

Plastic Deformation of Metals

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Abstract

By the plastic deformation of a metal, the slip along a slip plane of the metal crystal causes the smashing of the crystal into fine crystallites of scattered orientation. The lattice distortion and the uneven internal strain of the crystallites take place simultaneously. As to the boundaries between neighbouring crystallites, some are supposed to be cemented in the cybotactic sense, by the Beilby's amorphous layer, and the rest are considered to be weakened in intercrystalline cohesion. These facts help to explain the change of the mechanical properties of metals, single and polycrystalline, by plastic deformation, and by aging and light annealing.

Destruction of Metal Crystals by Plastic Deformation

Plastic deformation of a metal crystal is usually considered to follow a slip in a slip direction along a slip plane of the metal. Ordinarily the slip process never occurs in an ideal manner; and the crystal is, at the same time, smashed somewhere into fine crystallites of somewhat scattered orientation, the degree of scattering increasing, as is revealed by x-ray examination, with the amount of the slip. This smashing into fine crystallites appears to be caused by an irregular coercionary stress distribution due to imperfection in the internal structure of the crystal and also, in the case of polycrystalline material, to the interaction between neighbouring crystallites near the crystal boundaries. The new crystallites thus formed by the drastic process of smashing will be strained, by being stretched or compressed unevenly, and their lattices will be differently distorted. It is already stated in former papers¹ that the melting point of a very small and distorted crystal of submicroscopic size, can be reasonably supposed to be much lower than that of the adult crystal. Thus when very very fine and distorted crystallites are formed somewhere in the interstices between neighbouring larger crystallites, it may happen that they melt by the local heating occurring here and there during the slip process by the plastic deformation. If this has occurred, very rapid cooling to the normal temperature, which takes place at the

1. U. Yoshida: *These Memoirs*, A., 23, 207, 225, 237 (1941).

same time as the melting, will solidify the melt as its supercooled amorphous state, consisting of the cybotactic crystals and free molecules distributed at random as has been recognised before.¹⁾ Such supercooled solid is nothing but the so-called Beilby's layer which, owing to its isotropic strength, binds neighbouring crystallites firmly, except at high temperatures. Though neighbouring crystallites will be, to a considerable degree, cemented by the formation of Beilby's layer, the cementing will not be complete, and there will remain interstices between neighbouring crystallites where Beilby's layer may or may not be formed afterwards by aging or by light annealing. These portions of the interstices between neighbouring crystals which remain uncemented during the process of plastic deformation will be the localities of weak cohesion between neighbouring crystallites. Among these, some can and a few others cannot be transformed to the cementing Beilby's layer by aging or by light annealing after the plastic deformation. Moreover, it may be imagined that very fine fissures of a few atoms in width are formed somewhere between neighbouring crystallites by plastic deformation. These will also be the localities of weak intercrystalline cohesion, most of which can and a few others cannot be mended by aging or by light annealing. In such a way, the mending of most of the localities of weak intercrystalline cohesion by aging or by light annealing will harden the metal as a whole, as was detected by M. Sugihara²⁾ who noted the elevation of the elastic limit of a cold worked polycrystalline aluminium rod by a slight annealing. Aging or slight annealing will also diminish the uneven internal strain of the crystallites on the one hand, and their lattice distortion on the other. Of these two effects, the latter weakens the metal and the former tends to raise the elastic limit of the metal. As to the presence of a few localities of weak intercrystalline cohesion, which can not be mended simply by aging or by light annealing, they will not have any noticeable effect with moderate plastic deformation; but they will be the starting points of thicker fissures which give rise to the final failure with continued plastic deformation as observed in static tensile and fatigue tests.

The ideal slip which is supposed to occur in the slip direction along the slip plane does not affect the mechanical properties of metals. Thus the causes which arise from the plastic deformation and affect

1. U. Yoshida, loc. cit

2. M. Sugihara: *These Memoirs*, A, 21, 145 (1938); 22, 195 (1939).

the mechanical properties of metals will be: 1) Destruction of the crystals into smaller crystallites having scattered orientation. 2) Lattice distortion in crystallites. 3) Formation of uneven internal strain among crystallites. 4) Formation of the amorphous layer at the boundaries between crystallites. 5) Formation of localities of weak intercrystalline cohesion. Among these causes, 3) and 5) weaken the metal by making its elastic limit or yield point lower. The lattice distortion in crystallites hardens the metal by hindering the easy slip in the slip direction along the slip plane in the crystallites. 4) combined with 1) also hardens the metal by cementing the boundaries of the new crystallites which are formed by destruction and have different orientations, and thus by making the slip in neighbouring crystallites difficult by virtue of the slip interference at the crystal boundaries. Heating affects differently the above five causes. The small crystallites having scattered orientation mentioned in 1) can be brought to larger ones only by the process of recrystallization which takes place usually at higher temperatures than the aging and light annealing. 2), 3) and 5) can be restored largely, but not completely to the normal state by aging or light annealing as is stated above; and their further complete recovery requires annealing at higher temperatures such as recrystallization temperature range. Formation of Beilby's layer between crystallites denoted by 4) occurs partly, as is stated before, during the process of plastic deformation, but a further approach to completion will follow heating at higher temperatures.

