SOME METALLOGRAPHIC OBSERVATIONS ON THE TISHOMINGO, OKLAHOMA, METEORITE

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ABSTRACT

The Tishomingo meteorite was discovered in January, 1965, near Tishomingo, Johnson County, Oklahoma. The nickel content, 32.5 percent by weight is one of the highest ever found in iron meteorites. Metallographic examinations have been made of the meteorite and a uniquely coarse martensitic microstructure has been observed. Interpretations from the microstructural features have concluded that the coarse martensite occurred as the result of (1) direct transformation during cooling from austinite or (2) stress-induced transformation by shock pressures. Certain observed physical alterations of inclusions in the meteorite and the morphology of the martensite indicated that the Tishomingo meteorite experienced a shock event at some time. Further metallographic observations have permitted speculations concerning additional thermal and mechanical events which this meteorite may have experienced.

INTRODUCTION

The purpose of this paper is to describe the results of metallographic studies that we have made on a recently found meteorite called the Tishomingo meteorite. This meteorite was discovered in January, 1965, near Tishomingo, Johnson County, Oklahoma. To date, four pieces of the meteorite have been recovered weighing a total of about 600 lb. This meteorite has a nickel content of 32.5 percent by weight, one of the highest ever found in iron meteorites. The microstructure observed in the meteorite was very unique and, in fact, the Tishomingo find was not believed to be a meteorite until cosmic gas was identified within the mass.

METALLOGRAPHIC OBSERVATIONS

Microstructure: The microstructure of the Tishomingo meteorite was revealed by metallographic polishing and subsequent etching with either acidified Picral or Nital. Figure 1 shows the full cross section of one of the metallographic specimens and the macrostructural pattern of it. This structure is interpreted as consisting of unusually coarse martensite needles in a taenite (gamma iron) matrix. A martensite structure as coarse as this has never been reported for a meteorite; however, according to Massalski's recent classification[7], this structure would probably be called a Type II plessite. The volume percentages of martensite and taenite were determined by the method of point counting, and were found to be 79 percent and 21 percent, respectively.

A structural band was observed to cross the entire surface of the specimen, as seen in Figure 1. This band contains the same type of martensite-taenite structure as the remainder of the piece; however, most of the martensite needles in the band are oriented with their long axes parallel to the long dimension of the band, while the orientations of the martensite needles on either side of the band differ slightly. The differences of martensite needles orientations suggest that the band is an untwinned region while the areas on either side of the band are twinned regions of a single prior taenite grain.

A typical area of the Tishomingo meteorite microstructure is shown in Figure 2. The coarseness of the martensite needles is readily apparent in this figure. Numerous parallel striations were observed running entirely across many of the martensite needles. Some of the mid-ribs of the needles had jogs in them and every mid-rib jog occurred where a striation crossed the mid-rib; however, a jog was not observed at every intersection of a striation and mid-rib.

Under the electron microscope, two distinct phases were observed in the microstructure of the martensite needles, as shown in Figure 3.

Figure 4 shows a portion of the oxide scale (the dark-gray areas) on the meteorite surface, and some regions of oxidation penetration of the metal below the scale. Figure 5 shows some of the oxidation at higher magnification. Note that only the martensite needles have oxidized as a result of the penetration, and the taenite is unaffected. Although this figure appears to be etched, it is as polished. The detail in this figure shows that the entire area of a martensite needle is not oxidized, but only "pepper" particles within the bounds of a needle are oxidized. These "pepper" particles correlate with the two-phase structure shown earlier by electron microscopy. In areas near the maximum penetration of oxidation from the meteorite surface, the oxidation of the martensite needles was observed to have occurred first along the mid-ribs of the needles.

Inclusions: The inclusions observed in the Tishomingo meteorite appeared to be primarily troilite, FeS, containing some daubreelite (Cr,Fe)S. Evidence of a physical alteration of each inclusion observed was quite apparent. A troilite-daubreelite inclusion is shown in Figure 6. Figure 7 shows a physically altered troilite inclusion with a few daubreelite particles within it. The dark zone around this inclusion was found to be high in sulfur and contains essentially no nickel, while the center (light area) contained the nickel and much less sulfur. Figure 8 is a view of another troilite inclusion which shows a physical alteration of the troilite-metal interface and an unusual zone surrounding it containing no martensite.

DISCUSSION OF OBSERVATIONS

Microstructure: The unique microstructure of the Tishomingo meteorite prompts numerous questions. Foremost, there is the question of how the coarse martensite structure was produced. Agreement on the answer to this question has not been reached since there seems to be evidence supporting more than one method for producing the structure.

Studies of the martensitic transformation in the Fe-Ni system have been made by several investigators[1,2,4,9,10,11]. By comparing the structure of the Tishomingo meteorite with those reported for man-made iron-nickel alloys, there appear to be at least two possible sequences of events that could have formed the martensitic microstructure observed. First, the meteorite may have experienced a very low temperature, below the M_S temperature, which is reported[5] to be about -90°C, during its journey through space. This would have resulted in normal transformation of the taenite to martensite. The data of Kaufman and Cohen[4] indicate that exposure to a temperature in the order of -185°C would result in a transformation to martensite of about 80 percent of the taenite, the amount observed. Second, the taenite may have transformed to martensite above the M_S as a result of stress inducement by shock pressures, perhaps due to celestial collisions. Kaufman and Cohen have shown that the martensite transformation can be induced by plastic strain to produce martensite above the M_S.

