of high-carbon steel, preferably eutectoid steel (0.90 per cent carbon), attach a fine wire of platinum or of manganese steel as a support. Neither copper nor common iron wire is suitable for a support, the former because it conducts the heat away so quickly, the latter because it is itself magnetic.

Heat the steel wire to a yellow heat in a Bunsen burner, and hold it near a magnetic needle which has no protecting glass case. At first the wire will not attract the needle, but as it cools down it suddenly becomes magnetic, and at the same time brightens perceptibly, *i. e.,* recalesces. This can best be seen in a dark room, but a practiced eye can detect it even in a light room.

By quenching a series of wires just above, during, and just after the recalescence, and then determining their ductility by trying to bend them, and their hardness by filing them, the student readily finds that the recovery of the magnetic properties on passing through the recalescence is accompanied by the loss of the hardening power; but that these transformations are spread out over a considerable range of temperature, so that the wire does not lose the last traces of its hardening power until it is cooled many degrees below the recalescence, *i. e.,* until perhaps fifteen seconds after it has begun to recover its magnetic properties.*

209. Stress in Hardened Steel. — Austenite itself is an extremely hard and a brittle substance; but the brittleness of hardened steel is doubtless due in some part to the residual stress which the sudden cooling induces. This stress is in turn due in large part to the fact that the cooling of the interior of a suddenly cooled object lags behind that of the exterior, so that during the latter part of the cooling, when the outer part is already cold and rigid, the interior has still to cool through a considerable range of temperature. Such residual cooling should cause corresponding contraction; but the effort of the interior to accomplish this contraction is resisted by the now rigid exterior, with which the interior is integrally united. Hence the exterior is left in a state of compressive, and the interior in a state of tensile stress, a state of affairs readily detected by sawing open a suddenly cooled piece of steel, say of 0.20 per cent of carbon. Before such a piece is sawn open the stresses are generally nearly symmetrical, so that they balance one another and do not greatly deform the piece as

* "Metallurgical Laboratory Notes," the author, Experiment 2, p. 10.

a whole. If, however, we saw the piece open we destroy this balance, and certain of the stresses, no longer counterbalanced, distort the object farther.

The stress in hardened steel is probably much intensified in another way which I will now explain. Even in sudden cooling, a considerable amount of transformation from austenite into ferrite and cementite evidently does occur, especially in the interior of the piece, which must cool much more slowly than its very skin. To whatever degree this transformation takes place, to that degree is the cooling and the consequent contraction of the layer in which transformation is occurring retarded. As the cooling of the interior must always lag behind that of the exterior, so it will happen that this retardation of the contraction of the interior must occur later than the corresponding though slighter retardation of the exterior. In other words, after the contraction of the exterior has undergone its slight retardation and is again proceeding at full speed, the contraction of the interior undergoes its greater retardation, thus tending to crack the exterior by resisting its tendency to contract.

210. Simile to Explain Internal Stress. — Let an illustration make clear this conception of the state of stress which exists between the several layers of a suddenly cooled piece of steel or other substance. Suppose that through some disease both of my hands have swollen to double their natural size, though they retain substantially their normal shape. Suppose that while they are in this condition I put upon my right hand an iron glove which exactly fits it in its now swollen state, and that the hand and glove are firmly glued together by some efficient cement. Suppose that my health is now restored and that my left hand contracts back to its normal size. Evidently, my right hand at the same time will endeavor to contract in the same way to its normal size, but it will be prevented by the cement which glues it firmly to the incompressible iron glove. My hand will now be in a state of tension, endeavoring to reach its normal size, and through this endeavor it throws the glove into compressive stress. Here then we have a permanent state of stress between hand and glove. We have much the same condition of things between the different layers of a piece of suddenly cooled steel.

211. Stress may Weaken or Strengthen. — Let us now consider another case, that of a guitar, the strings of which have

been tightened up in the usual way. In such a guitar the strings are evidently in a state of tensile stress endeavoring to contract, and their endeavor is resisted by the rigidity of the body of the guitar: hence this body is in compressive stress. The arrows in Fig. 74 indicate the direction of the stress in the strings and the body respectively. Many of us have learned by experience that, if we leave a tuned guitar over night at the sea-shore without taking the precaution of slackening the strings, in the morning we may find these strings snapped. This means that the damp air has dampened the strings and so increased their desire or tendency to contract, and that this is resisted firmly by the body of the guitar. This endeavor to contract has resulted in tensile stress which has increased to such a degree that it has snapped the strings in two. Quite in the same way we often find that if we harden a piece of steel too violently, *i.e.*, if we cool it in water too suddenly, we induce stress so violent as to crack the skin of the piece quite as the excessive stress breaks the strings of the guitar.

