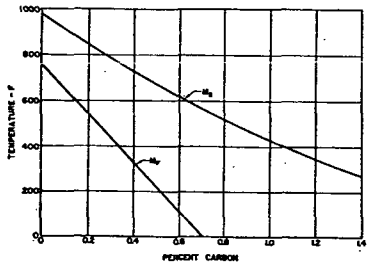

Fig. 2 .... Influence of Carbon on M_s and M_f Temperatures[1]

more useful product with increased ductility and toughness, but with corresponding sacrifice of strength and hardness. The crystal lattice reverts to a body-centered cubic equilibrium form with excess carbon separating out as iron carbide. Tempering causes an overall contraction. During the tempering process, any retained austenite tends to transform isothermally to bainite as a function of time.

The austenite-martensite reaction continues with falling temperature down to a temperature referred to as M_f, at which point the reaction ceases even though retained austenite may still exist. It is important to recognize that the M_f temperature does not necessarily mean that the structure is completely martensitic. The reason for retained austenite existing at or below M_f has been a subject of much conjecture. It is believed to be caused by a stabilization of the retained austenite which renders it sluggish in its response to conversion. Probably the most important factor in the stabilization of austenite, and hence its retention, is a delay in cooling to M_f. In the quenching of steels subject to retained austenite it is important to cool continuously down to M_f, since martensite only forms in the range M_s to M_f with decreasing temperature. Any appreciable delay at room temperature tends to stabilize retained austenite against further conversion. In the case of certain alloy steels which tend to retain austenite even after lowering the temperature to M_f, it is found advantageous to allow recovery to room temperature, or to a stress relieving temperature of 300 F, followed by a second and third cooling to M_f. With each cooling cycle a smaller percentage of retained austenite is converted to martensite.

Although the M_s temperatures have been determined by direct measurement in many alloys, they may also be approximated with reasonable accuracy for most practical applications by use of an empirical equation. One such equation, developed by Grange and Stewart, expresses M_s, as follows:

$$M_s = 1000 - 650\,C - 70\,Mn - 35\,Ni - 70\,Cr - 50\,Mo$$

where

M_s = temperature below which martensite occurs, Fahrenheit.
C = carbon content, percent.
Mn = manganese content, percent.
Ni = nickel content, percent.
Cr = chromium content, percent.
Mo = molybdenum content, percent.

This equation applies when all carbides are dissolved in the austenite, carbon content is 0.20 to 0.85 percent, molybdenum is below 1 percent and chromium less than 1.5 percent. Both M_s and M_f are lowered by carbon and alloying elements when

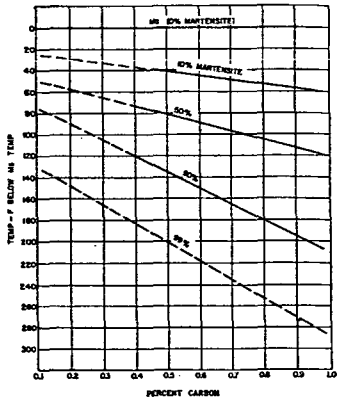

Fig. 3 .... Relationship Between Percent Carbon in Steel and Proportion of Martensite Formed at a Given Temperature[2]

dissolved in the austenite at the austenitizing temperature. The importance of complete austenitization, or solution of carbides prior to quenching, should be apparent since undissolved carbides will result in higher values for M_s and M_f than would be indicated by the actual chemical composition of the steel. The strong influence of carbon on lowering these temperatures is indicated by the carbon factor in the preceding equation and in Fig. 2.

Although a knowledge of M_s temperatures is vital for many heat treating operations, information on M_f temperatures is of equal importance wherever it is necessary to minimize retained austenite in quenched steels. Unfortunately, M_f temperatures are not readily determined, primarily because of the difficulty of measuring small percentages of retained austenite particularly of the order of five percent or less. These temperatures generally range 325 to 475 F below M_s with maximum spread in those alloy steels containing appreciable carbon, manganese, chromium or nickel. A representation of the proportion of martensite formed at given temperatures below M_s when carbon content is known has been prepared from experimental data (Fig. 3). Although considerable scatter may be noted with increasing martensite formation (decreasing retained austenite) the chart is useful in following the progress of austenite transformation.

CONVERSION OF RETAINED AUSTENITE

Retained austenite may be converted by: (1) heating above M_s and allowing isothermal transformation to bainite, as in the tempering operation with decrease in hardness or (2) cooling to M_f by cold treatment. Where maximum hardness is required, only the second method may be used. With M_f above room temperature, as in the case of low and medium carbon steels, cold treatment is not required to develop the full hardness for a given carbon content. When the carbon content exceeds about 0.65 percent in straight carbon steel some means of cooling or refrigeration is required to reach M_f. Since carbon content has the greatest influence in lowering M_s and M_f it would be expected that cold treatment would

have its greatest value in carburized steels and high carbon tool steels containing manganese, chromium and nickel.

