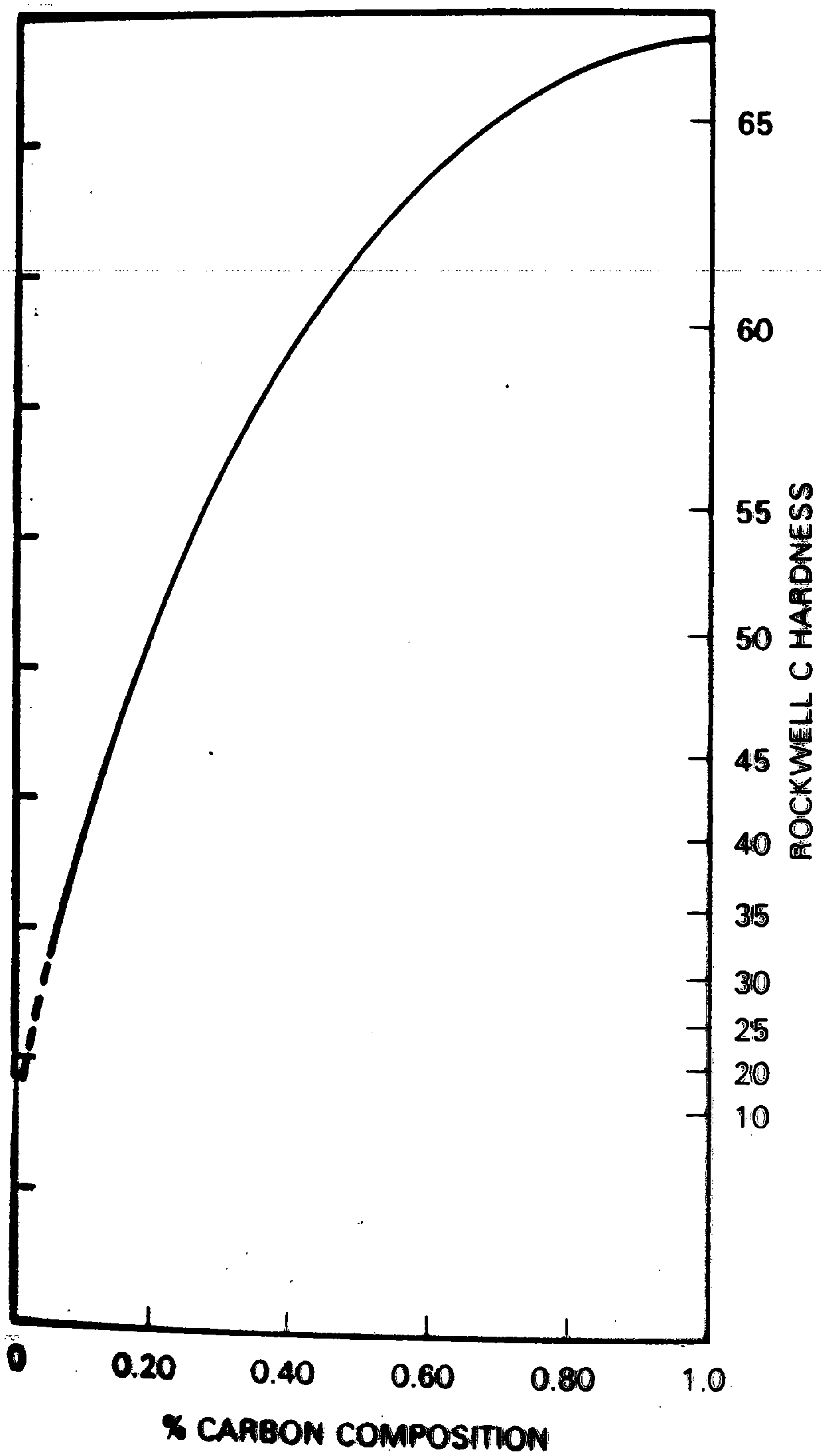


Figure 1–31a Tempered martensite of 4130 steel, tempered 1 hr at 300°C. Nital etch, magnified 690 times.



Figure–31b Highly tempered structure of 4130 steel. Tempered 1 hr at 700°C. Nital etch, magnified 368 times.



-Effect of Carbon on the Maximum Hardness of Martensite

Table 2:6. **Mechanical Properties of Ferrite, Cementite and Lamellar Pearlite**

Microstructural Constituent	Tensile Strength psi	Elongation %	Brinell Hardness Number
Ferrite	40,000- 50,000	40	90
Lamellar Pearlite	125,000-150,000	15	275
Cementite	325,000	Negligible	650

and also the relative effects of varying amounts of martensite.

The role of microstructure in determining the mechanical properties of steel should now be obvious. In a hypoeutectoid steel where much ferrite is present, we might expect the steel to be relatively soft and weak but quite ductile. In a hypereutectoid steel where much cementite is present, we might expect the steel to be strong, hard, and brittle. By altering the amount of the various constituents in the microstructure, practically any degree of strength, hardness and ductility, within the limits shown, can be obtained.

In Table 2:6, the microstructure has been varied by the amount of carbon in the steel, with the cooling rate of the steel through the critical ranges being very slow, i.e., a condition of near-equilibrium. The complete iron-cementite phase diagram is shown on the back cover as Fig. 2:12. It would be well to become thoroughly familiar with it so that it can be redrawn from memory.

As demonstrated in Table 2:5, the mechanical properties of steel can also be varied considerably by the process of heat treatment. When steel is cooled at rates faster than equilibrium, the structural changes which take place are more drastic and less well understood than those noted here. These additional structural changes have a considerable effect upon the mechanical properties of steel and will be discussed in greater detail in succeeding lessons.

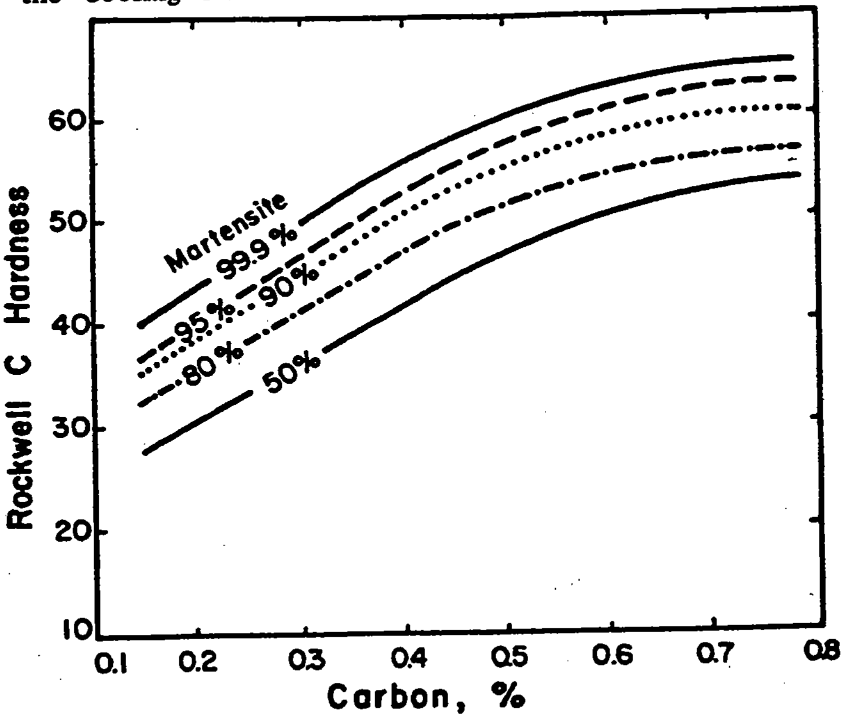


Fig. 2:10. Average Relationships Between Carbon Content, Hardness, and Percentage of Martensite in Quenching. (Transactions, AIME, 1946, V. 167, pp. 627-642.)

