Structure and Nature of Troostite [1]

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In this paper the structure and nature of the constituent troostite (found in hardened steels) is discussed. High power metallography was first applied to this problem about six years ago and the early results were presented in an address before the Franklin Institute.

Since that time many improvements in technique have been developed which have resulted in better resolution and definition. The subject has been reviewed in the past two years and with the aid of the improvements in technique, hardened steels are found to be largely mixtures of the things which metallographers call martensite and troostite.

In small specimens of 0.90 per cent carbon tool steel hardened to C-65 on the Rockwell scale, innumerable particles of troostite are found. When these particles of troostite are examined by present high power methods the structure is clearly resolved into laminated pearlite. In certain stages of development of a troostitic nodule its structure borders on the verge of present methods of resolution.

Nodular troostite develops under favorable conditions as a globular mass. At the center is a nucleus about which the growth occurred. Radial, fan-shaped grains extend outward from the nucleus and these grains show orientation phenomena when revolved about the optical axis of the microscope.

It is believed that when martensite forms, the structure develops on the old austenitic crystallographic planes. Troostite appears not to follow the old austenitic system but seems to be a reorientation of the freshly transformed alpha iron about a nucleus which usually is an inclusion, a void, a sharp corner in a grain boundary or some other detail of structure.

The structure of troostite in various stages of its formation is illustrated by means of high power photomicrographs, many of which are shown at this Congress for the first time.

The following conclusions were reached:

Nodular troostite appears to be an aggregate of ferrite and carbide and in the very early stages of formation its structure is on the border of present methods of resolution. The condition of the ferrite and carbide in relation to each other is not stable—they tend to stratify, forming pearlite.

Troostitic nodules grow about a nucleus which may be an inclusion, a void, a corner in a grain boundary or some other detail of structure. The nodules contain fan-shaped radial grains.

The development of troostite results in a reorientation of the ferrite—seemingly without particular reference to the old austenitic crystallographic planes. Martensite does follow the old system of austenitic planes.

The small fan-shaped grains in nodular troostite may persist as small grains or they may undergo grain growth by union. It is a matter seemingly dependent upon the thermal treatment of the specimen.

IN a paper [2] presented before the Franklin Institute in the year 1924 some observations on the structure and probable nature of the constituent troostite were given. Two types of troostite were shown to occur in hardened steels depending on the mode of heat treatment. If a bar of 0.50 per cent carbon steel is given a taper heat treatment,

[1] Presented by the author before World Engineering Congress, Tokio, Japan, October 30, 1929.

[2] Lucas, "High Power Metallography—Some Recent Developments in Photomicrography and Metallurgical Research," *Journal of the Franklin Institute*, Vol. 201, February 1926.

troostite occurs which was described as flocculent border type for lack of a better designation. It seemed to be largely ferrite and appeared to be the means by which the excess constituent (in this case ferrite) appeared at the grain boundaries.

If a small specimen of the same steel is heated to a high temperature and quenched in oil or water depending on the circumstances of the experiment, a structure results which may be largely martensite needles with scattered particles of troostite. Sometimes relatively large areas on the prepared surface of the specimen may be almost entirely of the constituent troostite. As is well known, this condition is controlled by the rate of cooling in the quenching operation. The type of troostite found in uniformly heated and quenched specimens was defined as nodular troostite. This paper deals further with this particular constituent of hardened steel.

Since these early experiments in which high power metallography was first applied with success to the structures of hardened steel, there have been many improvements in technique. These improvements have resulted in a much higher order of resolution and it is the object of this paper to review the past work in the light of the improved methods now available and to present some new results.

To quote from the Franklin Institute paper:

". . . These nodules develop from innumerable nuclei throughout the austenite and martensite matrix. . . . The nuclei increase in number and the developing nodules become larger and larger. Irregularities in growth due to interference of nodules occur as the growing particles increase in number and size until finally the whole mass seems to be composed of nodules, some spherical in shape but many deformed due to mutual interference and to irregularities in growth. A selectivity or preference in crystal habit probably prevails for crystallographic planes since spines, branches, and interconnected crystallites may be found occasionally. In reality these are poorly formed nodules, growth in some one or more directions having been arrested."

"It is quite evident that if the entire mass of the metal passes through the nodular troostitic stage, this constituent must contain carbide or carbon in some form."

"When one of the globular-shaped crystal masses which has developed under favorable conditions of growth is sectioned in such a way as to divide the mass along a plane passing through the center; the nucleus is found at the center and fan-shaped grains extending from the center toward the outside. When freshly formed and under the highest powers of the microscope these radial grains have all of the appearance of a solid solution. The nodule must contain carbon in some form, as stratification soon takes place."

Moreover, it was shown that each of the fan-shaped grains is a separate crystalline unit for if a nodule of troostite is revolved about the optical axis of the microscope, these very small fan-shaped grains display orientation phenomena in exactly the same way as a system of polyhedral grains in a pure metal will do if revolved about the optical axis of a microscope while being kept under observation at 100 or 200 diameters magnification. The only difference lies in the fact that in nodular troostite the grains are fan-shaped and quite small, making it desirable to carry out the observations with an oil immersion lens which will yield high magnifications.

Fig. 1 is reproduced from the Franklin Institute paper and illustrates a typical section on a plane passing through the center of a single nodule. Fig. 2, also from the same paper, is a diagrammatic representation of how the fan-shaped grains develop along axes of crystallization A, B, C, etc.

