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THE STRENGTH OF STEEL

Berkeley, California

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THE STRENGTH OF STEEL

Control of strength-producing mechanisms is closing the great gap between the attainable strength of steel and the theoretical value. The traditional strengthener, carbon, is missing from one new alloy

by Victor F. Zackay

The difference between the actual tensile strength of a crystal of pure iron and the theoretical strength of the crystal is represented by a factor of about 1,000. The actual strength is some 1,500 pounds per square inch; the theoretical strength is about 1.6 million pounds per square inch. Long before these figures were known—indeed, before anything was known of the composition and intimate structure of steel—artisans little by little discovered ways to increase the strength of iron alloys to about 150,000 pounds per square inch. This approximates the strength of the finest sword blades made in Damascus and Japan. Ordinary low-carbon, or structural, steel, which accounts for most of present production, has a tensile strength of between 45,000 and 60,000 pounds per square inch. Tool steels go up to about 300,000 pounds per square inch, and cold-drawn fine steel wire—the strongest commercial steel product—goes up to about 600,000.

Within the past few years, as a result of slowly developing insight into the factors that strengthen steel, new processes have been developed for producing a steel in bulk form that has a tensile strength of more than 400,000 pounds per square inch. Almost as strong as the steel in cold-drawn wires, the new material is being tested for a variety of automotive, aircraft and other applications in which the utmost in strength-to-weight ratio is required.

One of the tough new steels is made by the Ausform process, developed in the Scientific Laboratory of the Ford Motor Company. The process is an extension of concepts introduced by Dutch metallurgists. A second new process, called Maraging (a contraction of "martensite aging"), was developed by the International Nickel Company, Inc. The unique feature of Maraging steels, which are almost as strong as Ausform steels and even tougher, is an almost total absence of carbon. Historically the strength of steel has been related to carbon content. In the Maraging alloys the role of carbon is taken over by substantial percentages of nickel, cobalt and molybdenum, amounting to more than 25 per cent of the total alloy. The discovery that carbon is not essential to high strength should encourage the design of a whole new class of ductile alloys, both ferrous and nonferrous, free of an element known to cause embrittlement.

Increased understanding of the strength of steel and other metals has gone hand in hand with the development of instruments for seeing finer and finer details of physical structure. The first indication that steel and cast iron are crystalline solids came from the examination of their fractured surfaces with a hand lens. Later, when the surfaces were examined under the microscope, it was found that much greater detail could be seen if the samples were polished and etched to increase the contrast between crystals having different phases, or structural states. Such studies showed that metals are a composite of crystalline grains within which reside other crystalline phases varying greatly in shape, size and distribution. Today the electron microscope is widely used for studying metallic structure just above the level of the atom. And with X-ray diffraction methods and the field-ion microscope the probing can be carried down to the atomic level.

Early in this century it became possible to make a rough approximation of the theoretical strength of metals, based on the binding forces between the atoms in a crystal lattice. For iron the computed values were between a million and two million pounds per square inch. The problem then became one of explaining why real metals are so weak. The answer was suggested independently in 1934 by Geoffrey I. Taylor, Egon Orowan and Michael Polanyi. They postulated that metals contain dislocations, or linear defects, that move easily when extremely small stresses are applied [see "Observing Dislocations in Crystals," by W. C. Dash and A. G. Tweet; SCIENTIFIC AMERICAN, October, 1961]. The commonest form of dislocation occurs when a plane of atoms is missing from a crystal lattice, as shown in the top illustration on pages 74 and 75. (The dislocation can also be thought of as being produced by an extra plane of atoms.) When a small stress is applied, the missing plane (or the extra plane) slips freely through the lattice. The theory explained satisfactorily why real metals are far weaker than ideal, or defect-free, crystals. The theory also explained why "whiskers," or single-crystal fibers, of many metals have strengths equal to the theoretically calculated values. Either there are few dislocations in whiskers or those present are almost completely immobilized.

Conversely, the weakest form of a metal should be one containing dislocations that are not immobilized. A very pure single crystal that has been grown to bulk size meets this specification; it contains neither grain boundaries nor impurity atoms to impede the movement of dislocations. Thus very pure single crystals and metallic whiskers represent the floor and the ceiling of the strength of a given metal.

With the insight provided by dislocation theory, metallurgists have gained a better understanding of the traditional methods used to strengthen steel. They are effective to the extent that they impede or block the movement of dislocations. Five particularly effective methods