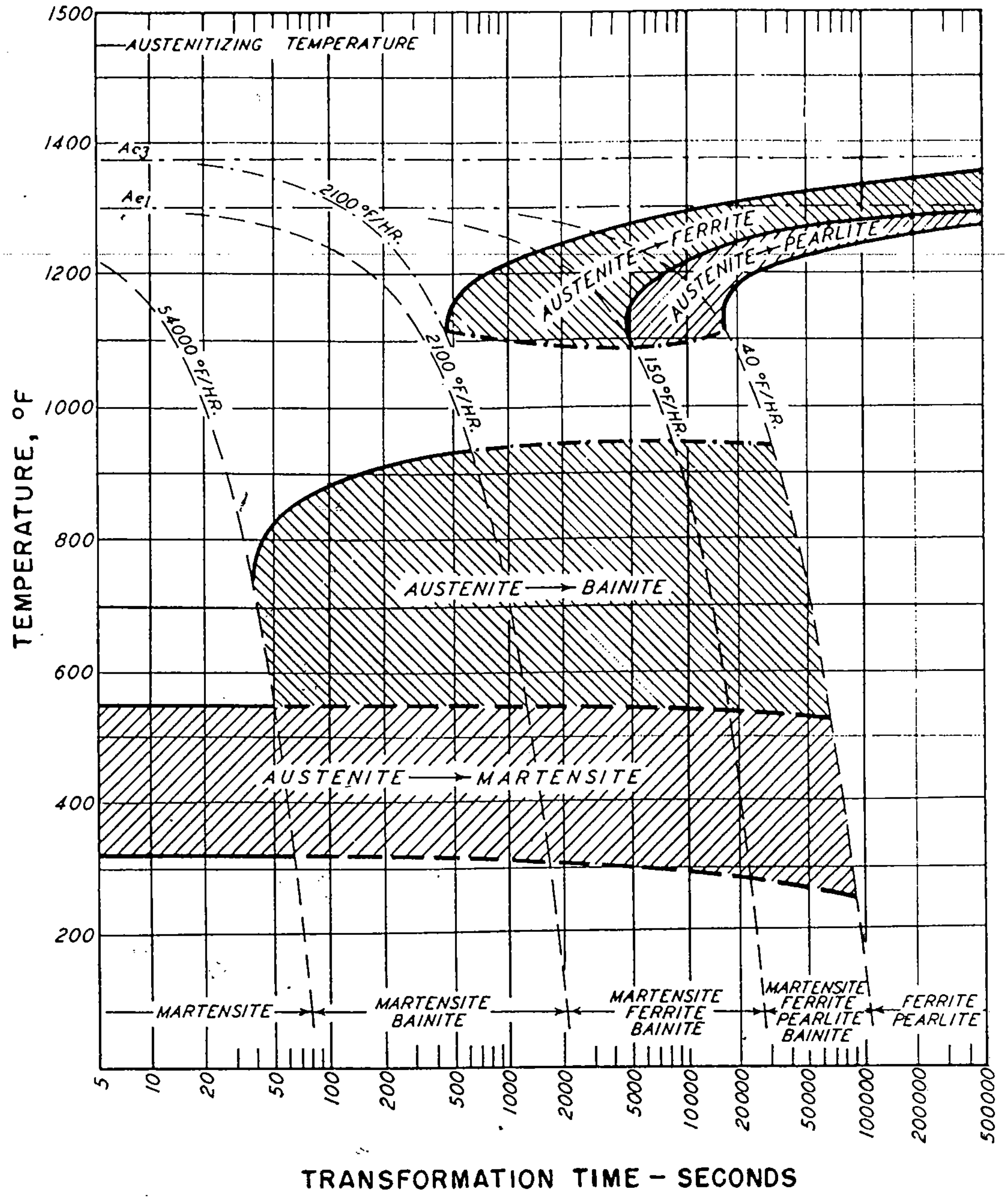


Fig. 42—29. Continuous-cooling transformation diagram for a 4340-type alloy steel, with superimposed cooling curves illustrating the manner in which transformation behavior during continuous cooling governs final microstructures.

Continuous Cooling Transformation

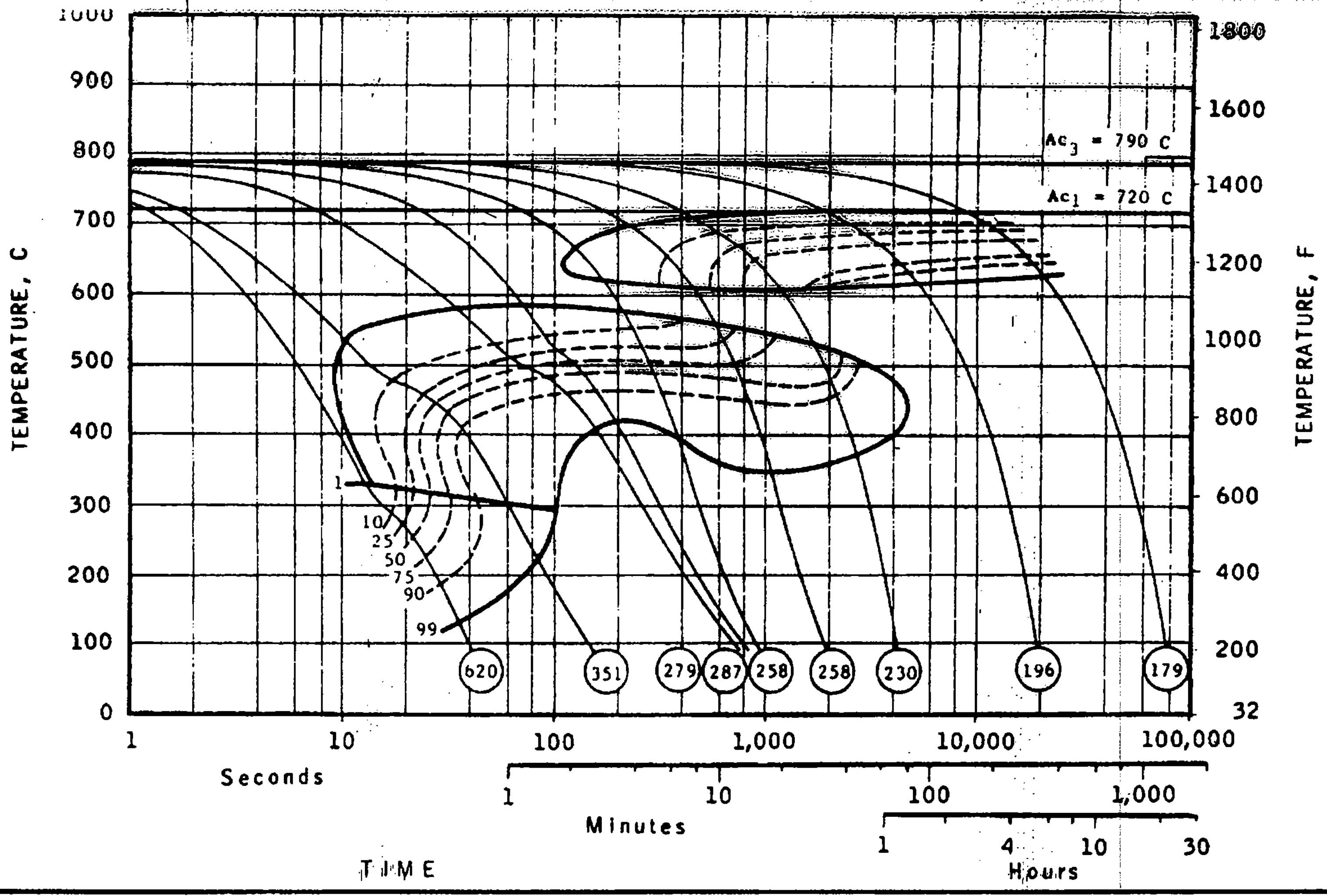


Figure 1–27 Continuous cooling transformation (CCT) diagram for AISI 1040 steel modified with 0.53% molybdenum (After Cias).