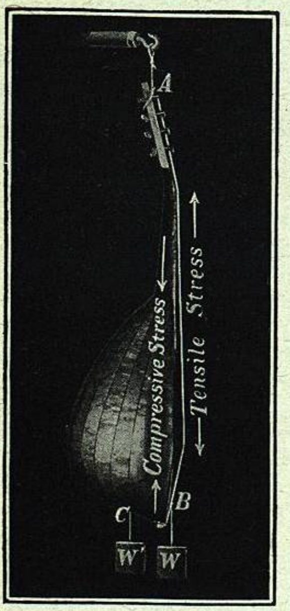

Fig. 74. The Influence of Internal Stress upon Strength, *i.e.*, the Power to Resist External Stress.

Suppose now that while our guitar is in this state of stress indicated in Fig. 74, we hang it by means of the point *A*, and attach to one of the strings at *B* a weight, *W*, which is just the weight that the string would be able to sustain without breaking if it were not under tensile stress. The string will break. Clearly if my muscular strength is such that when I am unencumbered I can lift just 1000 pounds and no more, then if somebody places a load of 500 pounds on my shoulders I shall have strength sufficient to lift only an additional 500 pounds. I cannot eat my cake and keep it. If half of my strength is temporarily in use in sustaining a load on my shoulders, only the remaining half of my strength is available for lifting any additional weight. Exactly in the same way, inasmuch as the string of the guitar is under initial tensile stress, its power to resist an external load is correspondingly diminished.

Suppose next, that we hang a weight, *W′*, to the body of the guitar at the point *C*. As this body was initially under compressive stress, so it is capable of upholding a greater weight at *W′* than if it was not under this compressive stress.

Now looking at the guitar as a whole and considering its strength, *i. e.*, its power to resist loads applied to it from without, we see that the degree to which the existence of the internal stress affects this power to endure external loads depends upon how those loads are applied. If an external tensile stress is applied to the part of the guitar which is already under tensile stress, then the initial stress weakens the guitar. If, on the other hand, the tensile stress is applied to the body of the guitar which is initially under internal compressive stress, then that initial stress in effect strengthens the guitar. Thus we see that it may occur that internal stress may actually strengthen a piece taken as a whole, as regards its power to resist external stress applied in certain specific well-defined ways.

If now we load the tuned guitar as it were uniformly, *i. e.*, making the load *W′* just that which the body of the guitar would be able to sustain if free from initial stress, and *W* just that which the string would be able to sustain if also free from initial stress, then the fact that the string is initially under tensile stress will cause that string to break; this will throw the whole load, $W + W'$, upon the body of the guitar, and will thus break it in turn.

The useful strength of a steel object may be defined as the power of resisting external stress. When a steel object is to be used for a great variety of conditions not accurately defined beforehand, it is in general better that it should be well adapted to resist well every variety of probable systems of external stress rather than that it should have great power to resist a particular set of external stresses applied in some particular way, and very little power to resist another probable system of external stresses applied in some other probable way. In short for indiscriminate use what may colloquially be called "good all around strength" is what is needed. On this account the presence of internal stress in a steel object, while useful for certain cases, such as that of gun-jackets, in which the direction of the chief external stresses to be endured in use is well understood, initial internal stress may be very valuable and may greatly strengthen the object for its one and only use; yet the existence of internal stress is in general undesirable in case of objects which in use are to be subjected to widely varying and indeterminate systems of important external stresses.

It was formerly thought that the hardening of steel was due to stress induced through sudden cooling; but while stress no doubt does exist and does contribute to brittleness in a material degree, yet it is perfectly clear that it is not the true cause of the hardening of steel. Two of the many reasons are quite sufficient to show this.

In the first place, if the hardening were due to stress then it should increase regularly with the temperature from which the sudden cooling occurs, or in short, with the quenching temperature. But in point of fact, far from this being the case, no true hardening takes place unless the quenching temperature is as high as the transformation range. And moreover, once this range is past, further elevation of the quenching temperature does not further increase the hardening. In other words, the hardening power is acquired in passing the critical range. In the case of eutectoid steel, that is to say steel of 0.90 per cent carbon, in which the critical range is extremely narrow, the whole of the hardening power is acquired in rising through this very narrow range of temperature.

The second reason is that if hardening were due to stress, then the other metals in general ought to be hardened by sudden cooling. But this is not the case. Manganese steel is made very ductile by sudden cooling, instead of being made brittle as carbon steel is. The fact that the hardening power is a special property which belongs chiefly to the iron-carbon compounds, and indeed is shared probably by very few other substances of any kind whatsoever, is in itself sufficient proof that the hardening is not the result of stress. Indeed, looking back now, it is astonishing that this stress explanation of hardening should have been put forth by such eminent writers for so long a period.