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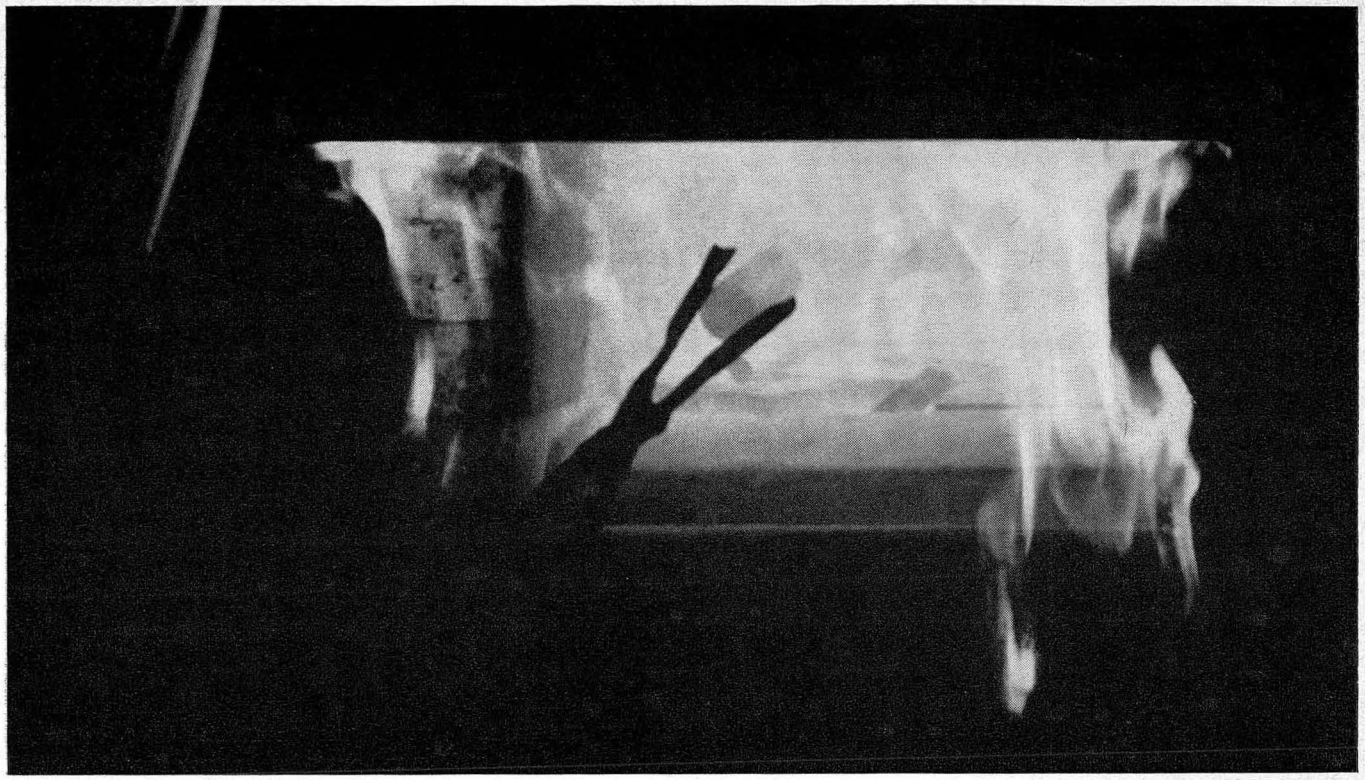
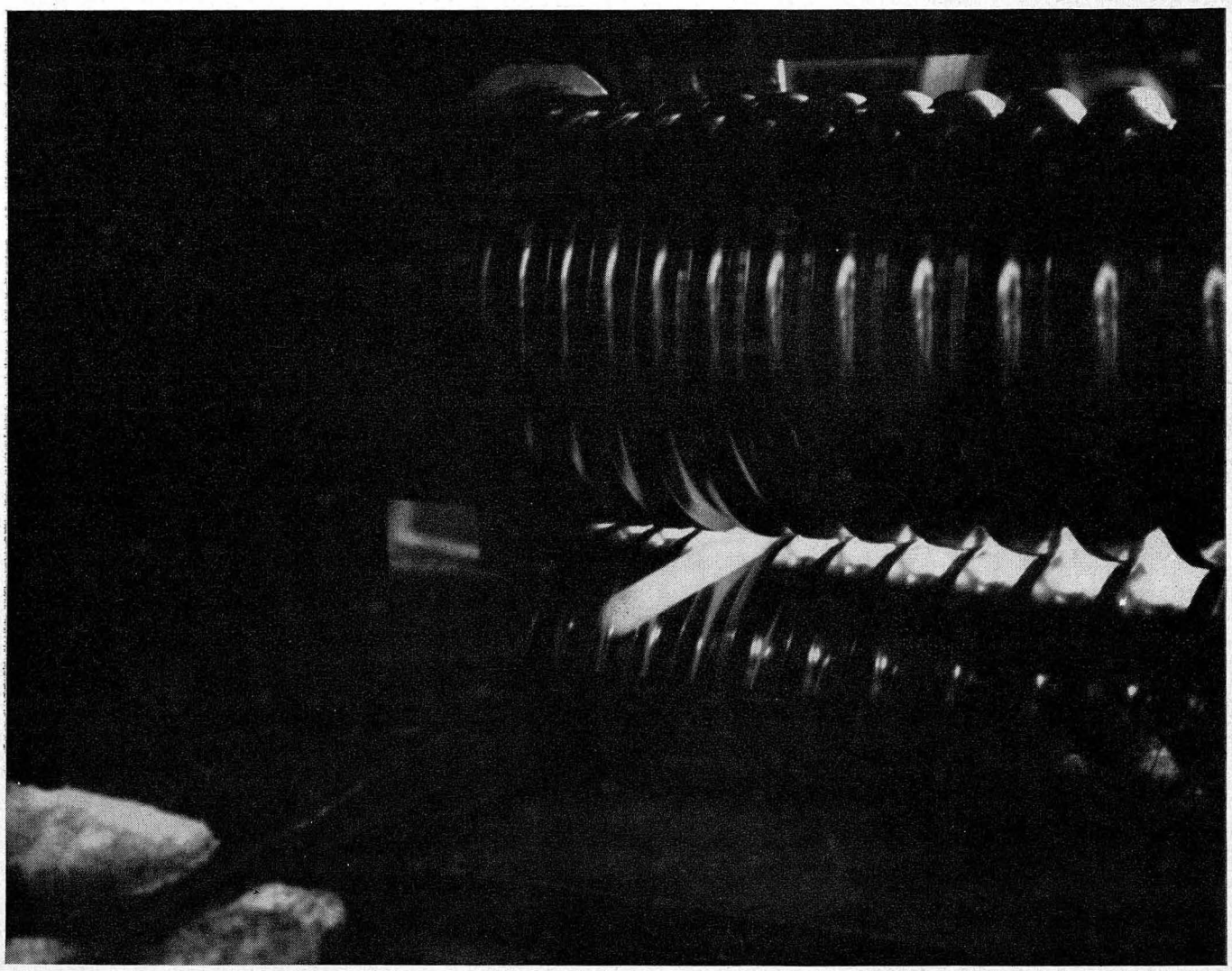
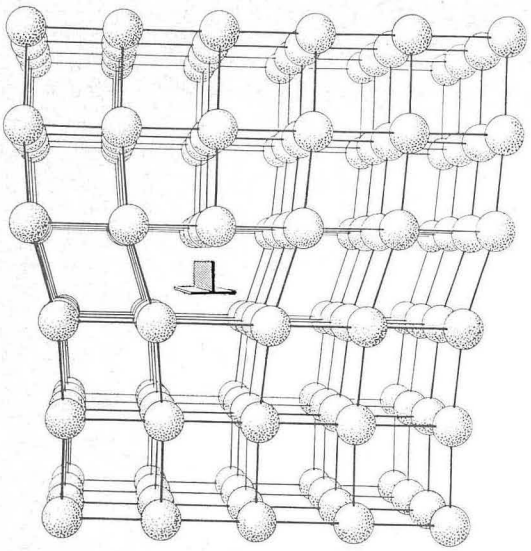
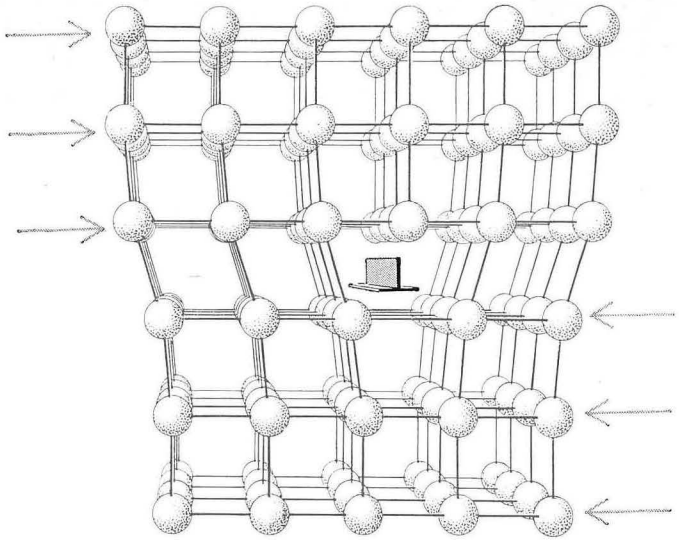




AUSFORM PROCESS, developed by the Ford Motor Company, creates a steel of great strength by deforming, or cold-working, suitable alloys. Top photograph shows an experimental billet being heated preparatory to quenching and deforming. Bottom photograph, taken on infrared-sensitive film, shows the billet being deformed in a rolling mill. To the eye the billet is not luminous.





MOVEMENT OF DISLOCATION accounts for the weakness of iron and other metals. The dislocation, represented by the black T-shape, occurs where a plane of atoms is missing from the lattice of a crystal. When a small shearing force is applied, a sim-

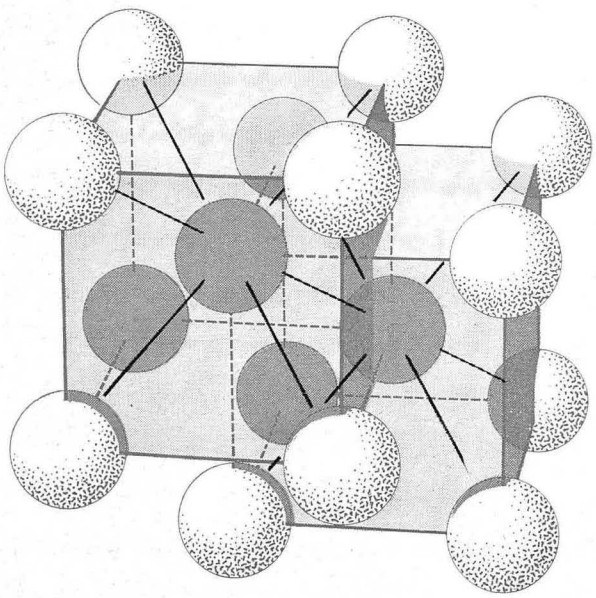
for increasing the strength of steel are: (1) addition of carbon, (2) reduction of grain size, (3) deformation of structure by "cold-working," (4) inclusion of hard particles or precipitates, (5) quenching, or quick cooling, to produce a structure whose strengthening mechanisms are only partially understood. Each of these will be discussed in turn.

Increasing the amount of carbon dissolved in very pure iron from .0001 to .005 per cent increases the strength of the metal by a factor of four. The carbon dissolves in the crystals of iron, which are in the form of ferrite, cubic crystals with an atom of iron in the center. The potent strengthening is thought to be related to the position of the carbon atoms in the iron lattice. The carbon may either be squeezed into the interstices of the lattice or clustered around the dislocations [*see bottom illustrations on these two pages*]. In either event the dislocations tend to be immobilized and a greater stress has to be applied to make them move.