The five causes mentioned above, which take place in crystalline structure by the process of plastic deformation, are not independent, but are intimately connected. However, their individual effect is different in degree from case to case, so that different causes predominate respectively in different cases.

Tensile Deformation of Single Crystals of Metals

By applying a tension or compression of sufficient strength, a single metal crystal deforms by slipping in a slip direction along a slip plane, that is, the weakest crystallographic direction and the weakest plane of the crystal. If the slipping process would happen in an ideal manner, the mechanical property of the crystal would remain unaltered by the slip. But this is not actually the case. The metal crystals harden by a plastic deformation, even with the small amount of plastic deformation caused by tension or compression, where the

slip is supposed to occur mostly in the slip direction along the slip plane. This shows that, as stated before, unideal processes take place together with the ideal slip; as is evident from the destruction of the crystal into fine crystallites of scattered orientation, as is revealed by x-ray examination.

Fig. 1

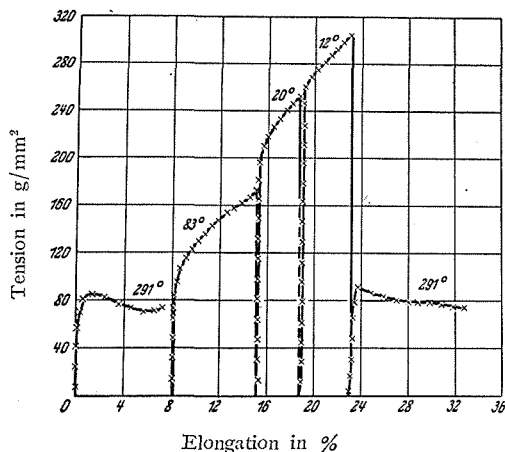
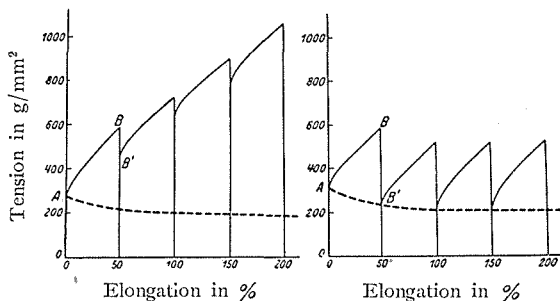


Fig. 1¹⁾ shows the results of the elongation test made on a single crystal of cadmium at various low temperatures. In this case the elongation took place by steps, and the temperature of the specimen was changed when unloaded. As is seen from the figure, the tension which is necessary to sustain a certain amount of elongation increases with the amount of elongation when the temperature is lowered from room

temperature to 12° K, and recovers to the original value when the temperature is again raised to the room temperature. This signifies that the cadmium single crystal hardens when elongated plastically at low temperatures, and recovers when its temperature is raised. Now let us consider the reason for this. The amount of destruction of the crystal into fine crystallites of scattered orientation will increase, of course, with the degree of elongation. Their unification to larger crystals cannot take place so long as the temperature is not raised higher to the recrystallization temperature range. Thus the recovery of the elastic and plastic property of the cadmium crystal at room temperature after the plastic deformation

Fig. 2



a, Rest interval: 30-40 seconds b, Rest interval: 24 hours

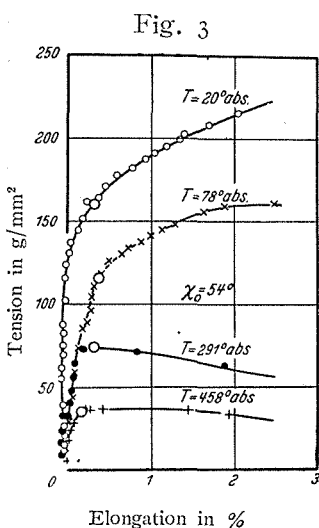
1. E. Schmid und W. Boas: *Krystalplastizität*, 156 (1935).