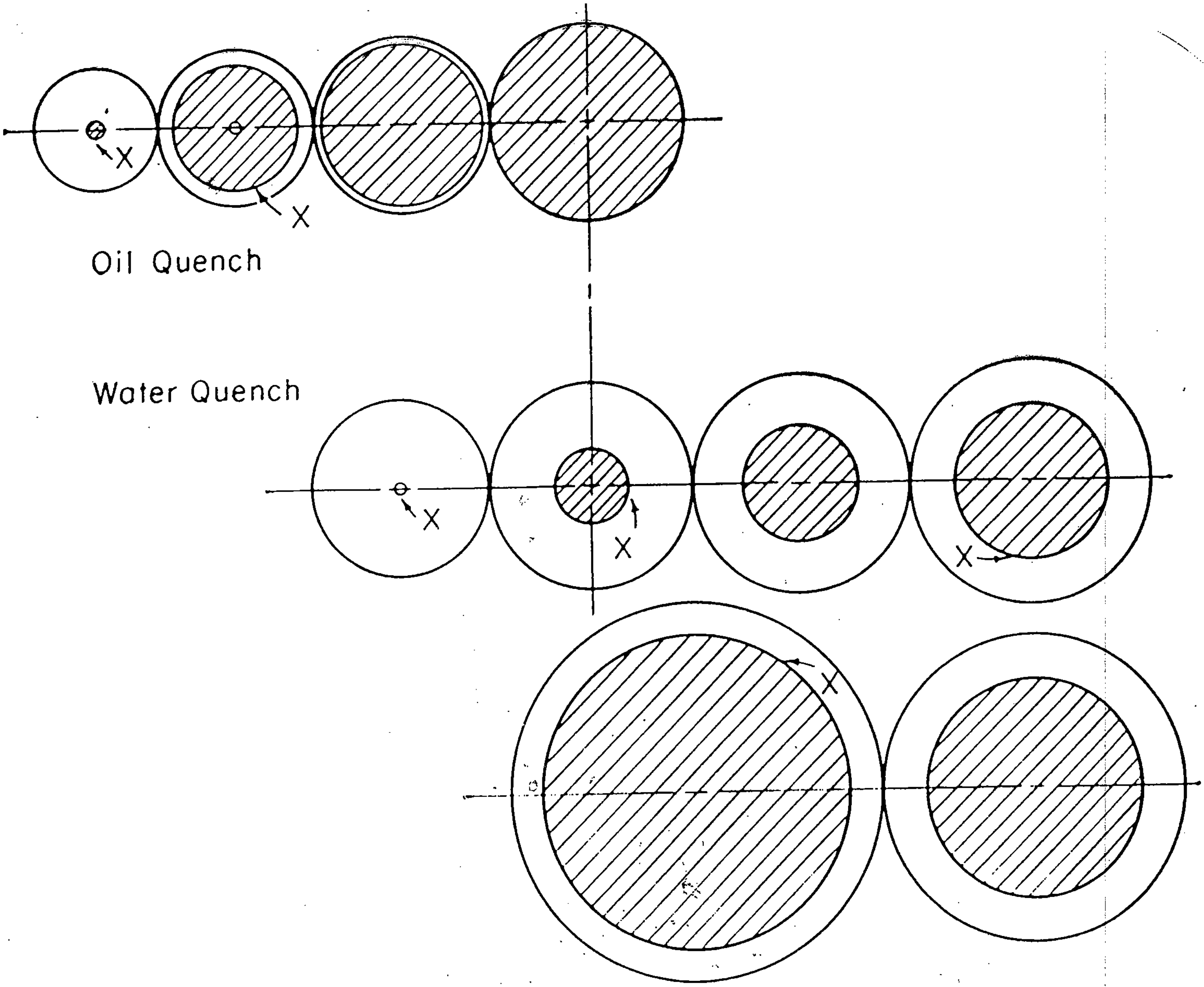


Fig. 62 SAE 3140 Steel Quenched in Oil and in Water. Diagrammatic Representation of Etched Cross Sections.

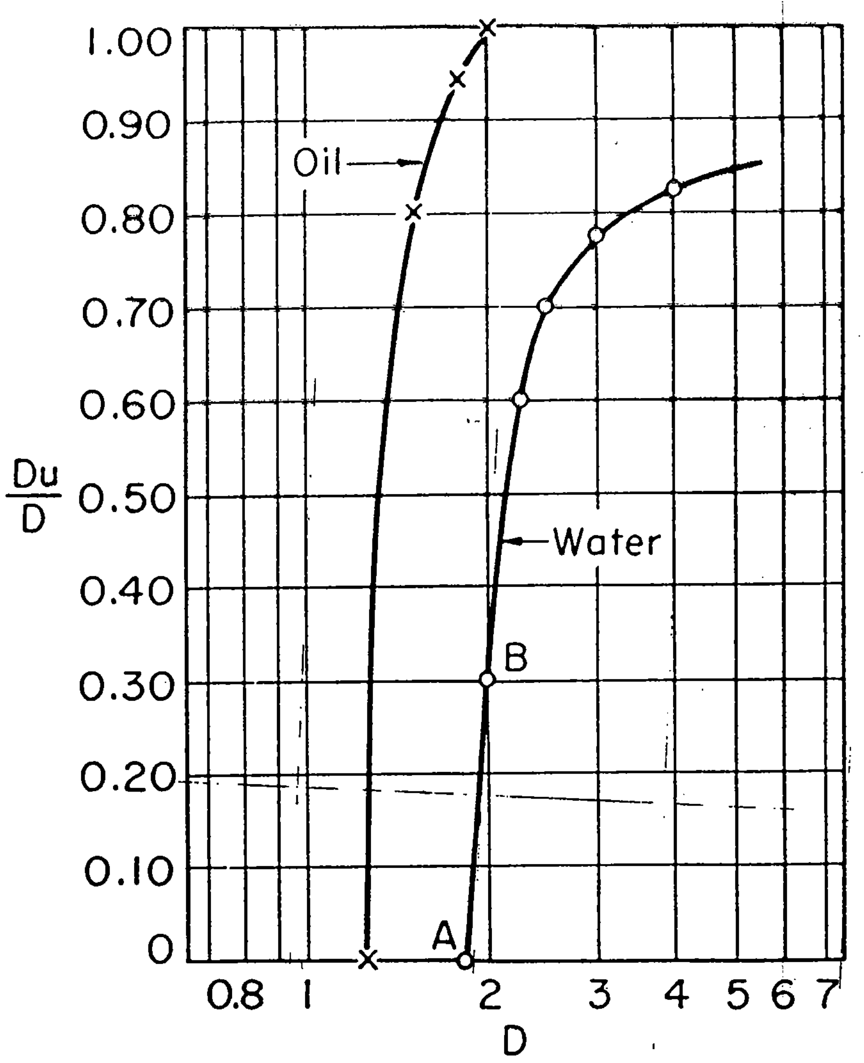
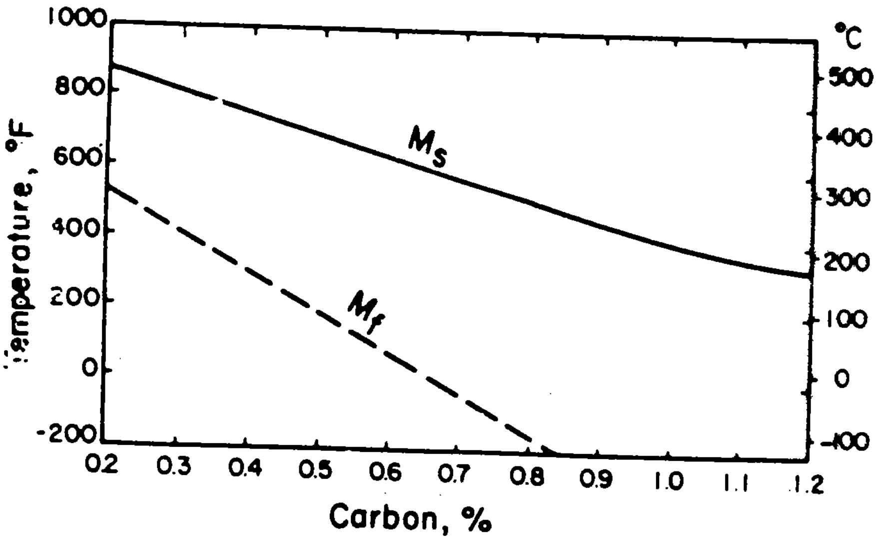
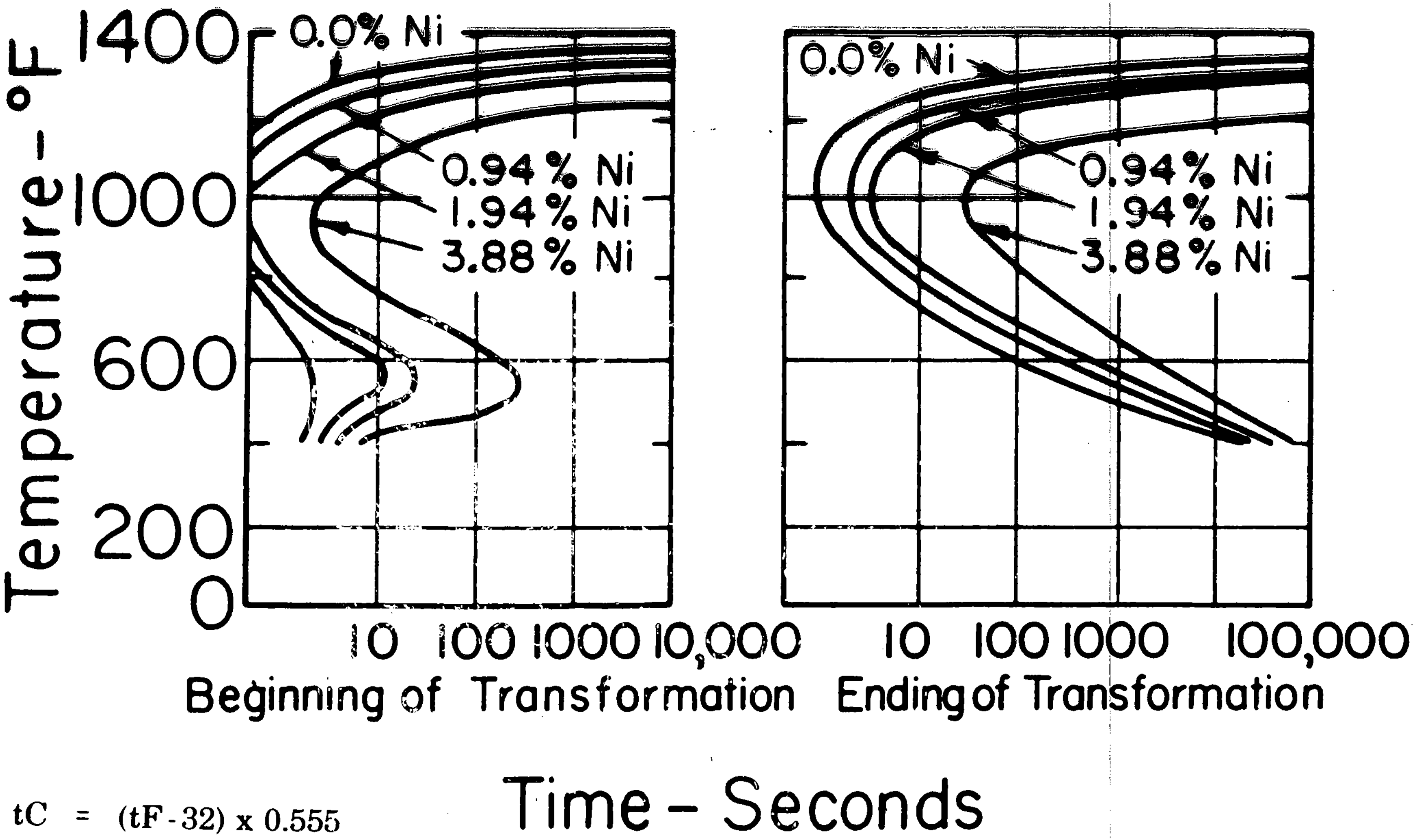