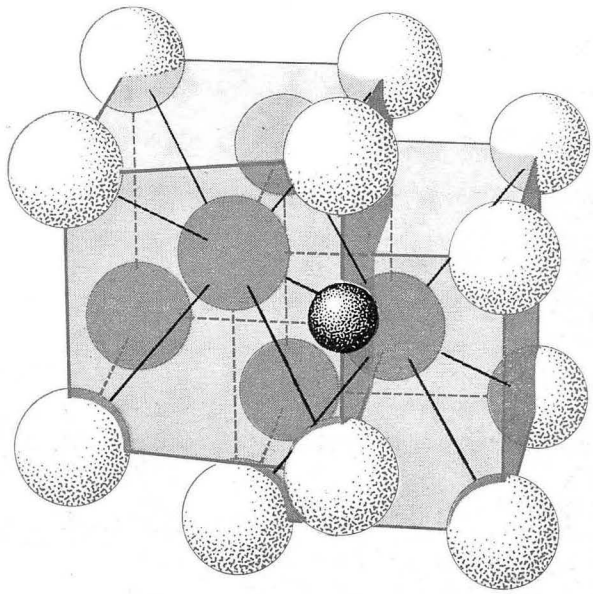
The second method for limiting the movement of dislocations is to decrease the size of the crystal grains in the metal. Although a dislocation can move through the crystal in which it originates, it cannot jump across a grain boundary and propagate itself in an adjacent crystal. By decreasing the grain size tenfold, thereby presenting many more barriers to dislocation movement, the strength of iron can be tripled. Grain size is established by the combination of thermal and mechanical processing that the metal has undergone. The upper electron micrograph on page 78 shows how dislocations have piled up at a grain boundary in stainless steel.

The third way to raise the strength of steel is to hammer, roll, forge, extrude or otherwise deform it. If the deforming is done at a temperature at which the metal is not in the plastic state, it is called cold-working. Severe deformation of iron at room temperature doubles its strength. The deformation produces complex tangles of dislocations that impede the motion of other dislocations [*see lower illustration on page 78*].

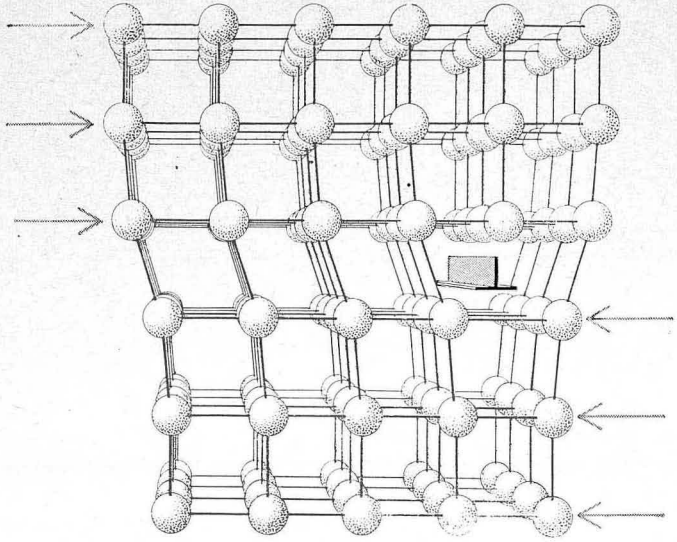
The fourth method of blocking dislocations is to disperse hard particles or precipitates in alloys. Steel normally con-

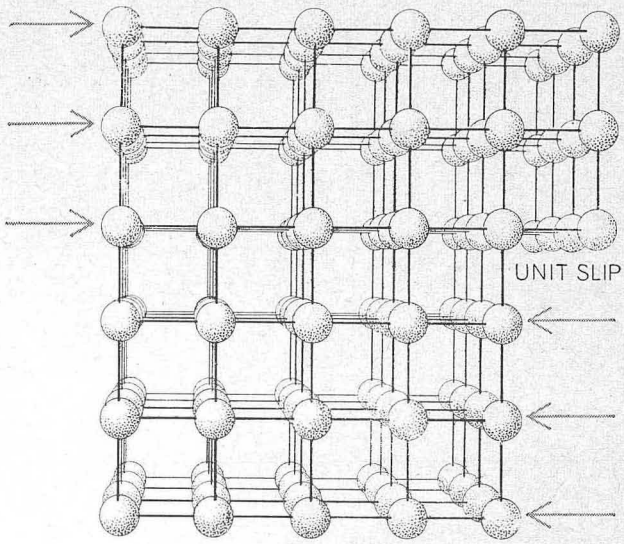


CRYSTAL OF FERRITE, one form of pure iron, consists of interlocking cubes, producing a "body-centered" structure (*left*).



Carbon can dissolve in ferrite to a small extent (*right*). A dissolved atom (*black*) occupies a site along the edge of a cube.



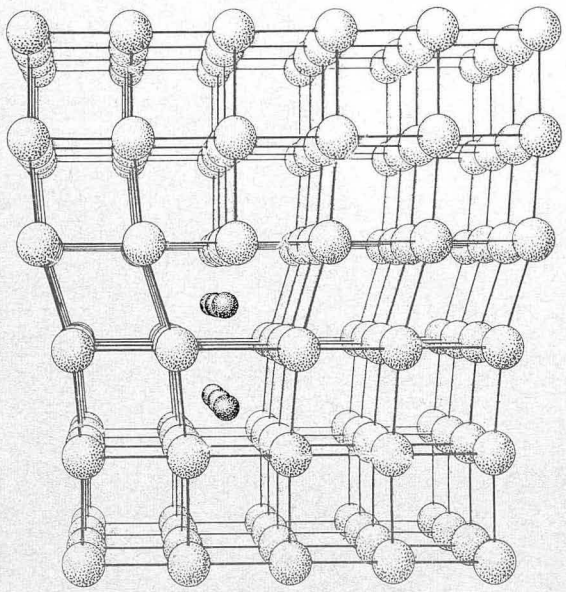


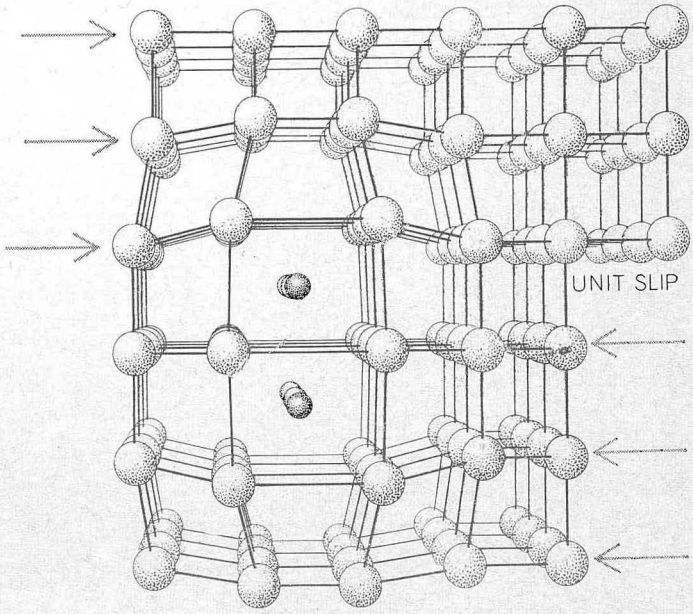
ple flip in atomic bonding allows the dislocation to jump one cell to the right (*second panel from left*). Ultimately the dislocation reaches the edge of the crystal, producing a unit of slip. Many such slips will lead to a visible change in the shape of the metal.

sists of hard and brittle iron carbides dispersed in a relatively soft matrix of cubic ferrite. The closer the spacing of these carbides and, to some extent, the smaller their size, the stronger the steel. Two of the most important forms of steel, pearlite and bainite, owe their strength to the particular shape and distribution of hard iron carbides. Pearlite contains alternating plates of hard carbide and soft ferrite. Bainite has a more complex structure in which the individual carbide and ferrite phases can be plate-like, needle-like or feather-shaped. The strength of both pearlite and bainite can be raised by decreasing the distance between carbide particles by alloying and heat treatment. Pearlite and bainite are included in the class of plain carbon steels in which the carbon content runs between .1 and .8 per cent. Their usable strength is between 30,000 and 150,000 pounds per square inch.

To obtain still greater strength one must resort to the fifth method of treatment, in which steel is quenched from a high temperature. The rapid cooling prevents the formation of carbide-ferrite microstructures like those of pearlite or bainite and yields the structure known as martensite. As a result of this type of heat treatment all or most of the carbon is retained in a supersaturated solution. Martensite can contain tens or even hundreds of times more carbon in solution than ferrite can. The strength of martensitic steels is directly proportional to the dissolved carbon. When the carbon is .4 to .6 per cent, the strength runs as high as 300,000 pounds per square inch.