made at low temperatures cannot be accounted for by this cause; and consequently, for the hardening by straining at low temperatures, another reason must be sought. Formation of the amorphous layer by plastic deformation at low temperatures increases the elastic limit or the yield point, and it does not accord with the recovery by raising the temperature to the room. Formation of localities of weak intercrystalline cohesion is in direct contradiction to the strain hardening at low temperatures. Increase of the uneven internal strain among crystallites by plastic deformation spoils the proportionality between stress and strain and it lessens the elastic limit. This is especially remarkable in the case of polycrystalline iron and steel as will be considered later. When polycrystalline iron or steel is plastically elongated beyond their yield point at room temperature, and an elongation test is repeated, we see that the elongation does no more increase proportionally with the tension. As the uneven internal strain can be removed by sufficient aging or annealing, its removal at such low temperatures as in the case of Fig. 1 cannot be acceptable. Thus the increase of the proportional part with decreasing temperature seems to be inconsistent with the supposed increase of the uneven internal strain. This inconsistency becomes clearer if we consider the experiment shown in Fig. 2a,¹⁾ where the elongation test on zinc single crystal was repeated stepwise at room temperature by interposing an unloaded rest for about 30–40 seconds. Here, contrary to the supposed decrease due to the increase of the uneven internal strain, the proportional part between tension and elongation increases again with the number of times the test is repeated. Taking these facts into consideration, strain hardening of single crystals of cadmium and zinc can be ascribed, in all probability, to the lattice distortion arising from the plastic deformation. The lattice distortion hardens the crystal by interfering with the crystal slip. Its amount increases with the degree of plastic deformation, and its recovery to the undistorted lattice is hastened by the thermal agitation with rise of the temperature; and the increase of the strain hardening of cadmium crystal at low temperatures with increased elongation and that of zinc crystal with repeated elongation at room temperature seems to be explained by the increase of the lattice distortion with increasing elongation, by being not much recovered at low temperatures, and with insufficient aging at room

1. E. Schmid und W. Boas: *Kristalplastizität*, 166 (1935).

temperature. Here it must be noted that the increase of interatomic cohesion with decrease of the temperature plays a part also in hardening the cadmium crystal at very low temperature. The strain hardening by lattice distortion recovers gradually with aging. When the time of unloaded rest is increased to 24 hours the zinc crystal hardened by previous loading softens at room temperature, to its original hardness, as in shown by Fig. 2b. The curves drawn in broken lines in Fig. 2 are those calculated on the assumption that the critical shear stress which is just necessary to cause the crystal slip is constant and is independent of the amount of elongation. The fact that the yield point of every one of the repeated elongation tests gets down to the theoretical curve in Fig. 2b shows that the recovery is already perfect with the aging of 24 hours in unloaded rest.

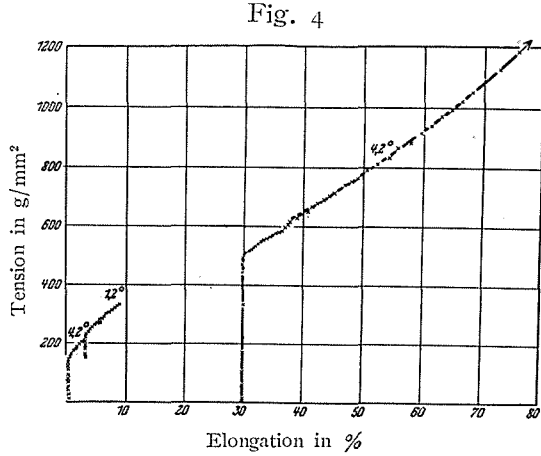
The recovery of the lattice distortion hardening is due to the thermal agitation of the constituent molecules. It is much retarded at very low temperatures, and, as is stated before, is increasingly



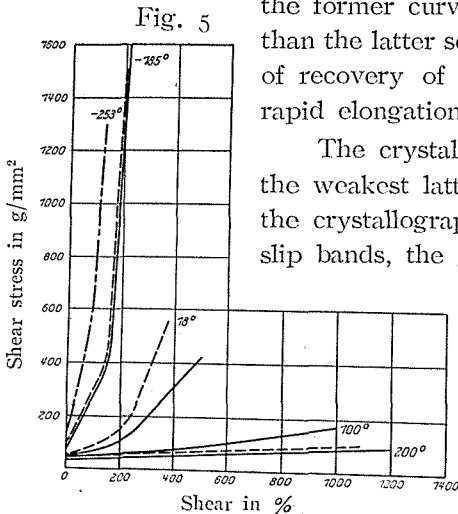
hastened with rise of the temperature. This point will be more clearly seen from the fact that the yield point of a cadmium single crystal manifests itself more sharply with rise of the temperature as shown in Fig. 3.¹⁾ When the lattice distortion is recovered, the cadmium specimen will behave in tensile test as if it were composed of a single crystal. Beyond the yield point, where the crystal slip begins, it goes on with a tension which is smaller than or at most the same as that at the yield point, by giving a sharp break to the tension-elongation curve at the yield point. The recovery of the lattice distortion with a single crystal of cadmium seems to be almost stopped at such a low temperature as 4.2° absolute as will be seen from the tension-elongation curve in Fig. 4,²⁾ where the tension which is necessary to cause a further elongation increases with the amount of elongation almost linearly up to 80% elongation. The dependence of the recovery of the lattice distortion on temperature is more clearly seen in Fig. 5.³⁾