Fig. 1 not only shows crystallization about a nucleus but it also supplies evidence for the conclusion at that time that nodular troostite is either a solid solution of iron carbide in iron or it is a very fine aggregate of iron and iron carbide—the carbide so finely dispersed as to lose its identity under the microscope. Failure at that time to resolve the structure of troostite into its ultimate constituents compelled one to recognize the existence of the two possibilities as to structure.

The improvements in technique previously mentioned have thrown some new light on the structures found in hardened steels and these have been discussed in later papers.[3, 4, 5]

Certain it is that the structures found in hardened steel are largely mixtures of the things which metallographers call martensite and troostite, the name martensite in this case meaning a needle-like structure. Troostite, generally, is regarded as a lower order of decomposition than martensite. This, however, is not believed to be substantiated by the evidence.

It has been shown[6] that martensite is a decomposition of the austenite along the octahedral crystallographic planes. That is, martensite is a structure superimposed by decomposition of the austenite on the old crystallographic system of the austenite. Two changes are in-

[3] Lucas, "A Résumé of the Development and Application of High Power Metallography and the Ultra Violet Microscope," Vol. I, *Proceedings International Congress for Testing Materials*, Amsterdam, September 1927.

[4] Lucas, "Photomicrography and Its Application to Mechanical Engineering," *Mechanical Engineering*, Vol. 50, March 1928.

[5] Lucas, "Further Obseivations on the Microscructure of Martensite," *Trans. American Society for Steel Treating*, Vol. XV, February 1929.

[6] Lucas, "The Micro-Structure of Austenite and Martensite," *Trans. American Society for Steel Treating*, Vol. VI, No. 6, December 1924.

volved: an allotropic change of the iron from gamma to alpha and a precipitation of the carbide Fe_3C. This matter is more fully discussed in a recent paper [5] to which those interested are referred.

Troostite is not like martensite in respect to habit of formation. It does not assume fully the old austenitic crystalline symmetry. It seems to have a new crystalline orientation of its own.

Troostite develops along grain boundaries and within the grains. It may develop as a spine or branch along a crystallographic plane. The nodules may be roughly spherical masses; they may be semi-spherical masses, the flat side being bounded by a crystallographic plane or a grain boundary, or they may be rounded but irregular shaped masses. In any event, whether in ball-shaped masses or some constricted form, the small fan-shaped grains are found radiating from a nucleus of growth. This nucleus in most cases can be identified as an inclusion, a void, or a sharp corner in a grain boundary. Thus the tendency is for reorientation of the iron to occur when nodular troostite develops.

It is well known that a slow rate of cooling promotes more troostite. Rapid cooling results in more needles or the constituent we call martensite. Evidently when the rate of cooling is favorable the freshly transformed alpha iron is given time to reorient itself and does do so by growing about some convenient inclusion or other body. Thus nodular troostite develops. Whether the carbide is held in solid solution in the freshly transformed alpha iron seems to be a matter of speculation.

A small specimen of steel weighing less than ten grams, heated to 1000° C. in a vacuum for a suitable length of time, and quenched in ice and brine will contain almost innumerable troostitic bodies, many of them very small, and some quite large. The larger ones perhaps are a few ten-thousandths of an inch in diameter and from this dimension the troostitic particles decrease in size to the vanishing point of present microscopic resolution which is around 200 atom diameters.

The specimen itself will have a hardness on the Rockwell scale of about C-65. Nevertheless the troostitic bodies have been clearly resolved to show the presence of fully laminated pearlite. So that in a small specimen of steel quenched from a high temperature in a very effective cooling bath, one finds not only the needle constituent martensite but nodules of troostite containing fan-shaped grains of fully stratified pearlite.

The question naturally arises as to whether the steel in its transition from austenite to pearlite first develops a needle structure (martensitic) and then this in turn is replaced by a nodular (troostitic) one.

Some light [6] was thrown on this angle of the problem by a high power examination of an iron carbon alloy. The carbon content was 2.65

per cent and by quenching small pieces from very high temperatures, polyhedral grains of austenite containing martensitic needles and troostitic nodules were found to occur. Both constituents were found to occur in the same grain and both seemed to be entirely surrounded by austenite. Had the needles formed first and the nodules developed from the needles, one might expect to find some nodules with untransformed needles sticking out around the boundaries of the nodules. This was found not to be the case. The boundaries of the troostitic nodules are always sharply defined.

In some specimens of commercial plain carbon steels in which some tempering had taken place troostitic nodules were found in which it appeared that the nodule had grown at the expense of some martensitic needles. The needles seemed to be dimly visible in outline in the background of the nodule. Cases of this kind appear very infrequently. Microscopic evidence does not support the conclusion that one type of structure replaces the other.

If a specimen of commercial tool steel heat treated to produce some troostite in a martensitic matrix is tempered, one might expect the troostite nodules to grow in size if the nodular form of structure replaces the needle structure. As a matter of fact the nodules remain the same size and the carbide which they contain tends to coalesce into small globular particles, marking not only the border outline of the nodule but also the outlines of the fan-shaped grains.

The needle and nodular patterns are structures which result from quenching and not from tempering. The excess constituent in the case of hypo- or hyper-eutectoid steels appears to be eliminated or cleared by means of the constituent troostite. The constituent martensite (needles) appears not to be involved in this phenomena in quenched specimens when both troostite and martensite are present.

If one examines a normalized specimen of plain carbon tool steel of about 0.90 per cent carbon content he will find a large polyhedral structure marked by a carbide network, but within these grains will be found a great many smaller grains of pearlite, usually fan-shaped. In many cases the outlines of the old troostitic nodules can be traced without difficulty. From the configuration of the pattern it seems likely that these small grains within the larger (old austenitic) grain must differ in their inner crystalline symmetry, i.e., it is probable that the ferrite is not everywhere oriented the same throughout the old austenitic grain. Under some circumstances controlled by heat treatment, it appears that grain growth does occur among these small fan-shaped grains and the old austenitic grain may be uniformly oriented ferrite containing spheroidized particles of cementite which by their positions mark the old structure and tell the history of the transformations.