Fig. 63—Unhardened Cores of Quenched Bars, One Series Quenched in Oil, One Series Quenched in Water. Data Same as Fig. 62.

Table 3-2. Effect of Alloy on the M_s Temperature of a 1% Carbon Steel for Each 1% of Alloy Added

Element	Change in M_s temperature F	Change in M_s temperature C
Carbon	-510	-285
Manganese	- 60	-33
Chromium	- 40	- 22
Nickel	- 30	- 17
Molybdenum	- 20	- 11
Tungsten	- 20	- 11
Silicon	- 20	- 11
Cobalt	+ 10	+ 6
Aluminum	+ 30	+ 17





tC = (tF - 32) x 0.555

Fig. 3-15. Effect of increasing alloy content (nickel) on isothermal transformation of 0.60% carbon steel.

Largely because of this hardenability limitation, austempering has found its widest application in the heat treatment of plain high-carbon steels in small section sizes, such as sheet, strip and wire products. It is, however, also being used for the heat treatment of alloy steels and cast irons for applications in which it is essential that distortion be held to a minimum.

Normalizing—Normalizing involves reheating the steel above its critical temperature (Ac_3) and air cooling. It has two primary purposes: to refine the grain, and to obtain a carbide size and distribution which will be more favorable for carbide solution on subsequent heat treatment than the as-rolled structure.

The as-rolled grain size depends principally upon the finishing temperature in the rolling operation. This is subject to wide variations and there is, therefore, a corresponding wide variation in the grain size of the as-rolled products. The normalizing operation, as the name implies, serves to refine a coarse grain size resulting from a high finishing temperature and to establish a uniform, relatively fine-grained microstructure.

In alloy steels, particularly if they have been slow cooled after rolling, the carbides in the as-rolled condition tend to be rather large and massive. These large carbides are difficult to dissolve on subsequent austenitizing treatments. This carbide size, likewise, will be subject to wide variations, depending on the rolling and slow-cooling practice. Here again, normalizing tends to establish a more uniform and finer carbide particle size which will facilitate subsequent heat treatment to a more uniform final product.

The usual practice is to normalize from 100° to 150° F above the critical temperature, but for some alloy steels with carbides that are soluble only with difficulty, considerably higher temperatures may be used to obtain carbide solution. Heating, in general, should be slow enough to insure uniform temperatures and low thermal stresses. It is now a very common practice to carry out this operation in continuous furnaces. Continuous normalizing is particularly well adapted to sheet and strip because it may be heated quickly, but it is also used for plates and bars. The heating operation may, however, be carried out in any type of furnace which will permit uniform heating and accurate temperature control.

Annealing—The principal purposes of annealing are to relieve cooling stresses or stresses induced by cold or hot working, and to soften the steel so as to improve its machinability or formability. It may involve only a subcritical heating to relieve stresses, to recrystallize cold-worked material, or to spheroidize the carbides or it may involve heating above the critical temperature with subsequent transformation to pearlite or directly to a spheroidized structure on cooling.

Full Anneal—As discussed above, the most favorable microstructure for machinability in the low- or medium-carbon steels is coarse pearlite. The customary heat treatment to develop this microstructure is a full anneal, illustrated diagrammatically in Figure 42—41. It consists of austenitizing at a relatively high temperature so that full carbide solution is obtained, followed by a slow cooling so that transformation occurs only and completely in the high-temperature end of the pearlite range. This is a simple heat treatment and is reliable for most steels. It is, however, rather time consuming since it involves a slow cooling over the entire temperature range from the austenitizing temperature to a temperature well below that at which transformation is complete.