1. E. Schmid und W. Boas: Kristallplastizität, 152 (1935).
2. Ibid. p. 153.
3. Ibid. p. 159.

In this figure are plotted the curves showing the relation between the shear and the shearing stress which is necessary to cause the former in a single crystal of cadmium at different temperatures. The change of the strain hardening with temperature is remarkable at intermediate temperatures, but is only slight at very low and at very high temperatures. At high temperatures where there recovery is nearly complete the curves run almost horizontally ; and



at very low temperatures where the recovery is almost suspended they stand close in a nearly vertical direction. The curves represented by broken lines in the figure show the results obtained with the loading of much higher velocity than those drawn in full lines. The fact that



the former curves are situated somewhat higher than the latter seems to be due to smaller amount of recovery of the lattice distortion during the rapid elongation.

The crystal slip takes place unevenly along the weakest lattice planes which are parallel to the crystallographic slip plane, giving rise to the slip bands, the glide lamellae and glide packets.

The coarseness of the glide packets depends upon the temperature and the rapidity of the slip. When the temperature is high or when the slip is very slow it becomes coarse. According to the writer's view some

portion of the crystal in a slip band or a glide lamella is smashed by the slipping into extremely fine and distorted crystallites. When the slipping is not very slow some of these fine and distorted crystallites will be melted down to the amorphous layer successively by the local

heating occurring here and there during the slipping. When the temperature is not high the amorphous layer will be solidified immediately and the further slip will proceed along certain remaining virgin lattice planes which are weaker than the solidified layer, making the glide packets finer. On the contrary, when the temperature is high the amorphous layer, when once formed, will remain unsolidified and will be weak for resisting a further slip, so that the subdividing of the glide packets becomes increasingly rare. Next when the slip is very slow the local heating will be so slight that it is insufficient to melt the very fine and distorted crystallites and to transform them to the cementing amorphous solid; and the portion in the crystal where the slip has once taken place remains so weak that a further slipping proceeds along that portion rather than along the remaining virgin lattice planes. Thus the subdividing of the glide packets into finer ones is also prevented in this case.

Above the writer has stated the possibility of formation of the amorphous layer in the portion of the crystal where the crystal slip has taken place. This agrees with the amorphous hypothesis proposed first by Beilby, in that both assume the formation of the amorphous layer on the planes of slip. But the writer's opinion is in many respects quite different from Beilby's, and the objections to the Beilby hypothesis as raised by Elam¹ seem to be avoided by the modified opinion. The main points of her objection are: 1) At the moment that the surface layer melts, the slip direction would presumably be obliterated, and the direction of slip would be the direction of greatest slope in the slip plane; but the actual case contradicts this since the slip direction along the slip plane is not altered up to a very large amount of distortion. 2) The planes upon which slip has taken place, having a greater amount of amorphous material, would be harder than other similar crystal planes, but this is not the case. Plastic deformation hardens the metal as a whole. As to the crystal slip in the slip direction along the slip plane, the writer does not consider it to take place entirely in an ideal manner. Beside the ideal slip, unideal slip is supposed to occur even with a single crystal, by virtue of the presence of some crystal defects. On applying a strong external force, these crystal defects will call forth an irregular internal stress distribution and consequently the destruction of the crystal into fine and

1. C. F. Elam: *Distortion of Metal Crystals* 166 (1935).

distorted crystallites throughout the crystal. This hardens the crystal as a whole. On the plane of slip such destruction into fine and distorted crystallites will be severest, and in some localities it will be melted by local heating and immediately solidified by rapid cooling during the process of slip. As such local heating and subsequent solidification are supposed to take place only in an instant here and there in the plane of slip, this plane will be hardened even during the slipping process. Moreover the ideal slip, by which the regular molecular arrangement in crystal lattice is not disturbed, is considered to take place at the same time in other localities in the slip plane, guiding the slip in the same slip direction. The localities in the plane of slip where melting and subsequent solidification have taken place will be the localities of new crystal defects, and will call forth a further hardening of the whole of the crystal by continued slipping.