Professor Honda believes that martensite forms first and troostite develops secondly, replacing the martensite.[7] In his discussion of the subject he appears to deal with the ultimate nature and composition of the constituents and not with their outward form.

A number of typical illustrations are included to show in detail the structure of troostite. For these experiments a high grade tool steel of about 0.90 per cent carbon was used. Small specimens weighing about 10 grams were suitably heated in a vacuum furnace to a high temperature and quenched in ice and brine solution. The hardness of the specimens was quite uniform and averaged C-65 on the Rockwell scale. From a study of the photographs it is quite apparent that in a specimen of the kind, we may have not only the constituents martensite and troostite, but in the troostite also the constituent pearlite in the form of fan-shaped grains. From the work of Mathews,[8] Bain,[9] Enlund,[10] and others, it is also apparent that some retained austenite may be present. Hardened steel, therefore, is a complex structural aggregate at best.

Conclusions

Nodular troostite appears to be an aggregate of ferrite and carbide, and in the very early stages of formation its structure is on the border of present methods of resolution. The condition of the ferrite and carbide in relation to each other is not stable; they tend to stratify forming pearlite.

Troostitic nodules grow about a nucleus which may be an inclusion, a void, a corner in a grain boundary or some other detail of structure. The nodules contain fan-shaped radial grains.

The development of troostite results in a reorientation of the ferrite, seemingly without particular reference to the old austenitic crystallographic planes. Martensite does follow the old system of austenitic planes.

The small fan-shaped grains in nodular troostite may persist as small grains or they may undergo grain growth by union. It is a matter seemingly dependent upon the thermal treatment of the specimen.

[7] Honda, "Is the Direct Change from Austenite to Troostite Theoretically Possible?" *Journal British Iron and Steel Institute,* 1926, Vol. CXIV, No. 2.

[8] Mathews, "Austenite and Austenitic Steels," *Trans. American Institute of Mining and Metallurgical Engineers,* Vol. LXXI, 1925; "Retained Austenite," *British Iron and Steel Institute,* 1925, No. 11, Vol. CXII.

[9] Bain, "The Persistence of Austenite at Elevated Temperatures," *Trans. American Society for Steel Treating,* Vol. VIII, 1925.

[10] Enlund, "On the Structure of Quenched Carbon Steels," *Journal British Iron and Steel Institute,* 1925, Vol. CXI, No. 1.