The value of converting retained austenite in hardened steel parts has been somewhat controversial. Some metallurgists claim that the presence of this soft, ductile phase in the quenched structure serves as a cushion which may tend to minimize quench-cracking. However, if such areas of austenite transform to martensite upon subsequent cooling from the tempering temperature they may then become brittle areas of untempered martensite. In general, the higher the M_s the less is the tendency of quench-cracking, probably because of greater simultaneous stress relief during the volume changes taking place in the martensite formation. Although oil or salt bath quenching tends to result in more retained austenite than water quenching, conversely the longer time in dropping to M_f may result in some isothermal transformation to undesirable bainite in the upper portion of the M_s to M_f range for certain steels. It should be remembered that martensite forms only with a falling temperature, whereas bainite forms isothermally with any pause in temperature drop. It is generally considered highly desirable to quench steel to produce initially a fully martensitic structure which, upon subsequent tempering, produces the best combination of strength and ductility. Aside from this, elimination of retained austenite results in maximum hardness, dimensional stability and improved magnetic properties.

When retained austenite is converted to martensite by cold treatment immediate tempering is necessary to relieve the stresses brought about by the volume increase. If several cold treatment-tempering cycles are employed for maximum conversion, the final process must be a retempering operation to stress relieve the final crop of martensite which is formed. Where maximum hardness is required this temperature will normally be 300 to 400 F in carburized and alloy steels. Tool steels which resist tempering, such as high speed steel, are normally retempered at the original tempering temperature extending up to 1000 to 1100 F.

PRODUCT IMPROVEMENT OF FERROUS ALLOYS

The principal areas in which cold treatment has been practiced to advantage in product improvement of ferrous alloys may be summarized as follows:

1. Increased hardness and wear resistance.
2. Dimensional stability of tools, gages and machine parts.
3. Elimination of grinding cracks.
4. Increased cutter tool life.
5. Improved magnetic properties.
6. Salvage growth of undersized dies, etc.

Since austenite is relatively soft and ductile, any appreciable quantity present in the surface structure of a tool or machine part will cause reduced hardness which may lead to more rapid wear. Probably the most fertile field for improvement in this area is in carburized parts manufactured from alloy steels which favor austenite retention, such as SAE 2317, 2512, 3310, 4320, 4620, 4820 and 9310. Increased hardness values of up to 15 points Rockwell C have been noted in carburized cases of SAE 3310 gears as shown in Table 1. This illustrates the value of multiple cold treatment-retempering cycles on a carburized case intentionally carburized to a high surface carbon content. The maximum improvement takes place as a result of the first cycle, with a smaller percentage converted in each succeeding cycle. Not all steels respond after the first cycle due to stabilization of the retained austenite and it is seldom necessary to employ temperatures lower than about −120 F.

Where maximum dimensional stability is required in tools,

Table 1 .... Influence of Cold Treatment on Case Hardness of SAE 3310 Carburized Gears

Depth below Surface, In.	Hardness Rockwell C Converted from 500 gram Knoop		
	As-quenched, 1700 F	1st Cycle, −100 F	2nd Cycle, −100 F
0.002	48	64	66
0.004	47	65	66
0.006	44	64	65
0.008	48	64	65
0.010	52	63	65
0.012	53	63	65
0.014	53	63	64
0.016	53	64	64
0.018	59	64	64
0.020	59	64	65
0.030	57	59	59
0.040	49	51	51
0.050	43	44	44

gages or machine components, cold treatment, or cold stabilization as it is also called, may be employed to bring about conversion of the retained austenite and resultant expansion prior to the final dimensioning of the part. The linear expansion resulting from transformation of 1 percent retained austenite is approximately 140 microinches per inch. In the manufacture of gage blocks, multiple cycling between −150 F and +275 F for 3 cycles of 1 hr duration immediately after quenching may produce blocks to a guaranteed life precision measured in millionths of an inch.

Although dimensional stability is important in gage manufacture it is no less important in close tolerance machine parts subject to subsequent low-temperature service conditions in high altitude aircraft applications. Among the steels used in such applications, SAE 52100 has been a popular choice. This steel is particularly sensitive to austenitizing temperature. When austenitized at 1700 F approximately 13 percent retained austenite exists in the quenched structure whereas quenching from 1450 F results in about 4 percent. The higher austenitizing temperature permits greater solution of chromium carbide and hence lowers the M_f temperature. For the greatest dimensional stability it is necessary to cold stabilize SAE 52100 as a continuation of the quenching cycle down to about −150 F with a minimum of delay at room temperature if stabilization of austenite is to be avoided. The great risk of quench-cracking of parts of complex design is again emphasized and must be balanced against the value of obtaining maximum conversion of austenite where drastic section changes or other stress raisers create a hazard. A stress relief in boiling water immediately after the quench and before the cold treatment offers a compromise where the austenite stabilising effect of a full tempering operation is to be avoided.

Seasoning is a variation of cold stabilization for dimensional stability which involves cycling several times over the temperature range to be found in service. Although conversion of retained austenite may occur, it is considered that stress relief or equalization of stress is an important factor in producing stability in this application. Formerly, iron castings were seasoned by storage for months before machining for applications requiring dimensional stability. Today, artificial seasoning consists of cycling cast iron parts from −150 F to 700 F, allowing for possible contraction.

The elimination of retained austenite in hardened steel reduces the possibility of grinding cracks which normally re-