In the above description, the strain hardening of metal single crystals is ascribed mainly to the lattice distortion. This is due to the fact that, with a small amount of plastic deformation, the scattering of orientation of the neighbouring crystallites formed by the process of slip is not remarkable, so that the effect of the lattice distortion is predominant over that of the slip interference at the crystal boundaries. However when a metal single crystal is subjected to plastic deformation of great amount, it takes on a polycrystalline structure, having been composed of small crystallites scattered to a considerable degree in their crystallographic orientation. In this state the effect of the slip interference at the crystal boundaries becomes predominant; the destruction of the crystallites into finer ones of scattered orientation, formation of the amorphous layers between neighbouring crystallites, and the setting up of uneven internal strain among crystallites by a plastic deformation, will play a more important part in changing the mechanical properties of a metal. As to the formation of the localities of weak cohesion between crystallites, it seems to be essential in causing the final fracture by the static tensile and the fatigue tests.

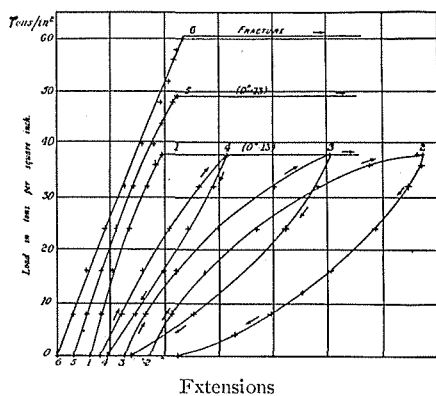
Tensile and Repeated Tests of Polycrystalline Metals

The elastic limit or the yield point of a plastically deformed polycrystalline metal increases by aging or by light annealing, as is seen from the experiments of J. Muir¹⁾ on iron and steel (Fig. 6) and from

1. J. Muir: *Phil. Trans. R. S.* 198, 1 (1902).

M. Sugihara's¹⁾ on aluminium. This is different from the case of a metal single crystal, where, as previously described, the yield point decreases by aging. According to Sugihara, the elastic limit of an aluminium rod, which is elevated by a slight annealing, decreases on further heating by the growth of the crystallites caused by the recrystallization. Thus it seems clear that the elevation of the elastic limit or yield point by aging or by light annealing is due primarily to the smashing of the crystallites into finer ones by the plastic deformation. A plastic deformation causes also other processes: formation of the amorphous layers between crystallites, uneven internal strain among crystallites, localities of weak intercrystalline cohesion and lattice distortion in the crystallites. By aging or by light annealing, most of the localities of weak cohesion are healed, uneven internal strain is reduced, amorphous layers increase and the lattice distortion is removed. Among these causes, the first three elevate the elastic limit or the yield point, by making the effect of the presence of finer crystallites greater than that due to the removal of the lattice distortion which softens the metal.

Fig. 6



Scale:—1 Unit = $\frac{1}{2000}$ th of an inch

- Curve No. 1—Primary test.
 " " 2—Shortly after No. 1.
 " " 3—1 $\frac{3}{4}$ days " " 1.
 " " 4—2 weeks after No. 1.
 " " 5—After heating to 200°C.
 " " 6— " " 200°C.

When polycrystalline iron or steel is deformed plastically beyond its yield point, it ceases to be elastic. The proportionality between stress and strain is obliterated; and the stress strain curve by loading and unloading develops into a loop, as is seen in Fig. 6. The loop becomes gradually narrower with aging, and at last the material recovers its initial elastic property, by a light annealing, having a higher yield point than before. Such violation of the proportionality between stress and strain seems to be caused mostly by the formation of an uneven internal strain among crystallites

1. M. Sugihara, loc. cit.

by the plastic deformation, by calling forth successively the crystal slip in different crystallites throughout the whole process of subsequent loading and unloading; this point will be considered later.

The effect of plastic deformation is revealed especially prominently in the case of hard metals such as iron and steel, owing to the slow recovery of their elastic property by aging or by light annealing. With soft metals such as aluminium the recovery is so rapid that the proportionality between stress and strain can be detected rather soon after the plastic elongation without any noticeable aging. The effect of aging or light annealing is only to elevate its elastic limit slightly. Moreover Hooke's law indicating the proportionality between stress and strain, is seen by Sugihara to be satisfied almost exactly by the tensile test with aluminium. This seems also to be due to the rapid and rather complete recovery of the elastic property by aging or by light annealing with this metal, the uneven internal strain among crystallites which are developed by a previous plastic deformation being mostly lost by the aging alone. However, in the case of iron and steel, of which the recovery of the elastic property is very slow, the exact proportionality between stress and strain below the yield point cannot be detected even after an annealing. This seems to show that the uneven internal strain among crystallites is very difficult to remove and, with these metals, some remains even after annealing.