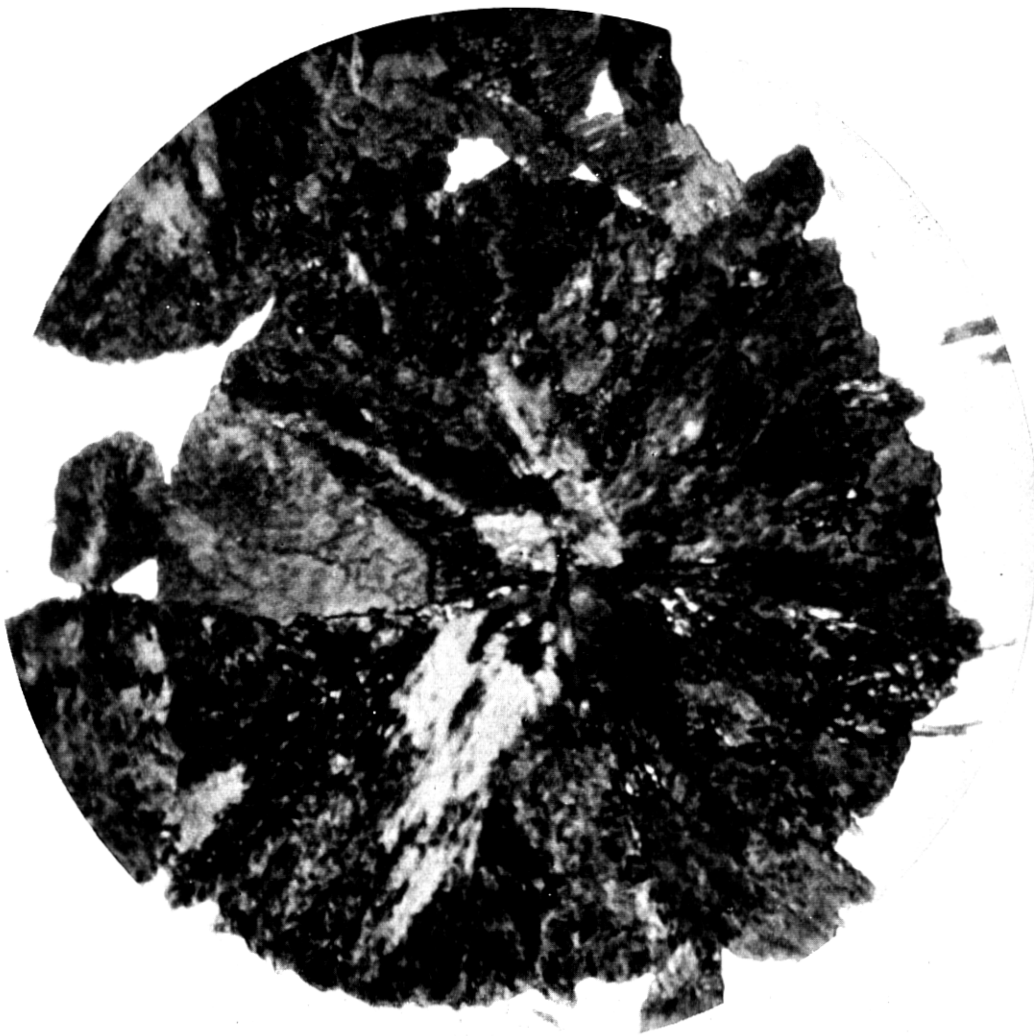


Fig. 1—Mag. 3230X. Fig. 1 is reproduced from the *Journal of the Franklin Institute* and shows a typical troostitic nodule sectioned on a plane passing through the center. The nodule has developed as a globular mass about a nucleus. Radial grains have developed. These grains change from light to dark when the nodule is revolved about the optical axis of the microscope. Therefoie it is clear that the small fan-shaped grains are differently oriented. Where nodular troostite forms regranulation must occur. Where changes in orientation take place, grain boundaries must result. The structure of the troostite has not been fully resolved in this photograph. Compare with others which follow.

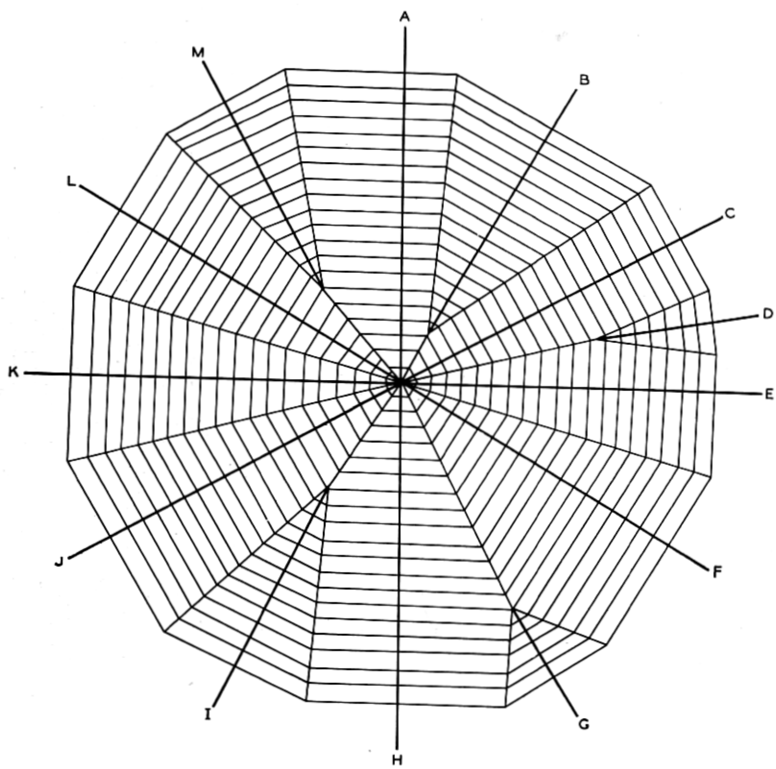


Fig. 2—A Diagram. Fig. 2, also from the *Journal of the Franklin Institute*, illustrates diagrammatically the mode of crystalline growth in a troostitic nodule.