The Heat-treatment of Steel, Processes Operating Chiefly Through Control of the Structure

212. Importance to the Engineer. — This subject of the structure of steel, its relation to the properties of the metal and to the thermal and mechanical treatment which it has undergone, is probably of much more direct practical importance to the young engineer than any other subject considered in this work. Its importance may be made clearer by means of an example. May its patness atone for its homeliness.

You cannot make a bad beefsteak good by the cooking; you can cook it better or worse, and it will be a worse or a less bad beefsteak, but always bad. On the other hand you can easily spoil a good beefsteak by bad cooking. Now, just as cooking is to food so is heat-treatment to steel. Indeed, a pedantic cook might reasonably call cooking heat-treatment. Bad steel, steel of bad chemical composition, cannot be made good by heat-treatment; we can give it different degrees of badness, but we cannot cure that badness. On the other hand we can easily make good steel bad.

In one case as in the other the excellence or the defects of the treatment can in large part be recognized by simple external symptoms.

The cooking, its effects, and its symptoms are of immediate importance to the housewife, because they are under her control through her employees. In exactly the same way and for pretty much the same reasons heat-treatment, and its symptoms, the structure of the metal, are of great importance to the practicing engineer, not only because it influences the properties of his metal very greatly, but especially because the heat-treatment itself is often given by his own employees, his smiths and his other workmen; and moreover because the symptoms of that heat-treatment are open to those employees, and, best of all, to himself.

Here the simile ceases to hold good, because whereas a burnt beefsteak cannot be made good, an overheated piece of steel can be restored nearly to its best condition.

Thus, the structure of steel, whether as revealed by the microscope or in the fracture of the metal, is an index, not only to the properties of the metal but to a certain extent also to the treatment, especially the heat-treatment which it has undergone, and of the further heat-treatment which is necessary to cure any injury which has already been caused.

213. Heat-refining Defined. — This is a process for curing by thermal treatment the injury which is done to steel by overheating, *i. e.*, by allowing it to cool undisturbed from an unduly high temperature. This injury is accompanied by a material coarsening of the structure, and indeed this coarsening is probably the immediate cause of the injury. To facilitate the discussion I shall provisionally assume this causal relation.

Before studying this curative process itself, we must, however, familiarize ourselves with the disease which it aims to cure, and with the symptoms of that disease. This we will do in the following sections.

Five important matters require our attention. These are as follows:

(1) The structure may be learned either by microscopic examination, usually of polished and etched sections, or by an examination of the fracture, usually with the naked eye.

(2) Each variety of iron or steel has its own normal type or types of fracture to which it naturally inclines; a type (usually the finest of all), corresponding to the best condition of the metal, another (usually the coarsest), corresponding to the worst condition, *etc.*

(3) Yet the structure of each variety of iron and steel varies very greatly with the heat-treatment which it has undergone.

(4) In particular, the structure of steel, especially of high-carbon steel, is made coarse by overheating, and this coarsening of structure is accompanied by a great injury to the quality of the metal.

(5) The coarseness and the accompanying injury can be removed by a process of heat-treatment called "heat-refining," or by mechanical means which for brevity we may call "mechanical refining" or "hammer-refining."

214. The Structure of Iron and Steel. — The microstructure of the metals in general as determined by examining polished and etched or heat-tinted specimens under the microscope, gives more direct and far more detailed information as to their structure than we can hope to find in the fracture itself; and no doubt we are approaching rapidly the day when microscopic

examination will in very many cases give a trustworthy diagnosis. At present, although the microscope has given invaluable information which has been essential in developing our present knowledge of the metallography of iron and steel, yet its indications are as yet so hard to interpret, thanks partly to the fragmentary nature of the evidence, to the very richness and complexity of the indications in each microsection, to the newness of this method of examination, and to the present very imperfect correllation of our data, that to-day the fracture probably gives, in many cases, indications more trustworthy than those of the microscope.

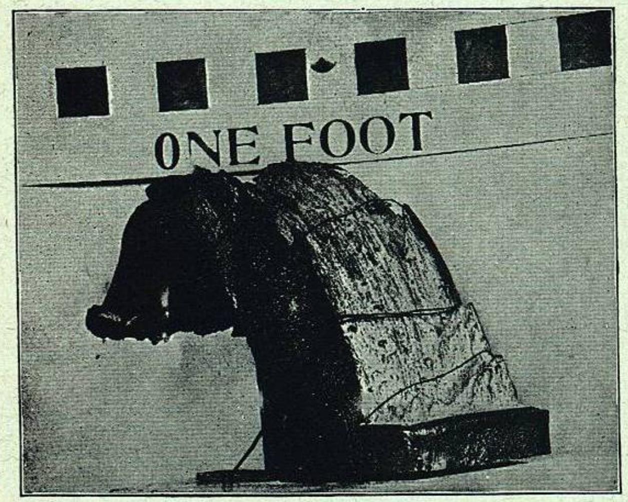

Fig. 75. Barked Wrought Iron, Stumm.