The various types of steel mentioned —pearlite, bainite and martensite—are simply names for particular microstructures that arise spontaneously as a consequence of carbon content, temperature treatment and one other factor: time. These relations are diagramed at the top of page 79. The black curve (*a*) in the diagram shows how a medium-carbon steel can exist in various phases, depending on temperature and time. Above 1,450 degrees Fahrenheit the steel is in the form of austenite. If it is cooled quickly, it becomes metastable austenite and, below 450 to 650 degrees F., martensite. If it is not cooled quickly but is held at a temperature between 750 and





CARBON-STRENGTHENING OF IRON may take place in two steps. Carbon atoms dissolve at the site of a dislocation (*left*). After a unit slip occurs, the carbon atoms create a stressed region (*right*), which interferes with the passage of other dislocations.

1,450 degrees, it decomposes spontaneously into ferrite and carbide. If the decomposition takes place near the higher temperature, the ferrite and carbide take the form of pearlite; if it occurs near the lower temperature, they become bainite.

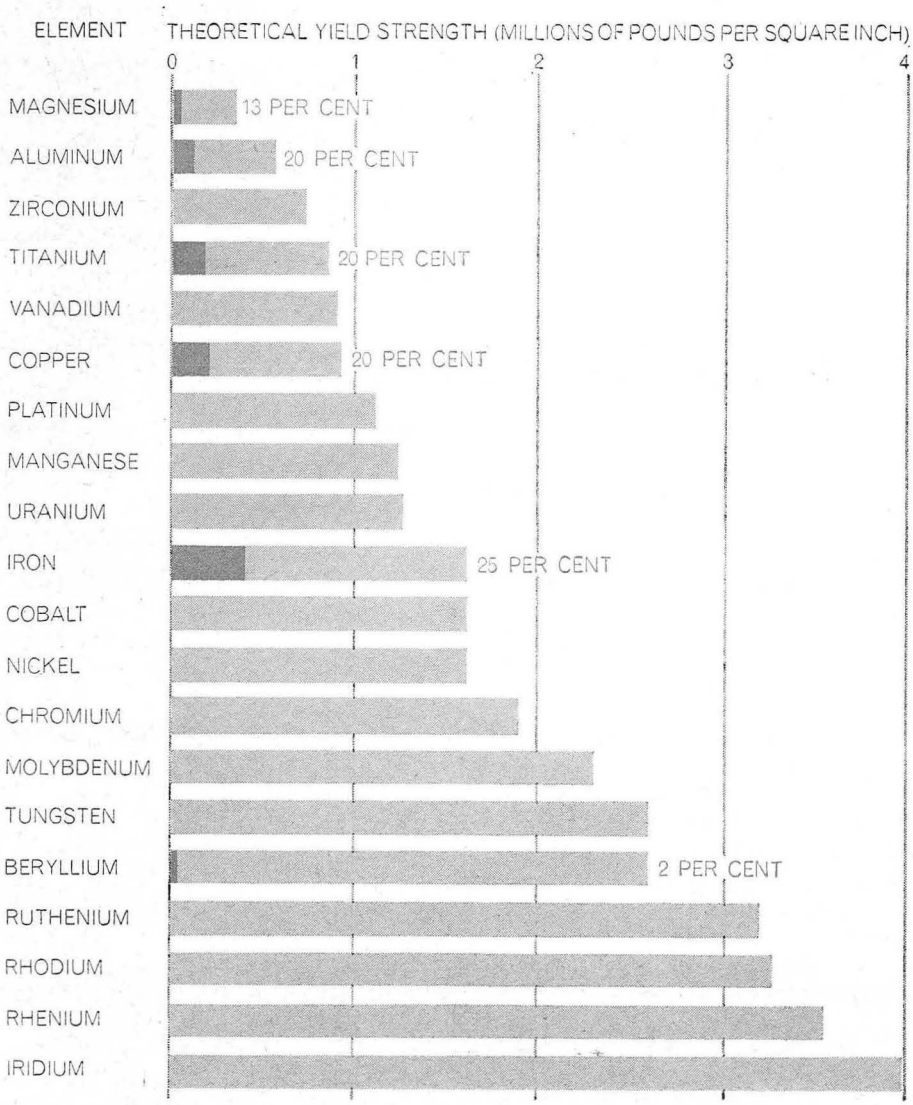
In making martensitic steel the austenite must be cooled fast enough to avoid decomposition into ferrite and carbide. Yet the quenching rate must not be so fast as to crack the hard but brittle martensite. Ductility is achieved later by a tempering operation, in which the steel is reheated to a temperature below 1,000 degrees and held there for about an hour [*see first panel in top illustration on page 80*]. Tempering sacrifices some of the strength and hardness of martensite for additional toughness. It is little wonder that in ancient times truly good swords were priceless and exceptional ones became the source of legends.

In 1954 two Dutch metallurgists, E. M. H. Lips and H. van Zuilen, announced a process for raising the strength of martensitic steel a full third over the previous values of 300,000 pounds per square inch. In their process austenite is either continuously deformed as it is cooled from about 1,700 degrees or it is deformed at a constant temperature just above the point at which martensite starts to form. When the metal is cold-worked above this temperature, an entirely new variety of soft, strain-free grain is created. This produces a stronger austenite from which the martensite subsequently arises. The deformed austenite is then quenched and tempered as in the conventional heat treatment of martensitic steels. The Dutch process is shown in the second panel in the top illustration on page 80.

A major difficulty in the Dutch process was that the cold-working of austenite at comparatively low temperatures caused the austenite to decompose rapidly, so that the final product was usually a mixture of ferrite, carbide and martensite of low strength. The initial encouraging results reported by Lips and van Zuilen were achieved with wires and thin sheets, in which quick deformation and quick quenching did not give the decomposition reactions time to take place. It therefore was clear that a new process was required if this technique of strengthening were to be employed in bulk steel parts having cross sections larger than those of wire, foil and thin sheet.

A search for such a process was begun about 1954 by a group of us at the Ford Scientific Laboratory, and after an intensive six-year effort the Ausform process was developed. Applicable to a wide variety of steel alloys and fabrication techniques, it solves the problem that frustrated the Dutch process. In the Ford process the decomposition of austenite is delayed by certain alloying elements, notably chromium. It had been known for many years that when chromium is used in a suitable alloy, a "bay" develops in the curve marking the decomposition boundary between austenite and martensite. This bay, shown by the colored curve (*b*) in the top illustration on page 79, indicates that the decomposition of austenite to ferrite and carbide is strongly suppressed over a wide region in the neighborhood of 600 to 1,000 degrees F. Once this region had been identified there was no great problem in confining the cold-working operations to it. The deformation is carried out under close temperature control so that no decomposition into pearlite or bainite takes place [*see third panel in top illustration on page 80*]. The cold-worked austenite is quenched to martensite and tempered. Many commercially available high-strength steels have compositions that lend themselves favorably to the Ausform process. One such steel, known as Type H-11, responds particularly well. In addition to iron it contains 5 per cent chromium, 1.3 per cent molybdenum, .5 per cent vanadium and .4 per cent carbon.

The principal factors controlling the strength of Ausform steels are the amount of deformation, the temperature at which the deformation is done and the carbon content. Lesser variables are the tempering temperature and the alloy content. The strength of any cold-



THEORETICAL STRENGTH is shown for 20 metals. The currently attainable bulk yield strength for six of them is indicated by dark color; the numbers indicate per cent of the theoretical value. The theoretical strength represents the atomic binding forces in a crystal.

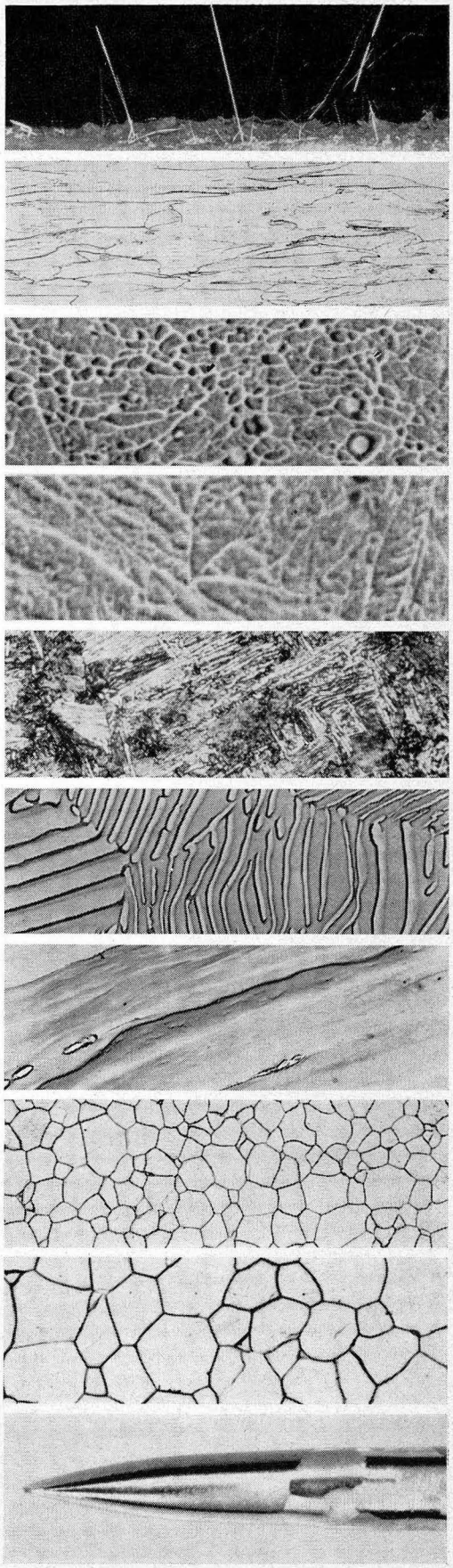
worked metal or alloy increases with the amount of deformation and decreases as the temperature of deformation rises. In other words, the lower the temperature at which the cold-working takes place, the better.