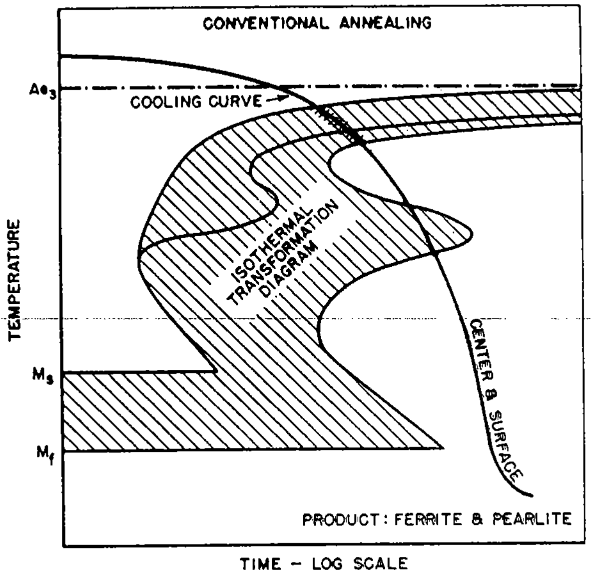


Fig. 42—41. Schematic transformation diagram for full annealing.

Isothermal Annealing—This annealing to coarse pearlite can, of course, be carried out isothermally by cooling to the proper temperature for transformation to coarse pearlite, and holding at this temperature until transformation is complete in a manner similar to the austempering procedure. This method is illustrated diagrammatically in Figure 42—42. Such an isothermal-annealing cycle may make possible a very considerable time saving over the conventional full-annealing treatment described above. Neither the time from the austenitizing temperature to the transformation temperature, or from the transformation temperature to room temperature is critical and these may be speeded up as much as is desired or is practical. Furthermore, if the extreme softness of the coarsest pearlite is not necessary, the transformation may be carried out at the "nose" of the curve where the transformation goes to completion most rapidly and the operation thereby further expedited; the pearlite is much finer and the hardness is higher.

Isothermal annealing is most practical for applications in which full advantage may be taken of the rapid cool-

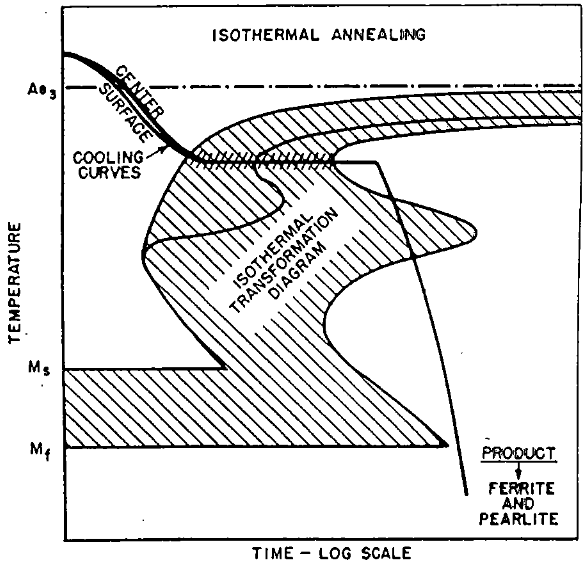


Fig. 42—42. Schematic transformation diagram for isothermal annealing.

for obtaining the uniform heating desired for tempering and are very commonly employed for this purpose. Oil or salt baths are very commonly used for low-temperature tempering and are generally safe, in spite of their rapid heating rate, since the temperature differential is low. Lead or salt baths may be used for higher tempering temperatures if the pieces to be tempered are not too large or irregular so that the heating stresses may be kept at a safe level.

Some steels exhibit a loss of toughness on slow cooling from temperatures of about 1000° F and above (the phenomenon known as "temper brittleness" which will be discussed further in another chapter) and therefore, a rapid cooling after tempering is generally desirable in these cases.

Martempering—As discussed above, the transformation to martensite, occurring during the rapid cooling through the martensite temperature range with the accompanying sharp temperature gradient, results in high stresses. A modified quenching procedure, known as martempering, which was developed by B. F. Shepherd, is helpful in lowering these stresses after quenching. This method is illustrated diagrammatically in Figure 42—39. In practice, it is ordinarily carried out by quenching the piece into a molten-salt bath at a temperature just above the M_s temperature, holding in this bath long enough to permit the piece to acquire the temperature throughout, and then air cooling to room temperature. Transformation to martensite then occurs during the relatively slow air cooling and, since the temperature gradient characteristic of the conventional quench is absent, the stresses set up by the transformation are much lower than in conventional quenching and tempering. Along with these lower stresses goes, of course, a much greater freedom from distortion and cracking. After martempering, the piece may be tempered to the desired strength level. Martempering has been applied to the heat treatment of tools, bearings, dies, etc. in which difficulty was encountered with quench cracking or distortion when heat treated by conventional quenching and tempering.

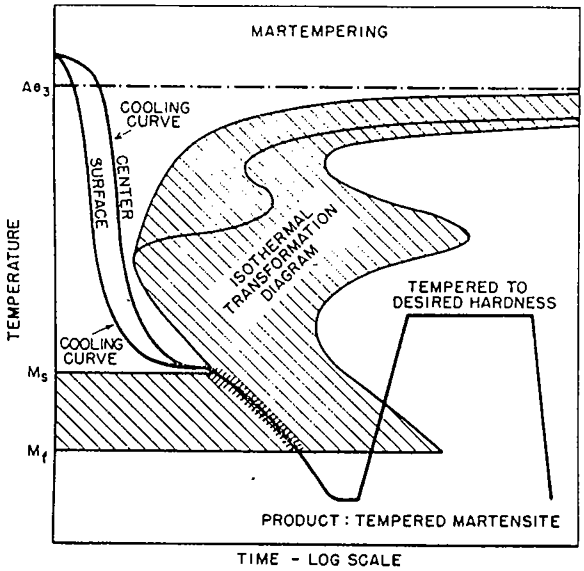


Fig. 42—39. Schematic transformation diagram for martempering.

Austempering—As discussed above, the properties of lower bainite are generally similar in respect to strength and somewhat superior in ductility to those of tempered martensite. Austempering, which is an isothermal heat treatment to lower bainite, therefore, offers an alternative method of heat treatment for obtaining optimum strength and ductility.

The austempering treatment is illustrated diagrammatically in Figure 42—40. It involves quenching to the desired temperature in the lower bainite region, usually in molten salt, and holding at this temperature until transformation is complete. It is the usual practice to hold for a time twice as long as that indicated by the isothermal transformation diagram to insure complete transformation of segregated areas. The piece may be quenched or air cooled to room temperature after transformation is complete and may be tempered to a lower hardness level if desired.

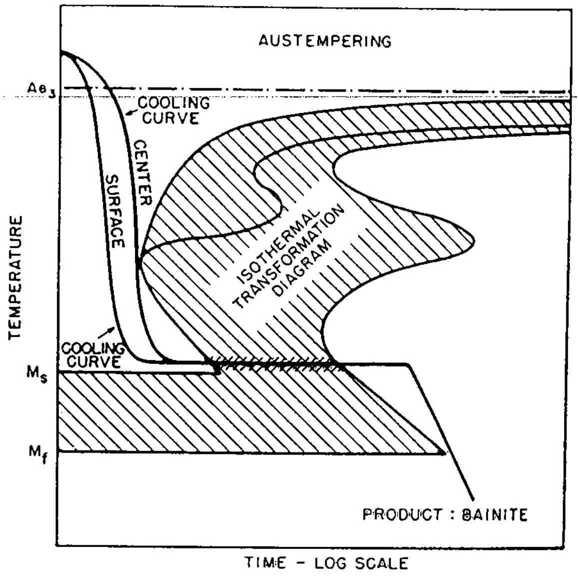


Fig. 42—40. Schematic transformation diagram for austempering.

Austempering has the tremendous advantage over conventional quenching and tempering that the bainite transformation takes place isothermally at a relatively high temperature so that the transformation stresses are very low, with a resultant absolute minimum of distortion and a practically complete assurance that quench cracking will not occur.

Austempering, on the other hand, has the disadvantage, which it shares with martempering, that, because of the slower cooling rates of the molten salt baths as compared with the usual water or oil quenches, a higher hardenability steel is required to prevent high temperature transformation during the cooling to the bainite temperature. Along with these higher hardenabilities also go longer times for complete transformation to bainite so that austempering may be considerably more time consuming than martempering or conventional quenching and tempering.