When a piece of metal is broken, rupture follows the surfaces of least resistance under the existing conditions; and these surfaces are what we see in the fracture.

Certain classes of iron incline readily to yield certain types of fracture; other classes to yield other types. Thus a very fibrous fracture, while readily induced in very ductile specimens of wrought iron, is harder to induce in the less ductile specimens, and cannot be induced at all either in cast iron or in normal high-carbon steel. A very fine, porcelanic fracture can readily be induced in high-carbon tool steel, but cannot be induced readily if at all in low-carbon steel or in cast iron.

Before going on to consider the structure of the metal further, the reader must be cautioned as to the very different kinds of fracture which may be given to one and the same piece of metal by breaking it under different conditions. Thus a bar of wrought iron nicked on one side only, and broken by bending it away from the nick by a succession of light blows, naturally yields a fibrous fracture, of which an extreme case is shown in Fig. 75; but, if nicked on all four sides and broken with a single sharp blow, it yields a bright crystalline fracture. This difference, however, is due to the fact that the surfaces of least resistance vary with the conditions under which rupture occurs. It warns us that tricks may be played in rupture to yield a desired fracture, and that we should be cautious in drawing inferences from the appearance of fractures, especially of those made in our absence.

Finally, and this is the important point to which attention is particularly called, for a given specimen of steel and for given conditions of rupture, the fracture varies very greatly with the thermal and mechanical treatment which the metal has undergone; and as the fracture varies so do the mechanical properties of the metal. Thus, if we know how a test or specimen bar has been broken, either from seeing it broken ourselves or from trustworthy report, the fracture may give very valuable information as to the condition of the metal and the thermal and mechanical treatment which have caused both that condition and that particular form of fracture. What the relations are between the fracture, properties, and treatment will shortly be explained.

215. A Coarse Fracture Suggests a Coarse Structure. — As the surfaces of least resistance which we see in the fracture are in general either crystal faces or cleavages, and as coarse cleavages are naturally associated with coarseness of the crystallization proper, so our natural working hypothesis is that a coarse fracture is simply a symptom of coarse crystallization; and that where the fracture is coarse, there we may expect to find the crystallization coarse. The converse we may also expect, though not so confidently; for fineness of fracture might readily be due to fineness, not of the true crystal size, but of the cleavage. Large coarse crystals might have very poorly defined cleavage, so that when rupture traverses them, instead of traveling long distances along a given cleavage surface, and so revealing large faces in the fracture, *i. e.*, yielding a coarse fracture, it might travel only a very short distance along a given cleavage plane before leaping across to another, and it might thus reveal in the fracture only minute portions of a great number of different cleavage planes, *i. e.*, a very fine fracture. But as far as our studies of iron and steel have gone, coarseness and fineness of fracture and of crystalline structure seem in general to go hand in hand; and in what follows, the teachings of fracture have to be supplemented in some cases by those of microstructure.

In short, when we speak of the coarseness of the grain of steel as shown in the fracture, we refer naturally to the size of the facets which we there see. And their size is probably in turn proportional to the coarseness of the crystals themselves, or to the coarseness of the network between the crystals of which the metal is made up.

To simplify the discussion we will hereafter refer jointly to the degree of coarseness of the fracture and the degree of coarseness of the microstructure as determined in polished sections under the microscope, as the "grain-size," assuming provisionally that the coarseness of structure in one of these respects is proportional to the coarseness in the other respect. We will further assume, provisionally, that the condition of any given variety of steel is the better the finer is the structure. It is this assumption that gives interest to the whole discussion, and indeed makes it of great importance to the practicing engineer. We shall see later that this assumption, while true in a general way, yet must be modified somewhat to meet varying conditions. For instance, while the general merit of the steel for miscellaneous uses may well be the greater the finer is the grain-size, yet for certain special conditions of use the qualities which accompany the very finest grain attainable may be less desirable than those accompanying a slightly coarser grain.

216. General Laws Concerning Fracture and Temperature. — Certain laws will now be formulated, representing some of our present information on this general subject. Let it be distinctly understood that these are simply early attempts to bring together into condensed form the results of our observations, that none of these laws is likely to prove rigorously true, and that most of them may have to be greatly modified later. Nevertheless it is thought that they will be of use as a temporary expedient, that by their aid our present fragmentary knowledge may be not only