These general principles have been found to hold for Ausform steels [*see bottom illustration on page 80*]. It is quite clear that the strength of the martensite of the Ausform steels directly reflects the increased strength of the cold-worked austenite from which it forms. An increase of 100,000 pounds per square inch in strength without a concomitant loss in ductility can be observed in Ausform steels in which the austenite has been severely deformed.

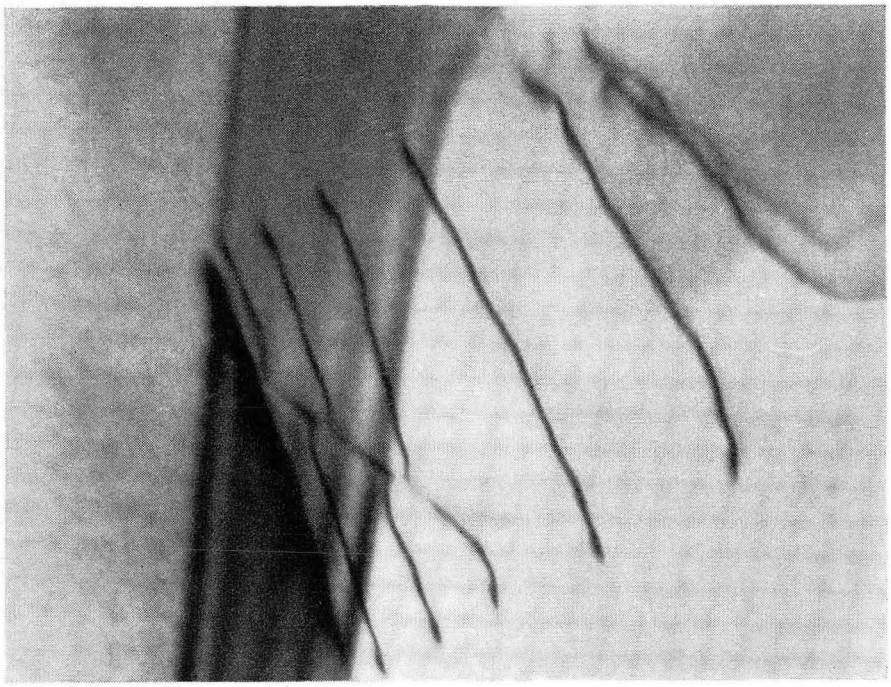
The highly distorted and deformed structure of the austenite of Ausform steels can be seen by deliberately allowing austenite decomposition to take place. This is most conveniently done by allowing the cold-worked austenite to cool slowly instead of quenching it. The decomposition products of ferrite and carbide precipitate preferentially on the slip bands, or flow lines, of the deformed austenite grains [*see illustration at top left in the group of four at bottom of page 82*]. Slip bands marked by such precipitates are said to be decorated. When only a few martensite plates are allowed to form, the interaction of these plates with decorated slip bands can readily be seen, as shown in the illustration at top right in the group of four on page 82. Conventionally formed martensite is observed within the undistorted grain in the bottom third of the photomicrograph. Several badly distorted martensite plates are seen in the deformed grain in the upper portion of the photomicrograph. Careful examination reveals that the forming martensite plates are offset each time they intersect a decorated slip band.

The strength and hardness of Ausform steels is maximized in a highly alloyed high-carbon steel that has been severely deformed in the austenite condition at a relatively low temperature. The mechanical properties of such a steel (Vascojet MA), containing .55 per cent carbon and a total of 12 per cent alloying elements, are shown as a function of tempering temperature in the top illustration on page 82. The strength (equivalent to that of a metal-cutting tool) is remarkably insensitive to tempering temperature. The yield strength of this steel is more than 400,000 pounds per square inch and its tensile strength is more than 475,000 pounds per square inch, over a wide range of tempering temperatures. The ductility is equal to or better than

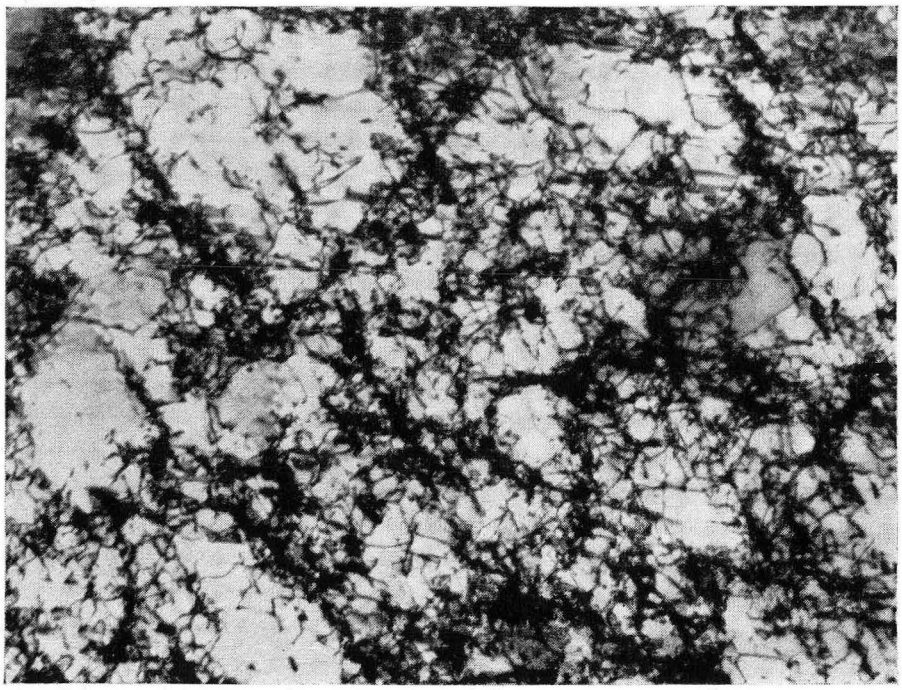
STRUCTURE	STRENGTH
IRON WHISKERS	1,600,000
COLD-DRAWN STEEL WIRE	600,000
AUSFORM STEEL	425,000
MARTENSITIC STEEL	300,000
BAINITIC STEEL	200,000
PEARLITIC STEEL	175,000
COLD-WORKED IRON	100,000
IRON OF SMALL GRAIN SIZE	50,000
IRON CONTAINING DISSOLVED CARBON	20,000
SINGLE CRYSTAL OF PURE IRON	1,500



STRENGTH OF IRON, given in pounds per square inch, can be raised by introducing various obstacles to the movement of dislocations. Such obstacles include dissolved carbon, grain boundaries and hard precipitates. Pictures are by U.S. Steel Corporation and Ford.



PILEUP OF DISLOCATIONS is shown by the series of lines that bunch up at a grain boundary (*dark vertical region*) in stainless steel. The boundary limits dislocation movement. Micrograph is by W. Roser and G. Thomas of the University of California, Berkeley.



TANGLE OF DISLOCATIONS is produced when a metal is cold-worked. The tangles themselves provide an obstacle to the movement of other dislocations, which are not visible. This micrograph of nickel was made by R. Nolder and Thomas of the University of California.

that of its conventionally heat-treated counterpart.