This hardenability limitation may be overcome to a certain extent by the introduction of a prequench in water or oil to a temperature just below the M_s temperature, so that some martensite transformation occurs prior to the final holding at the bainite transformation. The final product is then a mixture of tempered martensite and bainite and steel with this microstructure has good properties.

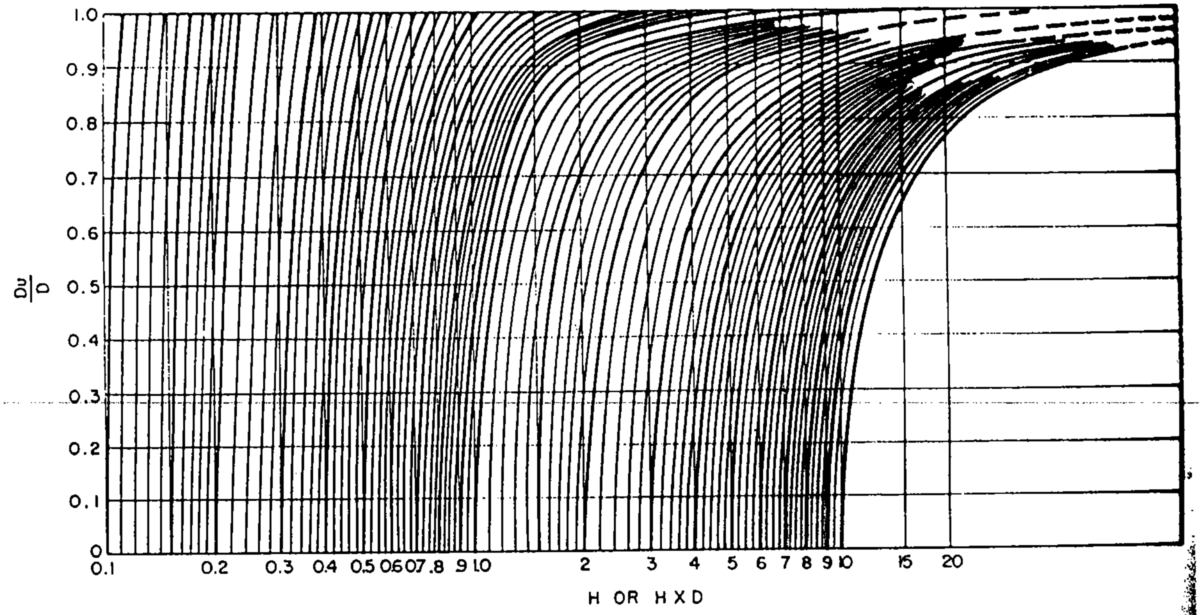


FIG. 42—32. Curves for estimating severity of quench (H) values from a cylinder series.

ameter and four inches long is heated to the desired hardening temperature and quenched in a fixture by a stream of water impinging upon only one end. The bar is then ground on two opposite sides to a depth of 0.015 inch below the surface and hardness measurements made at 1/16-inch intervals along the length of the specimen. The hardenability is expressed as a curve of hardness versus distance from the quenched end of the specimen. Figure 42—33 illustrates the type of quenching fixture used for this test and a typical end-quench hardenability curve is shown in Figure 42—34. Standard procedures for this test have been established by the American Society for Testing Materials and the Society of Automotive Engineers and the reader is referred to the publications of these societies for the details of the testing procedures.

This test furnishes a method of applying a continuous series of varying cooling rates to a single specimen, and, since these rates are known, the results can be converted to hardenability values in terms of ideal diameter. The curve used for this conversion is shown in Figure 42—[illegible] To use this curve, the distance along the end-quench bar to the desired miscrostructure, or corresponding hardness value, is noted and the ideal diameter corresponding to this distance is read from the curve. This ideal diameter value may then be converted into terms of bar size which can be hardened under any given quenching conditions, by the methods described above.

Hardenability and Heat Treatment—It has been emphasized in the preceding sections of this chapter that the most desirable microstructural constituents, from the standpoint of strength and toughness, are those involving transformation at the lower temperature levels —lower bainite and tempered martensite. In order to obtain these desirable structures, the transformation rates must be slow enough, or in other words, the

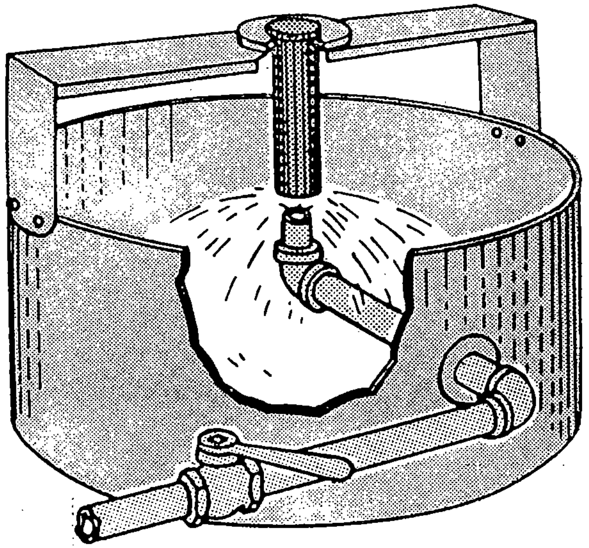


FIG. 42—33. Quenching fixture for end-quench test.