Bauschinger was the first to show that the limits of proportionality between stress and strain under repeated stresses are not only the quantities characteristic of the material, but that their positions could be modified by the application of cyclical variations of stress. Under such applications both limits could be lowered or raised, but not necessarily by the same amounts. Bauschinger then proposed a theory that the range of these new limits of proportionality constituted a safe range of stress which the material could resist for an indefinitely large number of repetitions- "fatigue range". He called the elastic limits, as found by a primary loading, the "primitive" elastic limits, and gave the term "natural" elastic limits to those obtained by the material after undergoing cycles of stress. Bauschinger's theory has been supported by Bairstow's classical experiment.

C. F. Jenkin¹⁾ ascribed the cause of non-proportionality between stress and strain to the crystal slip occurring during the tensile test

1. C. F. Jenkin: Proc. R. S., A, **103**, 121 (1923).

in some of the constituent crystallites of the material which have internal stresses in them before any load is applied. He supposed that all crystallites expand or contract elastically up to their own elastic limit with increase of the applied stress, then they slip along the slip planes in them with a resistance which is the same as or somewhat smaller than the cohesive force at the elastic limit. To test this idea, he constructed a spring-model and carefully explained the formation of the hysteresis loop by a cyclic extension-compression testing below the yield point, of some metals such as wrought iron, steel, etc. However, Jenkin's theory cannot cover the plastic behavior of metals beyond their yield point. By the continued plastic extension or compression beyond the yield point, all the crystallites would be slipping against the same resistances throughout, constant stress being sufficient to cause a continued deformation. Moreover the internal strain would be equalized among the crystallites rather than made uneven by the plastic deformation. These two conditions do not occur, usually, in the actual case; and some modification of Jenkin's idea is required. The resistance to the crystal slip in a crystallite, which takes place by extension or compression beyond its elastic limit, will be considered much smaller than the cohesive force at the elastic limit; and we shall regard it as approximately nil in comparison with the latter. Thus as soon as the crystal slip is started in a crystallite with negligible resistance, it will be at the same instant finished; and the two parts of the crystallite which have slipped on each other will be reunited as tightly as before the slip, by being released from the internal strain which has existed before the start of the slip. Consequently after the slip the crystallite will be ready anew for further elastic deformation. Generally such sudden slips in the crystallites will not happen simultaneously but in succession, moving from some to another. Moreover as the smashing of crystallites into finer ones and the production of the lattice distortion, act to elevate the elastic limit of the crystallites in a case when the localities of weak intercrystalline cohesion are recovered approximately during the plastic deformation, the plastic deformation does not necessarily cause strain softening, but rather strain hardening.

In the case of the plastic deformation of a metal single crystal, the crystal slip in the slip direction along the slip plane will not take place simultaneously along the whole portion of the slip plane. The slip will proceed in succession from some localities to others in the

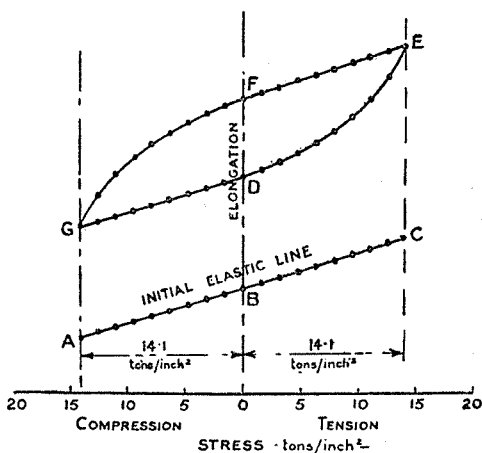
manner supposed by the dislocation theory of Taylor and others; and no sudden decrease in the shearing stress for the slip at the yield point will be noticeable; and this is actually the case.

With some kinds of steel the yield point in tensile test is very sharp. At the yield point the load which is necessary to give a further extension lessens suddenly and then causes jerks in the load-elongation curve in the succeeding course of extension. It seems probable that with these metals the mutual interference for the crystal slip between neighbouring crystallites is especially remarkable, so that every one of the crystallites can withstand with mutual interaction an applied stress stronger than their own. When a sufficient stress is applied to such a test piece, and the crystal slip is caused in the crystallites at several localities in the test piece, then the crystal slip of smaller resistance will spread suddenly and pulsatorily throughout the whole portion of the test piece, travelling from one crystallite to the next in succession due to the successive release of the interfering action for the slip.