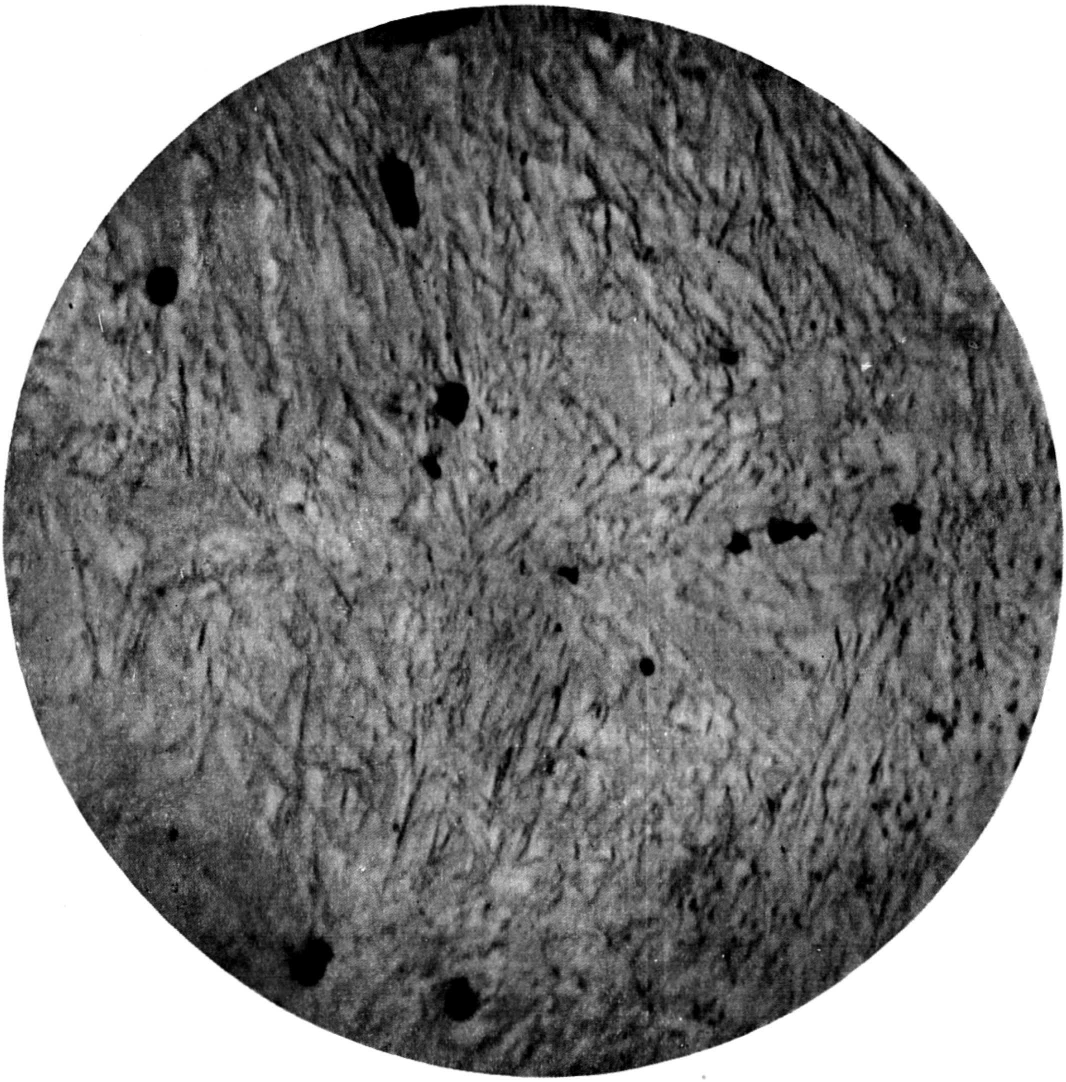


Fig. 3—Mag. 3500X. Fig. 3 shows the early stages in the formation of troostitic nodules. The background will be recognized as martensite. The dark particles are troostite. The field is on the border of an area containing large well developed nodules. This position in the specimen is one in which thermal conditions promoted the development of the needle structure but did not fully inhibit the development of nodules. The very small dark particles are about five-millionths of an inch in diameter. The larger ones are from about ten to twenty times larger.

Fig. 4—Mag. 3500X. Fig. 4 shows a somewhat later period in development of troostite. The troostite appears to have formed along grain boundaries. The excess constituent is clearly seen, and here and there a laminated structure, pearlite. Evidently whatever the state of the carbide with reference to the iron in troostite—whether contained in solid solution as first formed or whether disposed as a fine aggregate with the iron—the condition must be very unstable, otherwise evidences of finely laminated pearlite would be lacking.

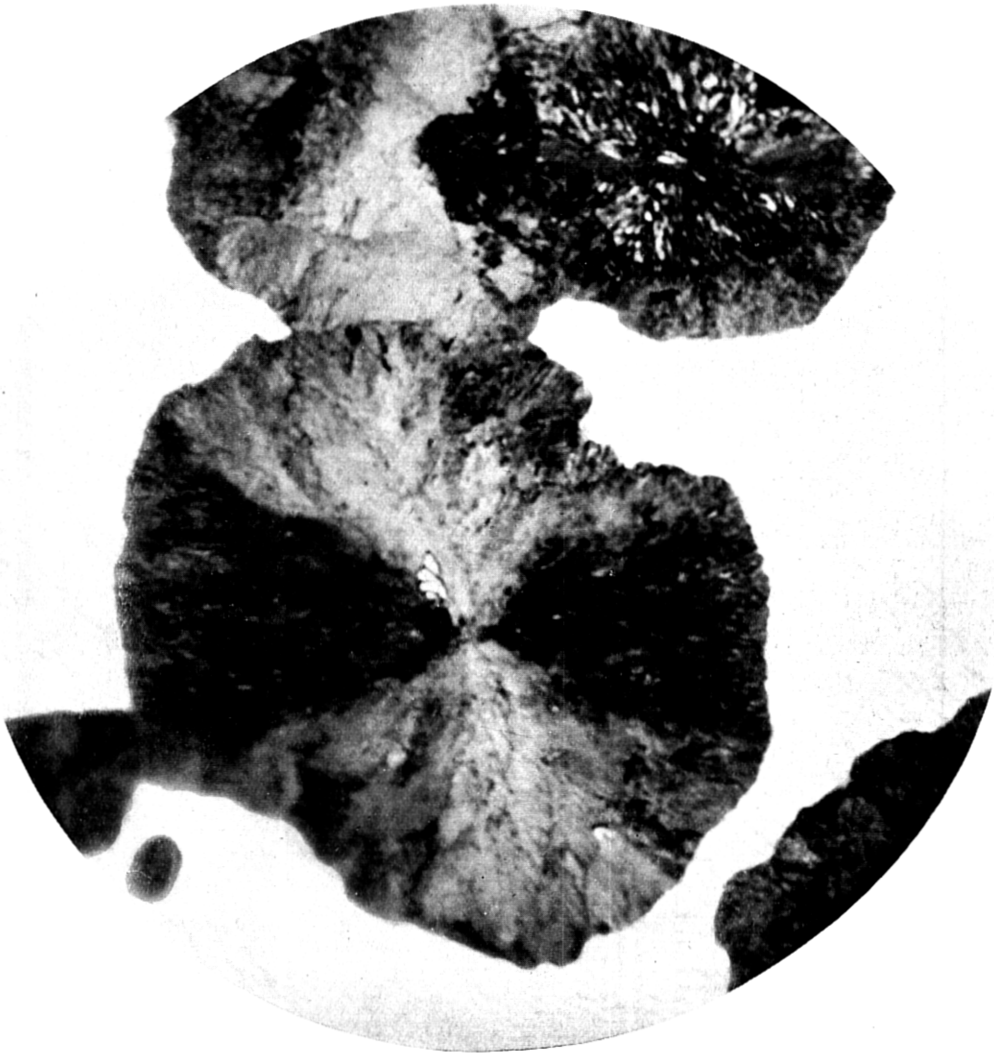


Fig. 5—Mag. 3500X. Fig. 5 is of a small but well developed nodule showing four fan-shaped grains about a nucleus of growth. Some excess constituent has appeared but only the very early stages in the process of stratification to pearlite are visible. It is apparent, however, that the nodule is not composed of a solid solution. The nodule is about eight ten-thousandths of an inch in diameter.