H-Band & Standard AISI Steels

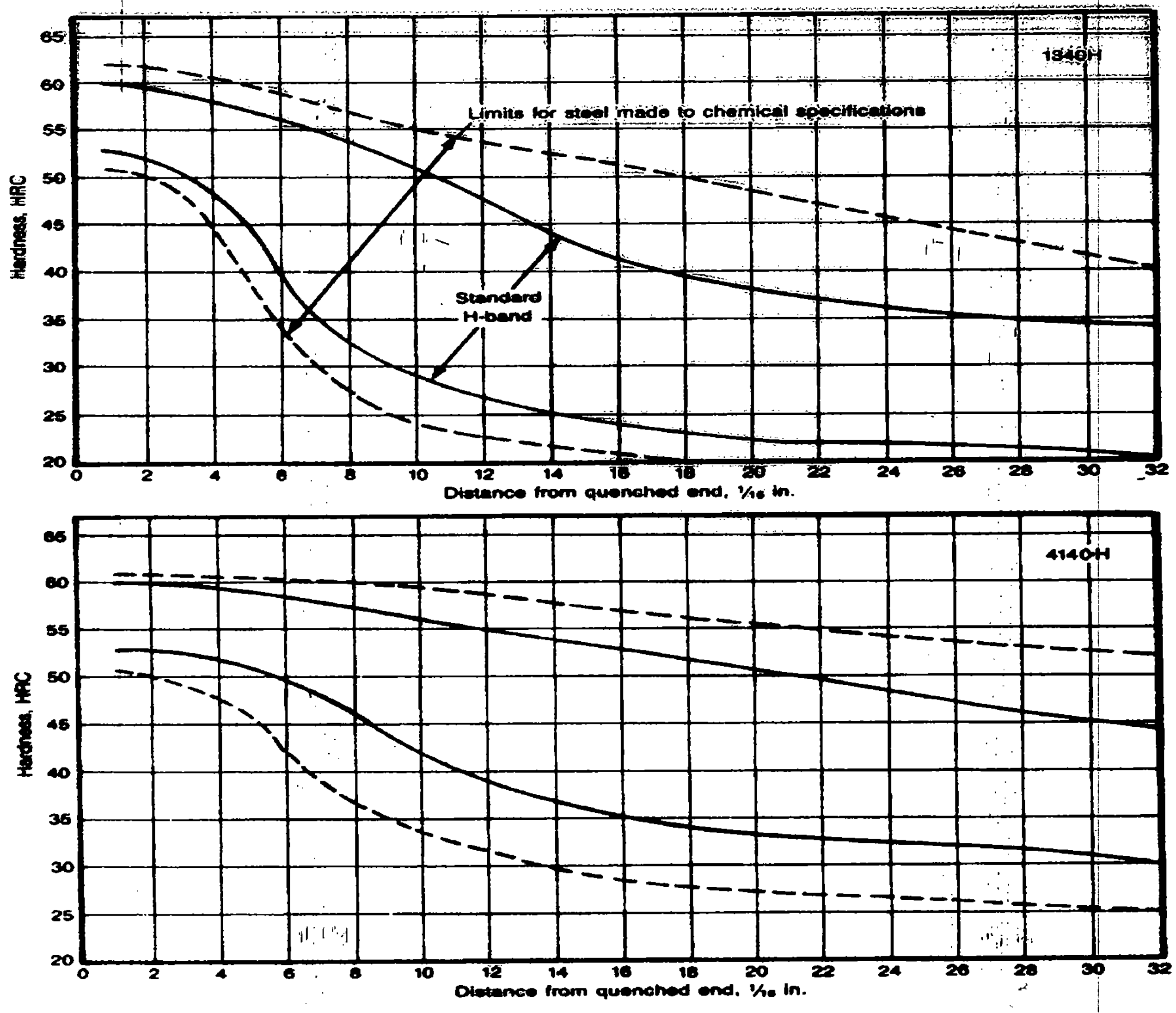


Figure 1–28 Comparison of standard H–bands and wider limits for similar steels made to AISI specifications (After *Jatczak, Metals Handbook,* 1978).

Hardness & Yield vs Tempering Temperature

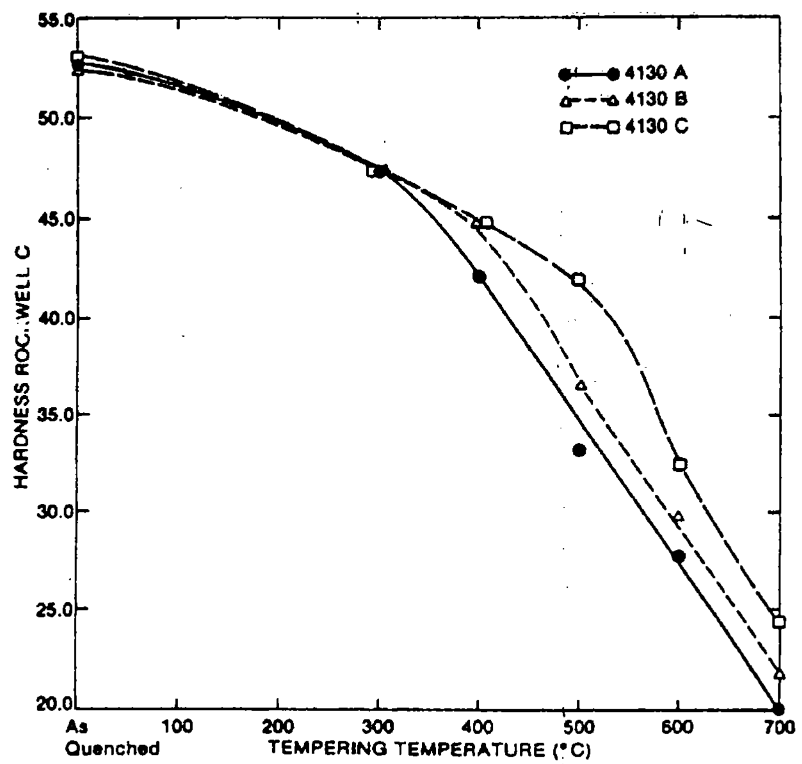


Figure 1–29 Reduction in hardness with increasing tempering temperature for AISI 4130 steel and two modifications with 0.50% molybdenum (4130B) and 0.75% molybdenum (4130C).

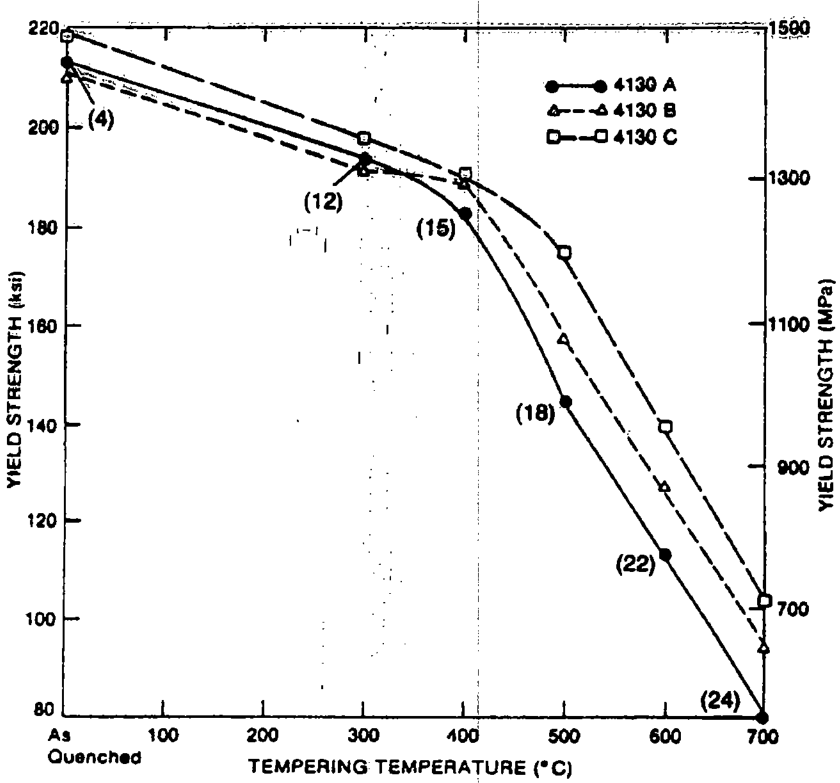
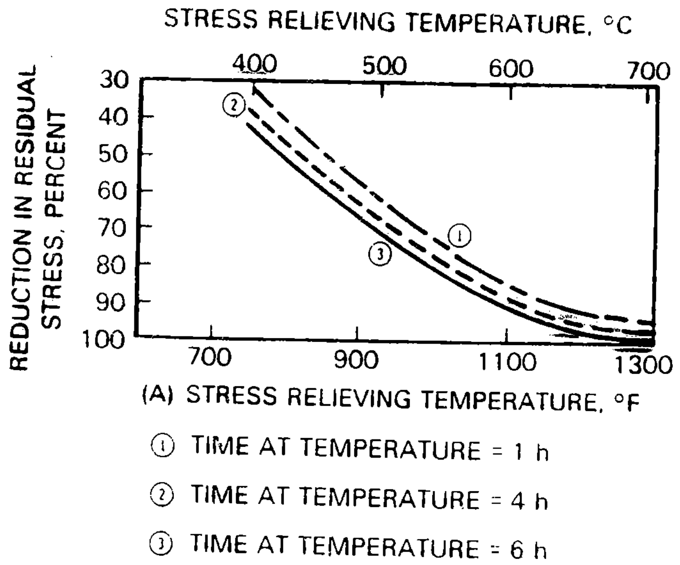
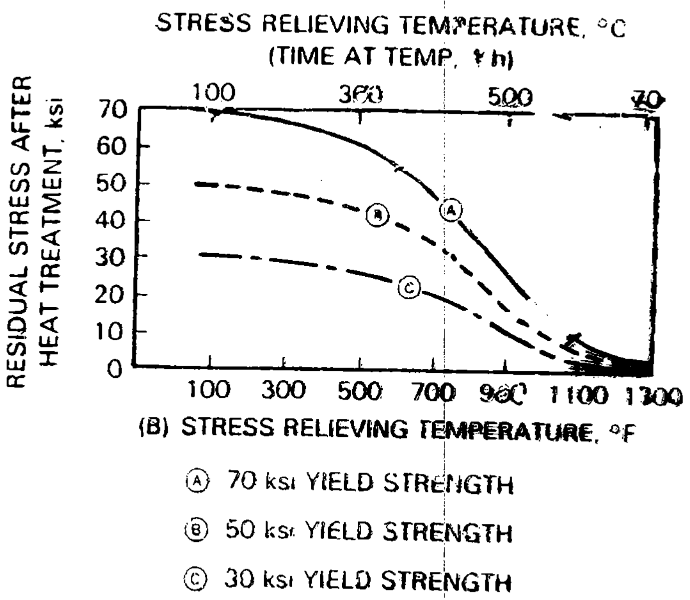