With Jenkin's idea modified as before, Bairstow's experiments¹ of applying repeated cycles of tension and compression to a test piece of axle steel seem to be clearly understood. His experiments were carried out in the following way: To the test piece are applied direct tension and compression, the values of the range and mean stress of the cycle being adjusted as desired. The amounts of extension and compression of the specimen were measured by means of a mirror-extensometer. The first range of stress was certainly below the yield point observed in a static tensile test, and the first cycle loading indicated that the material was elastic.

On further repetitions of stress, the straight line developed into a hysteresis loop. Fig. 7 illustrates the form of this loop obtained by giving the same range for the tension

Fig. 7



1. L. Bairstow: *Phil. Trans. R. S., A*, 210 (1910).

and the compression (mean stress=0). In this case the loading was carried out in the direction DEFGD, and EF and GD were found to be parallel to ABC. At the first cycle, where the stress is proportional to the strain, the majority of the crystallites are supposed to be free from internal strain; and they can be compressed and extended equally well elastically. However, it may be imagined at the same time that a few of the crystallites have suffered the crystal slip in this cycle, owing to the presence in them from the beginning of internal strain to a considerable amount. Though the slipped crystallites are few in number on the first cycle loading, they will cause added internal strain in their neighbours; and in the following cycles these strained neighbours will suffer the crystal slip in succession. Thus after the repetition of a very large number of the cycles, the majority of the finer crystallites will come to have internal strain of different amounts and of different signs even at the state of no load. Now let us consider the cycle DEFGD, and suppose the state at D. At this state about one half of the crystallites will be stretched and the rest compressed; and the greater part of them, having only a small amount of internal strain, will follow the cycle elastically. As the D state is attained by expansion from the G state by unloading in compression, we cannot expect that there will be crystallites of noticeable number which are still considerably compressed at this state. However, the crystallites which are considerably stretched will be much more numerous, and these crystallites will slip along the loading curve DE in tension. On passing the point E, where the majority of the crystallites are supposed to be in a stretched state, they will contract elastically to the point F along the unloading curve EF in tension. At this point the circumstances are similar to those at the point D. Some crystallites which are severely compressed at this point will slip along the loading curve FG in compression. Lastly, after passing the point G, where the majority of the crystallites are supposed to be compressed, they will expand elastically to the point D along the unloading curve GD in compression. The formation of the Bairstow's hysteresis loop seems thus to be understood clearly.

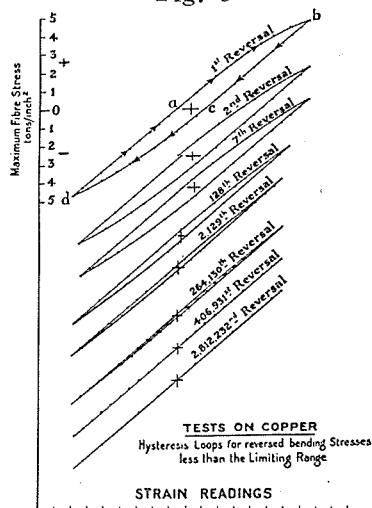
Bairstow made his experiment with steel. Steel is a material whose natural elastic limits for reversed stresses are less than the primitive limits of proportionality. This is due to its slow recovery of the elastic property by aging. By a plastic deformation the crystallites are smashed into finer ones, having the lattice distortion and the

uneven internal strain. And at the same time localities of weak intercrystalline cohesion and amorphous cementing layers are produced here and there in the specimen. The recovery is a process which removes the lattice distortion and the

uneven internal strain, and heals the weak intercrystalline cohesion merely by the thermal agitation or by increasing the amorphous layer. Thus by applying repeated stresses of sufficient strength to a test piece of such a metal as steel, it gradually loses its elastic property as is seen in Bairstow's experiment, on account of inability to recover with sufficient rapidity. This is in marked contrast to the case of such material as copper, where the recovery is remarkable even at room temperature. Fig. 8 shows the results of the experiment

made by Gough,^D by applying reversed bending stresses to a test piece of annealed copper. Annealed copper has no primitive elastic limit, and describes a wide hysteresis loop on first reversal. As the number of reversals increases, the width of the loop diminishes gradually, and at last the metal becomes elastic. As the recovery is rapid with copper, the lattice distortion of the crystallites and the uneven internal strain among the crystallites are both to a large degree removed during the course of the testing, and at the same time the localities of weak cohesion are almost healed; so only the effect of the presence of much finer crystallites is left and this elevates the elastic limit considerably by means of the slip interference at the crystal boundaries.