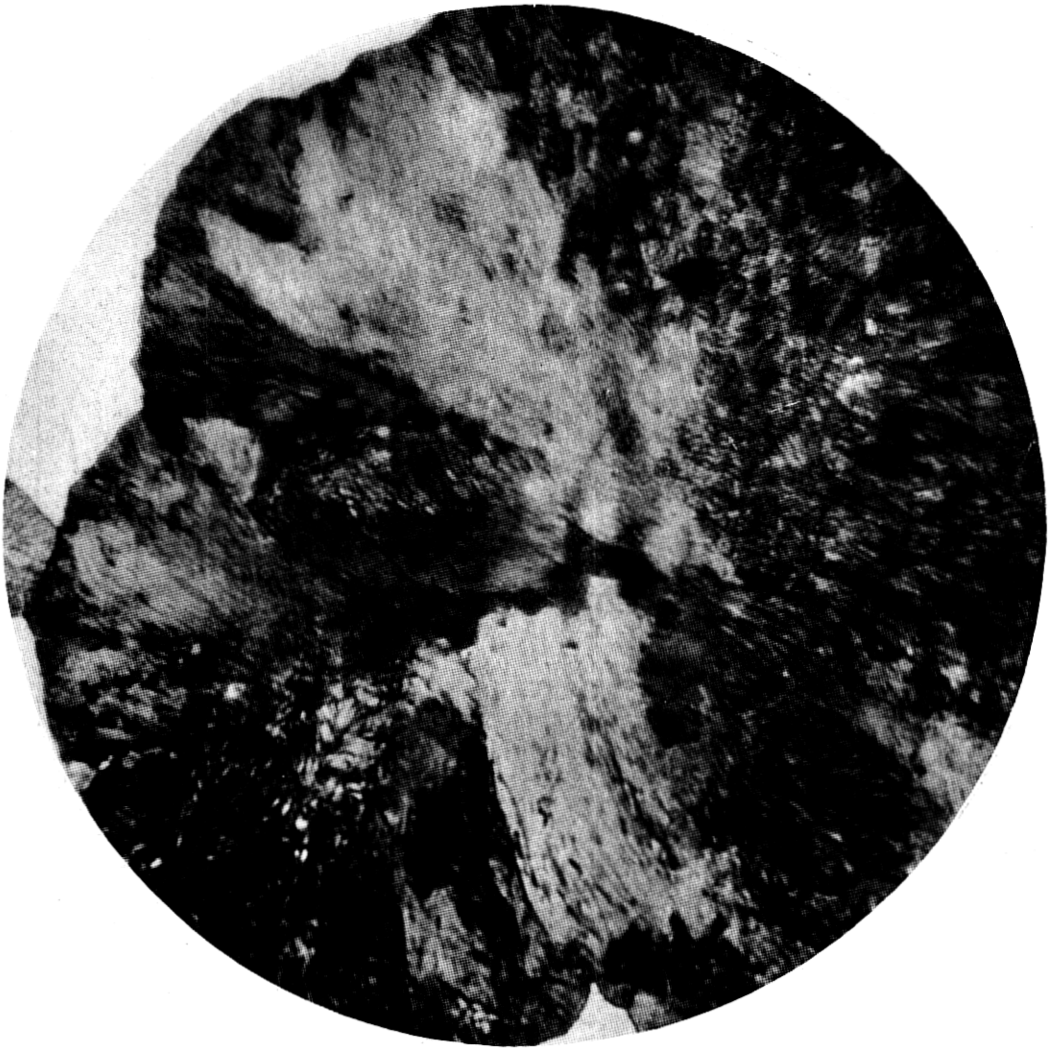


Fig. 6—Mag. 3500X. Fig. 6 is of a larger nodule than illustrated in Fig. 5 and shows obviously a little later stage in the process of stratification. This nodule is about the same as the one illustrated in Fig. 1 except that the structure has been resolved.