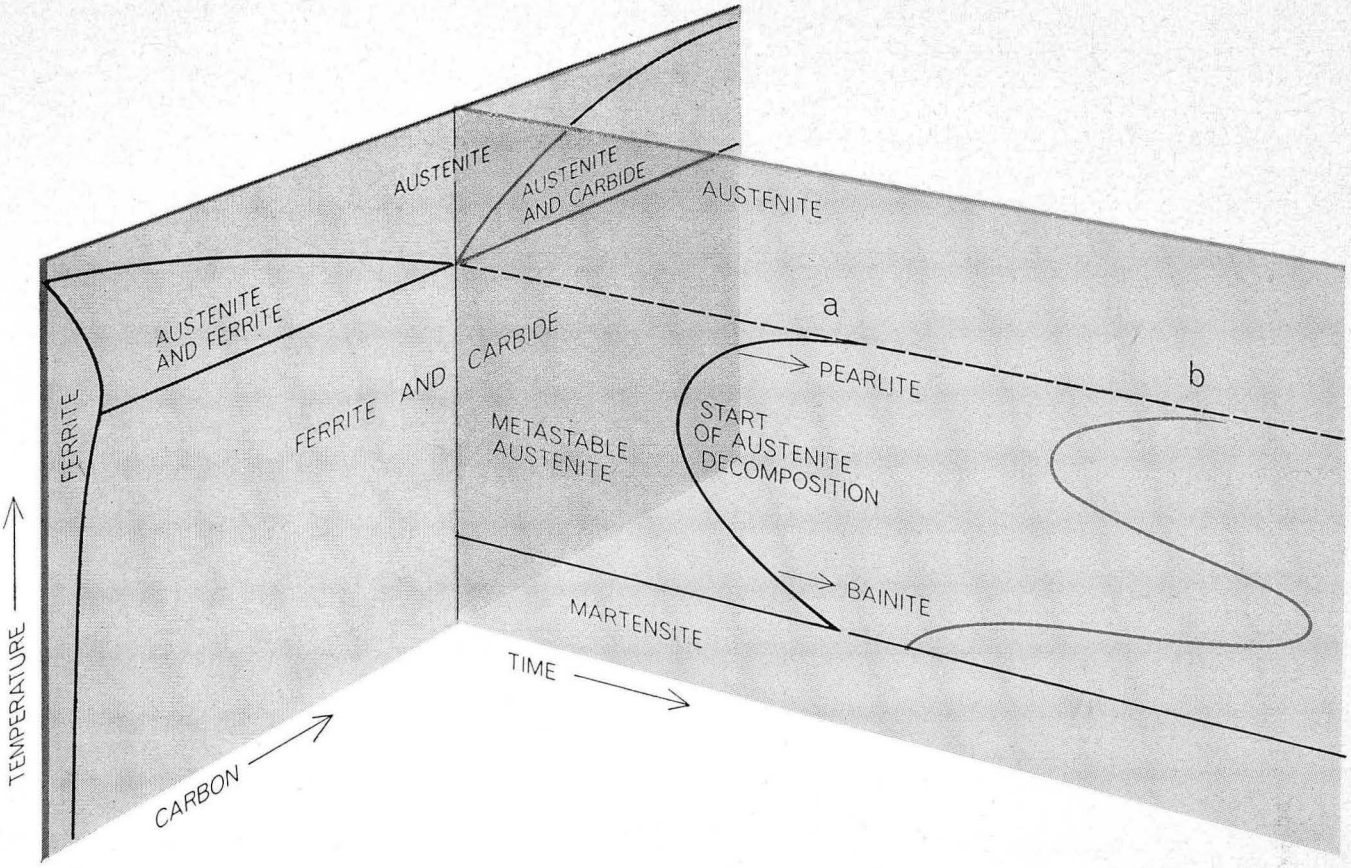
The Ausform process combines fabrication and heat treatment in one operation. This is its source of both strength and weakness. The requirement that the steel be cold-worked at or below the comparatively low temperature of 1,100 degrees F., and that this be done over a limited temperature range, currently poses some manufacturing limitations on the process. At this temperature the steel becomes stronger as it is cold-worked, and equipment must be rugged to deform it. There is also a need for fast-acting temperature-sensing devices to maintain the steel at the proper temperature. Steps are presently being taken to meet both needs

Because Ausform steels are strong, hard and ductile they should be useful for making tools such as punches, dies and shears. Great strength, coupled with excellent resistance to fatigue failure, also recommend their use in automotive suspension systems, aircraft landing gear and high-strength bolting. Several of the highest strength experimental bolts ever tested were made of Ausform steel. Other applications of interest include the manufacture of missile cases and vehicle armor.

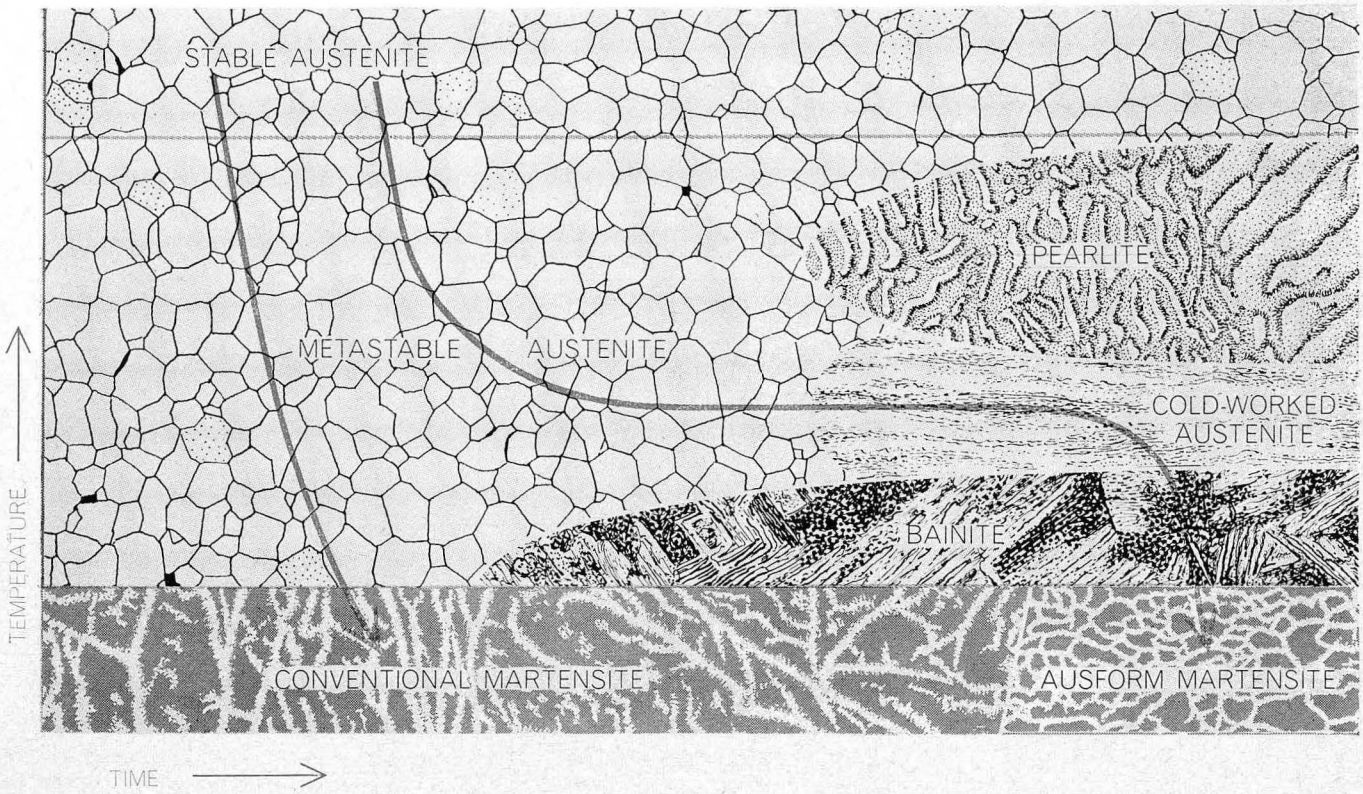
Where extreme toughness and ductility are required, Ausform steels have now been surpassed by International Nickel's Maraging alloys—the alloys that surprised metallurgists by containing virtually no carbon. A typical Maraging steel contains, in addition to iron, 15 per cent nickel, 9 per cent cobalt, 5 per cent molybdenum and .5 per cent titanium. When heat-treated as shown in the fourth panel in the top illustration on page 80, its tensile strength is more than 300,000 pounds per square inch. The alloy is heated to about 1,500 degrees F. and allowed to cool to room temperature in air. Drastic quenching is not required, nor is cold-working. The martensite that forms is soft and malleable, unlike that in quenched steels, and it can easily be fabricated into useful shapes prior to further heat treatment. The martensite is then aged at about 900 degrees F. for several hours. The aging step turns the soft martensite into a tough, hard material. Exactly why this happens no one knows.