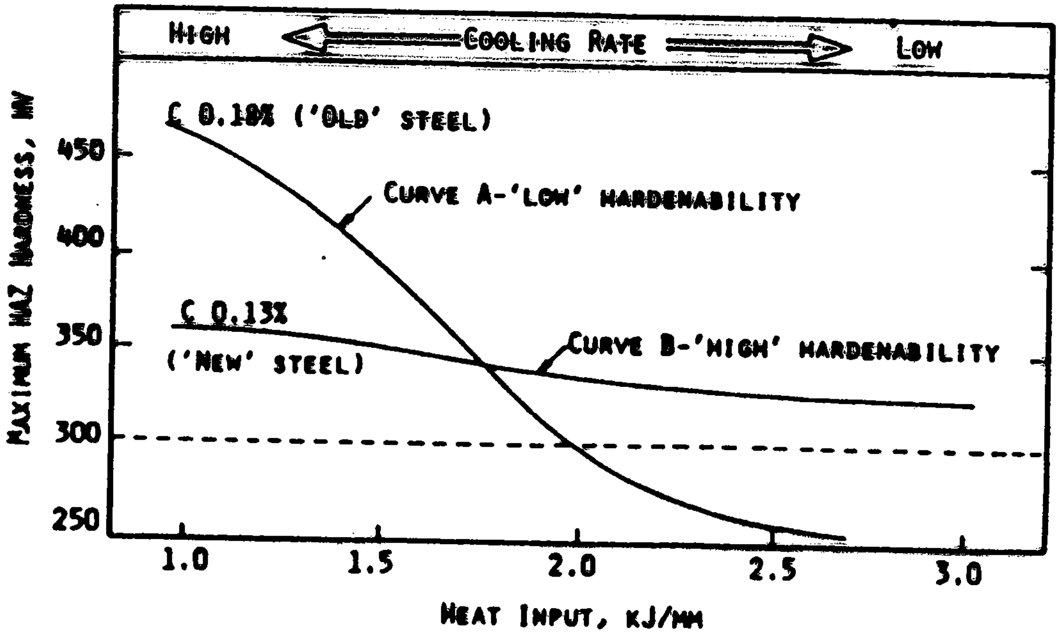
Figure 1–30 Reduction in yield strength with increasing tempering temperature for the same series of alloys shown in Figure 1–29. Values in parenthesis are % elongation in 2 in.



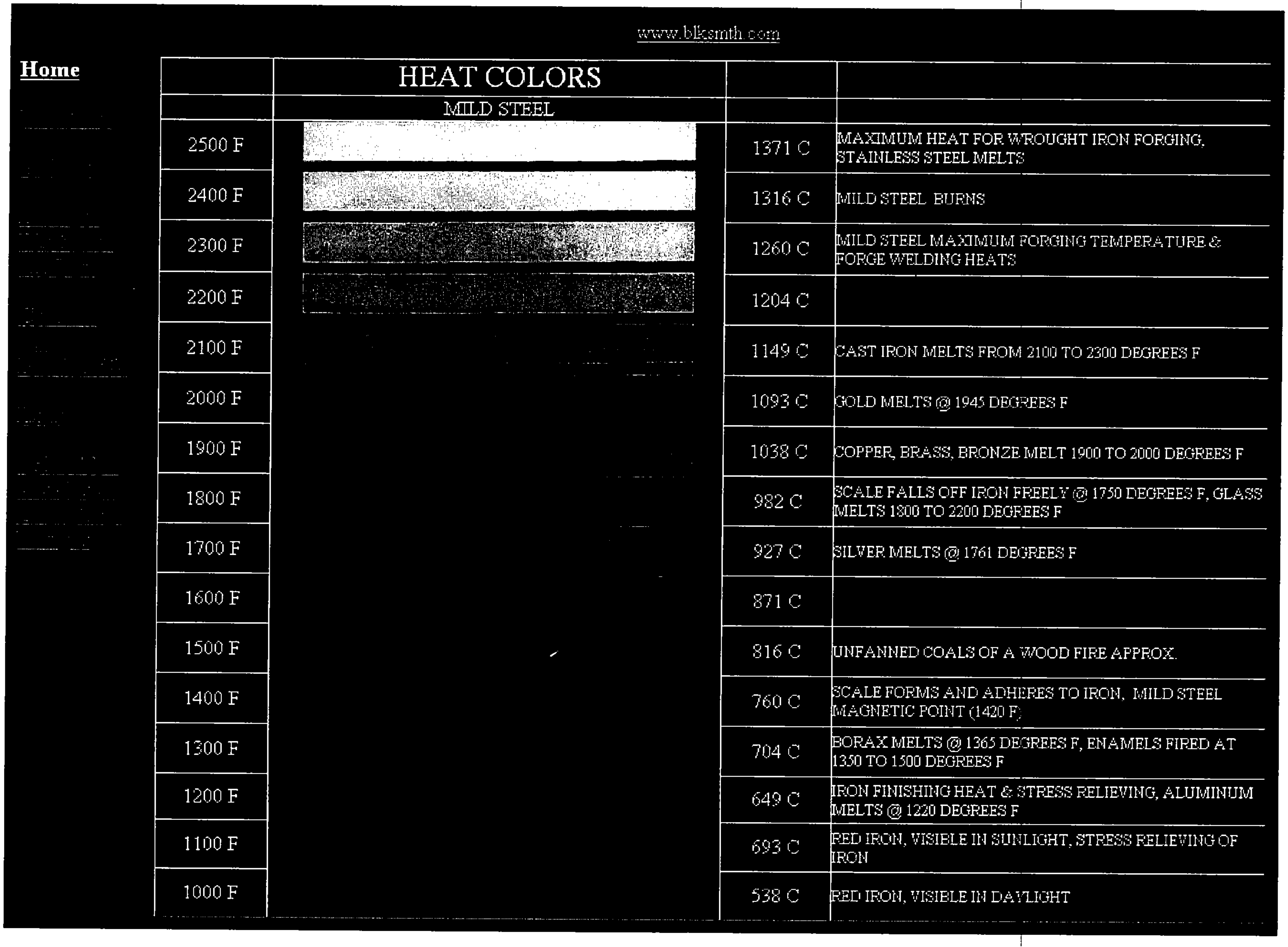
–Effect of Time at Temperature on the Reduction of Residual Stresses



–Effect of Stress Relieving Temperature on Residual Stresses



5 - Representation of the effect of heat input on the change in maximum HAZ hardness in C-Mn structural steels Ref. 9



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2000 F		1093 C	GOLD MELTS @ 1945 DEGREES F
1900 F		1038 C	COPPER, BRASS, BRONZE MELT 1900 TO 2000 DEGREES F
1800 F		982 C	SCALE FALLS OFF IRON FREELY @ 1750 DEGREES F, GLASS MELTS 1800 TO 2200 DEGREES F
1700 F		927 C	SILVER MELTS @ 1761 DEGREES F
1600 F		871 C	
1500 F		816 C	UNFANNED COALS OF A WOOD FIRE APPROX.
1400 F		760 C	SCALE FORMS AND ADHERES TO IRON, MILD STEEL MAGNETIC POINT (1420 F)
1300 F		704 C	BORAX MELTS @ 1365 DEGREES F, ENAMELS FIRED AT 1350 TO 1500 DEGREES F
1200 F		649 C	IRON FINISHING HEAT & STRESS RELIEVING, ALUMINUM MELTS @ 1220 DEGREES F
1100 F		693 C	RED IRON, VISIBLE IN SUNLIGHT, STRESS RELIEVING OF IRON
1000 F		538 C	RED IRON, VISIBLE IN DAYLIGHT