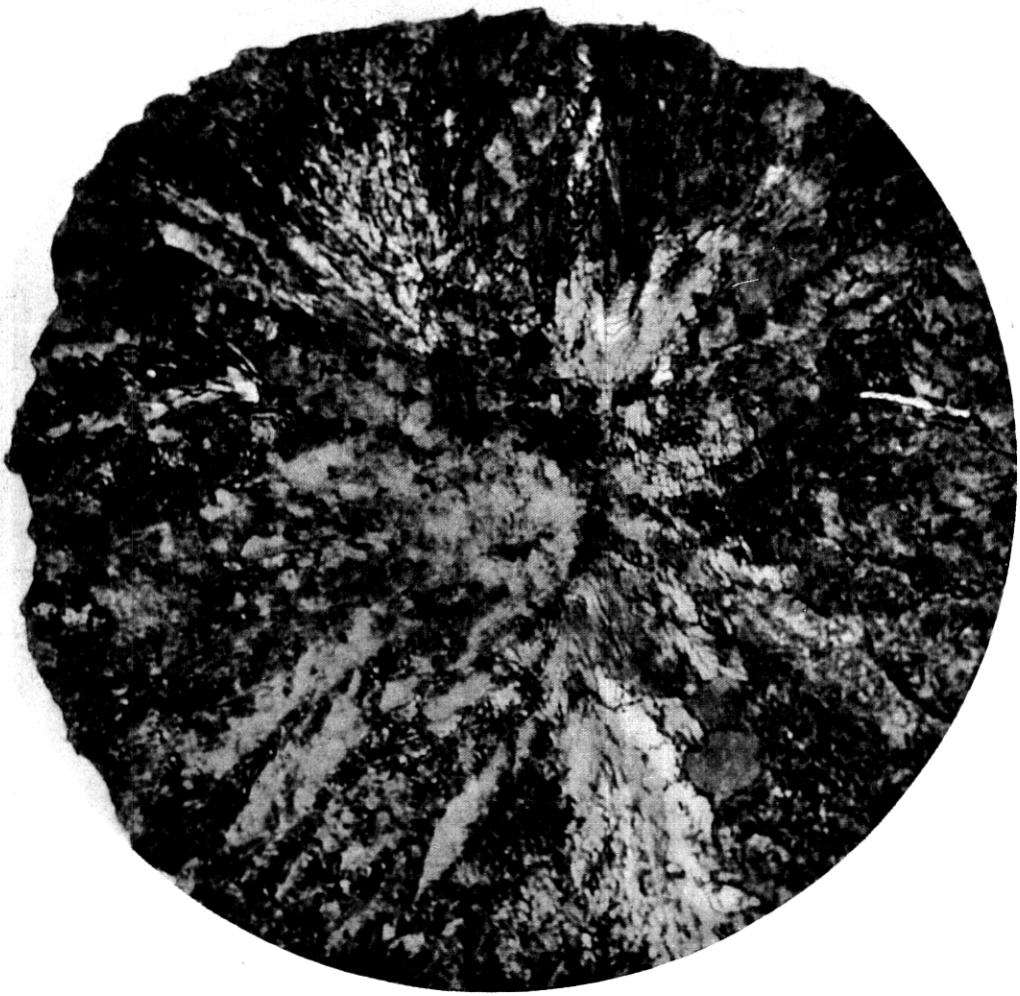
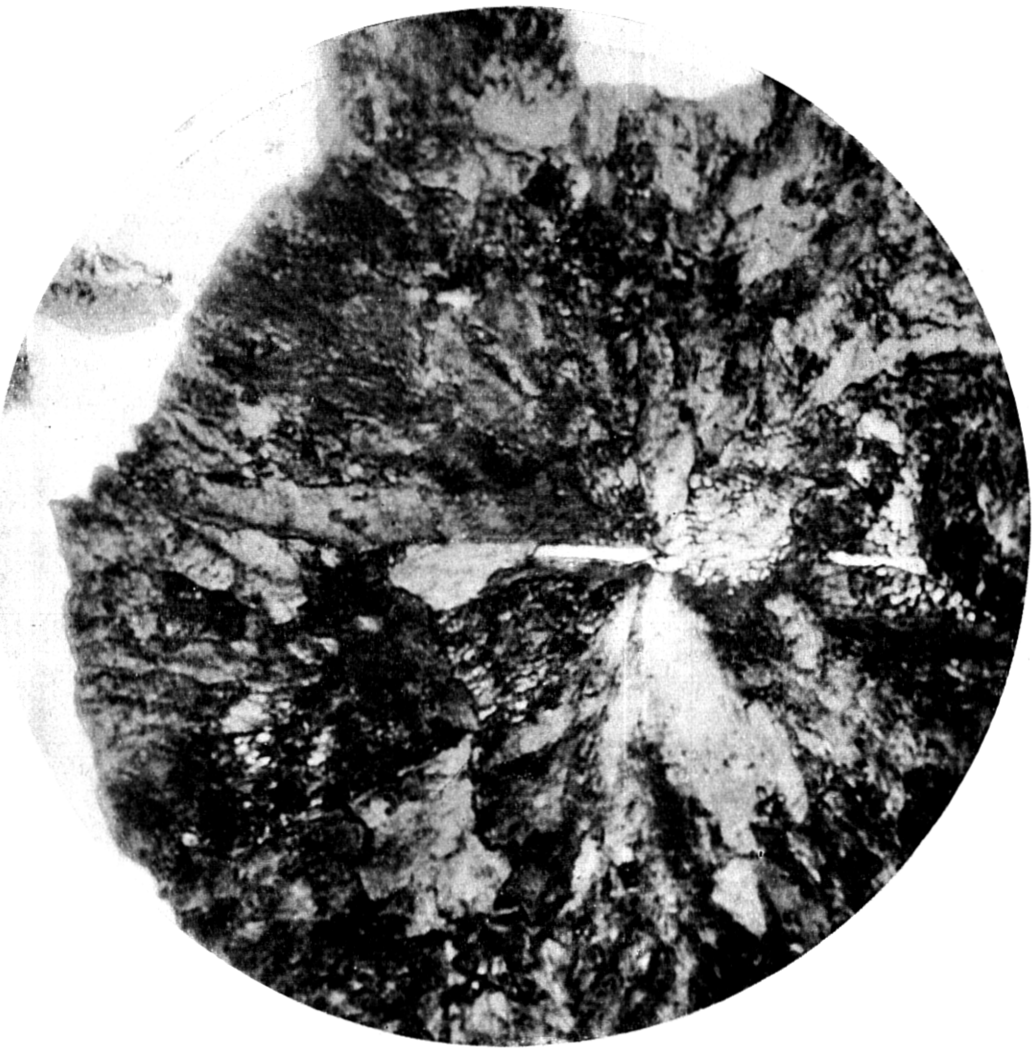


Fig. 7—Mag. 3500X. Fig. 7 illustrates a condition somewhat further advanced than that shown in Fig. 6. Stratification is well advanced and is plainly shown throughout.