Maraging steels have about twice the ductility of conventional martensitic and Ausform steels. Furthermore, their toughness is in a class by itself. Maraging steels have exceptional ability to resist brittle fracture when they are flawed by deep scratches or nonmetallic inclusions. Their advantages include simple heat treatment, excellent welding characteristics and good strength and ductility at temperatures well below zero Fahrenheit. Suggested applications include highly stressed rotating mechanical parts, aircraft landing gear, hulls for deep-diving submarines and containers for holding liquid hydrogen in rockets. At present Maraging steels are several times more costly than Ausform steels.

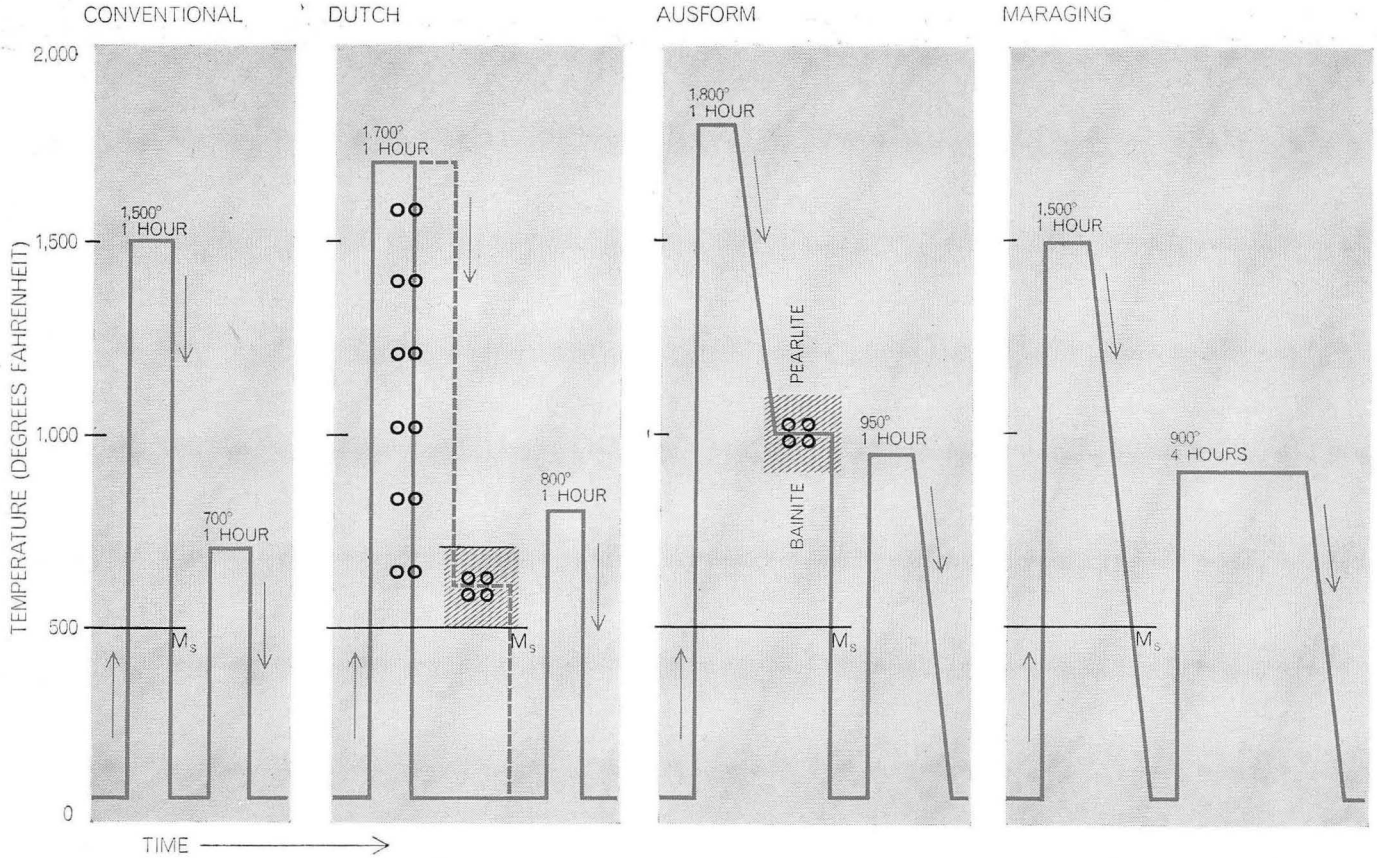
The structural features responsible for the excellent combination of strength and ductility in the Maraging alloys are being intensively sought. P. Swann of the United States Steel Corporation Laboratory has identified a precipitate, visible only in the electron microscope, that may be the first clue to the strength of these alloys. Evidently some component in the alloy is playing the role nor-



PHASE DIAGRAM OF IRON AND STEEL shows the effect of temperature and carbon content (*left*) and the further effect of time (*right*). Ordinary steel (*a*) decomposes quickly into pearlite and bainite, alloys that contain hard precipitates. The Ausform process requires alloys (*b*) in which the decomposition is postponed, allowing time for metastable austenite to be cold-worked.



MICROSTRUCTURE OF STEEL varies with time, temperature and deformation. In the conventional process austenite is directly quenched to martensite. In the Ausform process the austenite is quenched to an intermediate temperature and cold-worked. As a result of cold-working the strength of martensite is raised from about 300,000 to more than 400,000 pounds per square inch.

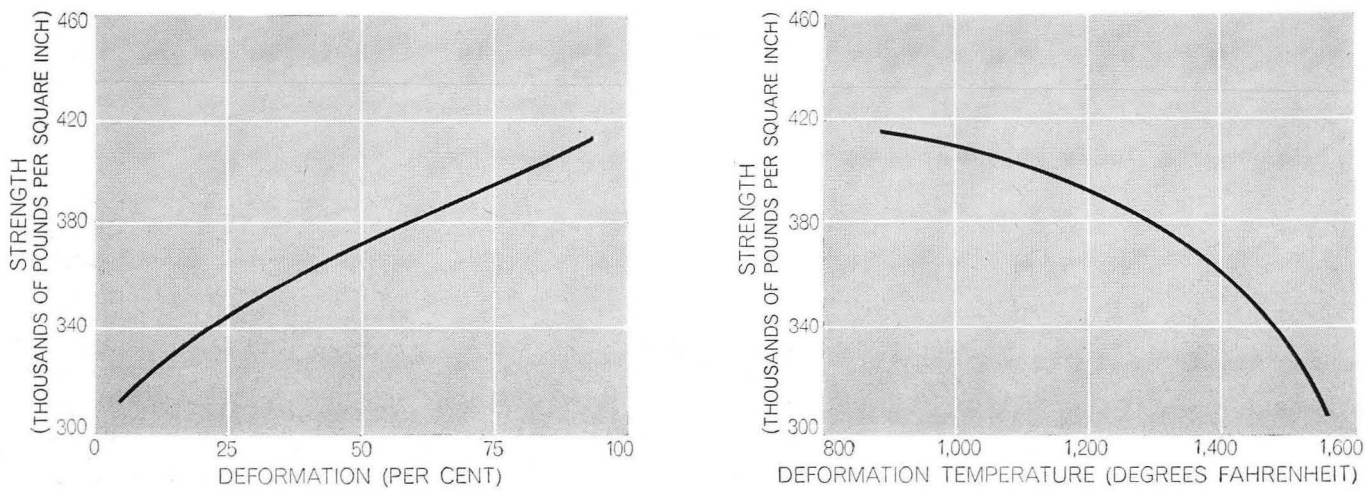


FOUR STEELMAKING PROCESSES, described in the text, all yield a strong product. The Dutch process was devised by E. M. H. Lips and H. van Zuilen and the Maraging process by International Nickel Company, Inc. Cold-working is symbolized by rollers. In the Dutch process the broken line indicates an alternative path. "M_s" signifies the temperature at which martensite starts to form.

mally played by carbon in conventional high-strength steels, and playing it more effectively.

Somewhat more has been learned about the factors contributing to the strength of martensite, but even here there is no general agreement among experts. Morris Cohen and P. G. Winchell of the Massachusetts Institute of Technology concluded from studies of iron-nickel-carbon alloys that carbon in solution and precipitation-hardening by carbides are the chief strengthening mechanisms in martensite.