Fig. 8



Creep, After-Working and Recovery

When a metal test piece is plastically deformed by applying a given load the deformation is not completed at the same time with the application of the load, but it continues to proceed slowly and ceases only after the lapse of a considerable period. This is the creep phenomenon. On the contrary, when the test piece is unloaded

1. H. J. Gough: *The Fatigue of Metals*; p. 129 (1924).

after it has been deformed plastically, the final settling of its form requires a considerable time. This is termed after-working. These two phenomena are essentially the same, and signify that in a plastic change of material, it takes a long time to attain the state of structural equilibrium. As to the mechanism of these phenomena a clear explanation has already been given by Gough and Hanson.¹⁾ When crystal slips occur in some of the crystallites, their effects will be transmitted to their neighbours in succession and will call forth slips in other crystallites of the specimen. Such effects are reciprocal to each other, and the final settling to structural equilibrium will be reached only after a long time. Recovery by aging or by light annealing is also a phenomenon of settling down to structural equilibrium, and is essentially the same as the creep and after-working. The only difference is that creep and after-working refer to the outer form and size of the material, and recovery relates mainly to its mechanical property. By aging or light annealing the lattice distortion of the crystallites diminishes, uneven internal strain among crystallites lessens, amorphous layers cementing the neighbouring crystallites are increased and the localities of weak intercrystalline cohesion are largely healed. These recovering actions will not necessarily take place simultaneously in all portions of the material, but will start at many distinct localities and spread to the other portions by passing through the intervening neighbours in succession. As is stated above the creep and the after-working are essentially the same phenomenon. The only difference is that, the former takes place on the loading and the latter occurs on the unloading. The effects of plastically deforming a solid and of the recovery of its mechanical property seem to stand entirely in the same relation as creep and after-working. Thus structurally considered, the recovery is essentially the same process as the plastic deformation; and it seems not unreasonable to imagine that such severe processes as the crystal slip and the formation of the amorphous layer, which are supposed to occur usually with the plastic deformation, take place also in the recovery, though very slowly.

Fatigue Test and Fracture

It is already stated that the elastic limit of a metal changes on applying repeated cycles of tension and compression, and that it rises or falls according to the kind of metal, and reaches the so called

1. H. J. Gough and D. Hanson: Proc. R. S., **104**, 538 (1923).

natural elastic limit. When the range of stress applied is within the natural elastic limit, the metal can withstand an infinite number of reversals of stress without fracturing. In this case all the crystallites are stretched and compressed elastically without suffering any crystal slip which brings about structural change in the material. On the contrary, when the stress applied is above the natural elastic limit, the metal suffers a plastic deformation on each reversal of stress. In this case fissures will be ceaselessly produced in the test piece during the course of the fatigue test. Many of them may be healed by the recovery or by the application of succeeding reversals of stress, but there will be some which widen gradually to be fatal with the progress of the test. Such fatal fissures, though only few at the beginning, will become so numerous at last that a greater part of the interior of the test piece is sectioned by their net-work, making the material very brittle. At this state the fracture of the test piece will occur immediately along a part of the net-work which offers macroscopically the least resistance to the stress applied, when a further cycle loading is repeated. The local contraction in cross sectional area at the fractured part, which is ordinarily observed in a static tensile test, does not commonly occur in the fatigue test. This fact accords well with the above view. In the case of the static tensile test, where the plastic deformation of the test piece before the fracture is great, the number of the fatal fissures will be only a few, and the major part of the material will be deformed plastically in a ductile and tenacious state, so that the contraction in the cross sectional area accompanies the elongation of the test piece. In this case, the stress concentration at the edges of such fatal fissures acts to develop the fissures and weakens the material. The portion of the test piece where the fatal fissures accumulate will be more stretched and consequently more slender than elsewhere, bringing finally the fracture at that point.

According to the static tensile and fatigue tests carried out at high temperatures, the tensile strength of a metal diminishes with increase of temperature, but its fatigue limit remains nearly unaltered up to a certain temperature. Generally the interatomic and intercrystalline cohesions weaken with rise of temperature, and this acts to diminish both the tensile strength and the fatigue limit in the same way. However the rapid healing of the localities of weak intercrystalline cohesion and of the primitive fissures at higher temperatures

prevent the metal from losing its ductility and tenacity, the qualities whose loss is fatal in the fatigue test. This recovering action counteracts to the reduction of fatigue limit of the material with rise of temperature, and helps it to maintain its health. In the case of a static tensile test, the tensile strength relates mainly to the strain hardening, which the material will acquire during the test. The diminution of such strain hardening, caused by quicker recovery and recrystallization at higher temperatures, assists in lessening the tensile strength with rise of temperature.

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