Fig. 8—Mag. 3500X. Fig. 8 shows a troostitic development which had formed along an old austenitic grain boundary. The excess constituent is starting to clear at the grain boundary. Well developed pearlite is revealed. The large light-colored grain covering the center of the field is just starting to break up into two constituents. Formerly grains of this kind, because of lack of resolution, were thought to be in all probability solid solution grains. These grains must represent a state very nearly that of freshly formed troostite.



Figs. 9 and 10—Mag. 3500X. Figs. 9 and 10 show two typical nodules along grain boundaries or crystallographic planes. The excess constituent, the radial grains, some practically irresolvable and others fully resolved, and the center of growth (in Fig. 9) are clearly revealed.

Fig. 10—Mag. 3500X.

Fig. 11—Mag. 3500X. Fig. 11 illustrates the wide range in structure to be found in hardened steel. The background is martensite whicn contains a troostitic nodule. One grain of the nodule is fully laminated pearlite. The other grains are in all stages of stratification.

Fig. 12—Mag. 3500X. Fig. 12 illustrates the condition which prevails when growing nodules interfere and the whole area is troostite. Small fan-shaped grains are found in the different stages of stratification.

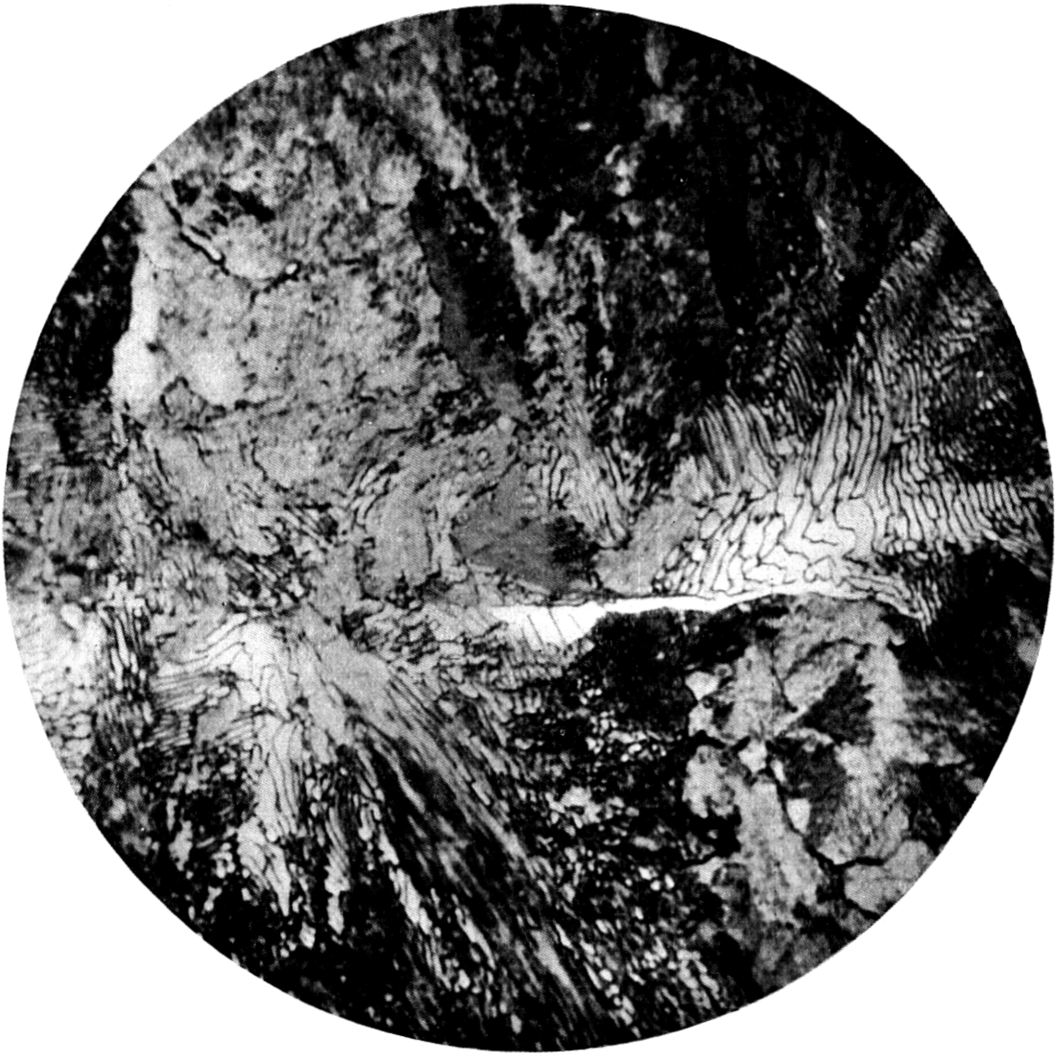


Fig. 13—Mag. 3500X. Fig. 13 is of a field similar to Fig. 12 except that a more advanced stage in stratification is present. This photograph is reproduced from the *Proceedings of the International Congress for Testing Materials.*

Fig. 14—Mag. 3500X. Fig. 14 is of a specimen which was quenched and then drawn for ten minutes at 650° C. The outline of a troostitic nodule is clearly marked by globular carbide particles. The hardness of the specimen was C-28 after tempering.