P. Kelly and J. Nutting of the University of Leeds postulate a different mechanism. They find that the strength of martensite is proportional to the number of martensite plates incorporating fine internal twin crystals. The twins show up in electron micrographs as very



STRENGTH OF AUSFORM STEEL increases with the amount of deformation, or cold-working (*left*), and decreases as the deformation temperature increases (*right*). The per cent deformation is the per cent reduction in cross section when a billet is rolled.

straight, thin, paired structures, and characteristically many twins are found lying side by side in a regular array [*see illustration at bottom left in the group of four on next page*]. There is no doubt that such structures must present an effective barrier to the movement of dislocations. Moreover, Kelly and Nutting have shown that the number of twinned plates is proportional to the amount of carbon in solution, thereby satisfying the empirical observation that the strength of martensite is proportional to carbon content. Although twinning undoubtedly contributes to the strength of conventionally quenched and tempered steels, other mechanisms are probably also important.

At the Ford laboratory D. J. Schmatz, F. W. Schaller and I have concluded that Ausform martensitic steels are primarily strengthened by precipitation-hardening or by solid-solution-hardening. Although we also see more twins in Ausform steels than in conventional martensitic steels, we hesitate to credit them as a major source of strength. The argument in favor of precipitation-hardening or solid-solution-hardening runs as follows. As noted above, the strength of Ausform steel is relatively insensitive to tempering temperature. This implies that most of the strength in the steel is developed during either cold-working or quenching. In either case the time available for the formation of a precipitate is limited and, if a precipitate forms, it will have to be uniformly dispersed and consist of particles less than 100 angstrom units in diameter. (An angstrom unit is a hundred-millionth of a centimeter.) The alternative explanation is that the carbon is not in the form of a precipitate but is actually held in solid solution. Dislocation theory predicts that either a fine precipitate or a solution of carbon atoms could account for the high strength of Ausform steels.

By a suitable technique it is possible to see in the electron microscope whether or not a sample of steel contains hard carbide precipitates that are larger than 50 angstroms in diameter. When this technique is used to compare Ausform and conventional heat-treated steel, it is found that the density of coarse carbides is much less in the Ausform steel [*see illustration at bottom right in the group of four on next page*]. It is evident that the large amount of carbon in the Ausform steel is either in solid solution or in the form of a precipitate smaller than 50 angstroms in diameter.

Looking toward the future, one can make a few fairly safe predictions. Ductile steels with a tensile strength of

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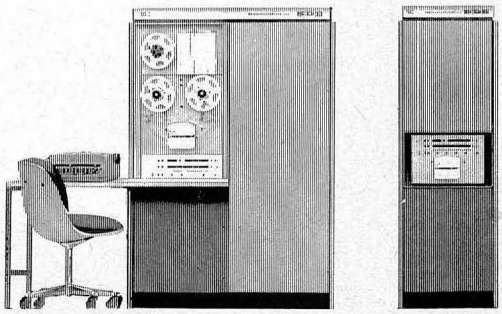

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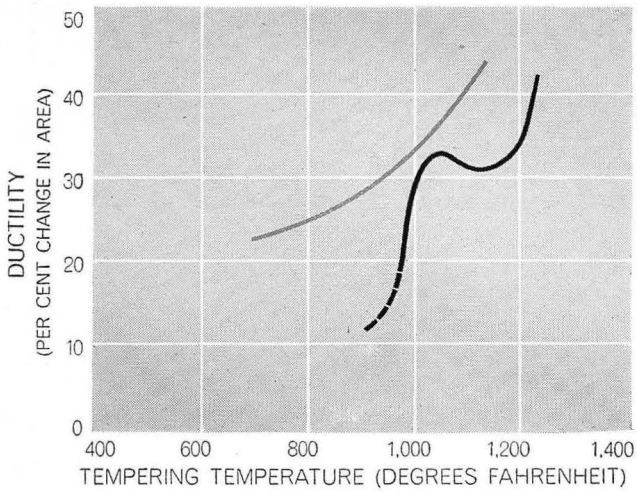
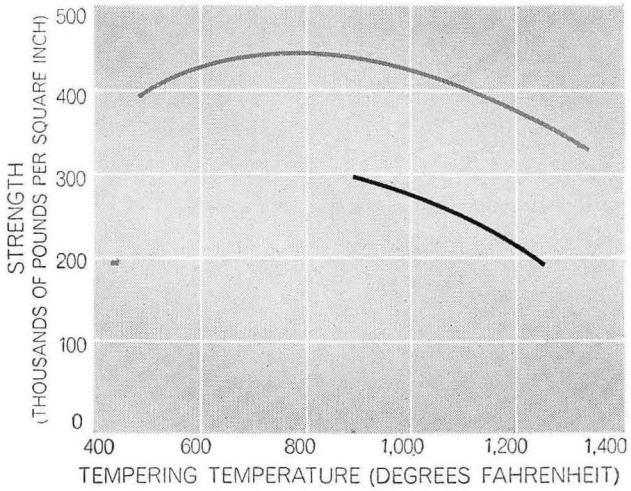
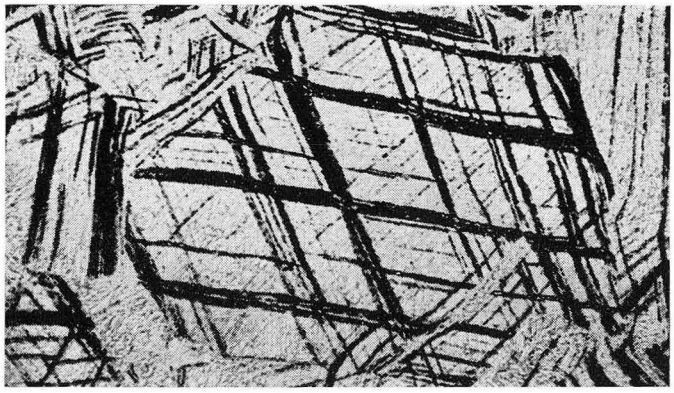




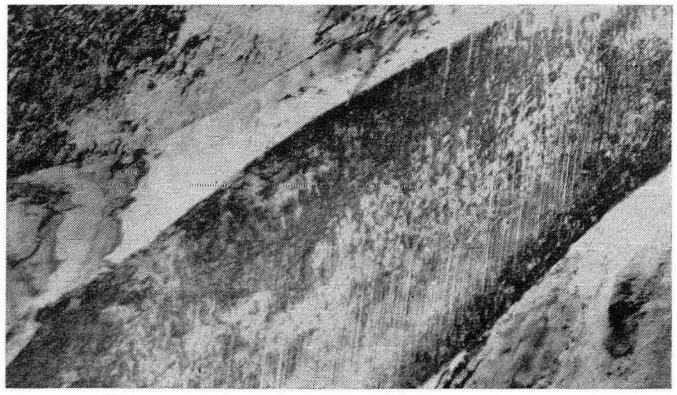
STRENGTH AND DUCTILITY are generally traded when conventional martensitic steel is tempered (*black curves*). Ausform steels (*color*) match conventional steels in ductility (*left*) without significant loss of strength at high tempering temperatures (*right*).

500,000 pounds per square inch will be an engineering reality before the end of the decade. To an increasing degree noncarbon alloys will replace carbon-containing steels for difficult jobs. Later, perhaps not in this decade, noncarbon alloys will begin to replace the more common structural steels. This development, however, will await a detailed understanding of how the Maraging alloys are strengthened without carbon. Wherever the paths of research may lead, they will probably support the canny observations of the 17th-century natural philosopher Joseph Glanvill, who wrote: "Iron seemeth a simple metal... but in its nature are many mysteries... and men who bend to them their minds shall, in arriving days, gather therefrom greater profit, not to themselves alone but to all mankind."



DEFORMATION MARKINGS, or slip bands, can be made visible if Ausform steel is allowed to cool slowly after deformation. Hard carbides precipitate along the slip bands, "decorating" them.

MARTENSITE PLATES, dark jagged shapes, grow to large size (*lower left*) in nondeformed region of martensite. In deformed region (*upper right*) plates are deflected when they meet slip bands.



TWINNED MARTENSITE PLATES appear as fine parallel lines in this electron micrograph of Ausform steel by P. M. Kelly, University of Leeds. Such crystal twins block movement of dislocations.

CARBIDE PARTICLES larger than 50 angstrom units in size are shown in ordinary martensitic steel (*left*) and in Ausform steel (*right*). Most Ausform carbon is in solution or in fine particles.