A study of the martensite morphology in the Tishomingo meteorite should be helpful in determining which of the two events caused the martensite transformation. Reed[10] discusses the martensite morphology of Fe-Ni alloys with nickel contents between 28.5 and 36 weight percent. Microstructures of the product of stress-induced transformation of Fe-35Ni alloys that he showed exhibit a striking resemblance of some of the martensite needles observed in the Tishomingo meteorite. On the other hand, many of the martensite needles observed in the Tishomingo meteorite resemble Reed's photographs of martensite in Fe-33Ni transformed spontaneously below the M_S on cooling to -130°C. These similarities suggest then that the transformation of taenite to martensite in the Tishomingo meteorite may have occurred by both (1) stress inducement, and (2) cooling to a temperature below the M_S; each event could have occurred at different times.

There have been several interpretations of the significance of the many striations observed in the martensite needles as seen in Figure 2. They may be mechanical twins that formed where one martensite needle penetrates another martensite needle, resulting in jogs in the trace of the mid-rib at the point of penetration. This has been described by Patterson and Wayman[8]. Reed suggests that secondary needles of this type are deformation twins or stacking fault clusters in the taenite which were induced and later consumed by the transformation. Possibly the striations are mechanical twins produced by a deformation event after a spontaneous martensite transformation, like a collison shock, causing a shear deformation of the mid-ribs and strain throughout the specimen. The smaller secondary needles may be stress-induced martensite resulting from the deformation event. The shorter striations which crossed some of the mid-ribs are believed to be the result of some other phenomenon, and may be internal martensite transformation twins which are illustrated and discussed by Patterson and Wayman.

The "pepper" appearance in the optical photomicrographs of the etched martensite needles and the unetched oxidized needles is believed to be evidence that the microstructure of the needles consists of two phases: the electron micrograph of Figure 3 also revealed a particle phase dispersed throught a matrix phase. Since martensite transformed from taenite is a single phase, the Tishomingo martensite must have been altered in some manner after its formation to produce the two phases observed. Consequently, we are technically in error to call this structure "martensite". The microstructural alteration of the "as transformed" Tishomingo martensite which produced the two phases may have been the result of (1) an incomplete reverse transformation of the martensite back to taenite, (2) decomposition of the martensite, or (3) an "aging" or "tempering" effect on the martensite. Several studies[3,5,6] have been made of the reverse transformation of martensite to taentie in the Fe-Ni alloy system. However, none of the martensite microstructures after reverse transformation shown by these studies resemble the Tishomingo martensite microstructures. Rather, the appearance of the Tishomingo martensite microstructure suggests that the original martensite was altered by decomposition or aging.

Martensite is a structure which is not in a state of equilibrium and may possess considerable internal stresses. From our present knowledge of the Fe-Ni alloy phase relationships, one would expect that the unstable condition of the martensite would promote its decomposition into a stable, heterogeneous mixture of taenite and kamacite (alpha iron) during long-time exposures within the temperature range of about 200 to 450°C, which is the approximate temperature range of the stabilized taenite and kamacite phases in a 32.5 percent Ni-Fe alloy. When one presumes that "time was no obstacle" for meteorite heat treatments in space, the martensite in the Tishomingo meteorite might have decomposed into two phases at ambient temperatures. An accurate description and understanding of the altered martensite microstructure will require positive identification of the two phases in the martensite needles.

The physical alteration of the inclusions suggests that they were remelted at some time and reacted to some extent with the surrounding matrix. A shock wave passing through the meteorite could conceivably have caused melting of the inclusions. The absence of martensite in a zone around some of the inclusions might be due to a composition gradient of Ni in the surrounding matrix which increases toward the inclusion.

SUMMARY STATEMENTS

There is considerable evidence in the microstructure of the Tishomingo meteorite that it experienced a shock event, probably through celestial collisions or during impact with the earth when it fell. Also, certain features of the microstructure can best be explained by considering that the meteorite was exposed to a low temperature, possibly in the order of -185°C. This evidence leaves us with numerous questions for which answers will be required before the historical events encountered by this meteorite are fully understood. For example: Was all, part, or any of the martensite transformation induced by strain resulting from a shock event? Assuming that the martensite transformation was strain-induced by the shock event, what combination of temperature and shock pressure must the Tishomingo have experienced to cause its structure to be 80 percent martensite and 20 percent taenite? Or is it possible that the Tishomingo meteorite first experienced cryogenic temperatures below the M_s, and that the shock event occurred after most or all of the martensite transformation? If this is so, then one might inquire what times and temperatures would be required to cause a decomposition of the Tishomingo martensite regardless of how it formed? Needless to say, additional studies of the Tishomingo meteorite are necessary to seek the answers to these and other questions concerning the Tishomingo microstructure.

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FIGURE CAPTIONS

1. Macrostructure of the Tishomingo meteorite metallographic specimens. Nital etch. 7½ X.
2. Coarse martensite needles with striations and mid-rib jogs. Nital etch. 100X.
3. Microstructure of the Tishomingo meteorite observed with the electron microscope. 23,600X.
4. Surface oxidation and oxidation penetration of martensite needles. As-polished. 100X.
5. Oxidation corrosion of martensite needles. As-polished. 500X.
6. Altered troilite-daubreelite inclusion. Picral etch. 500X.
7. Altered troilite inclusion. As-polished. 200X.
8. Altered troilite inclusion with a zone free of martensite surrounding it. Oblique illumination. 20X.

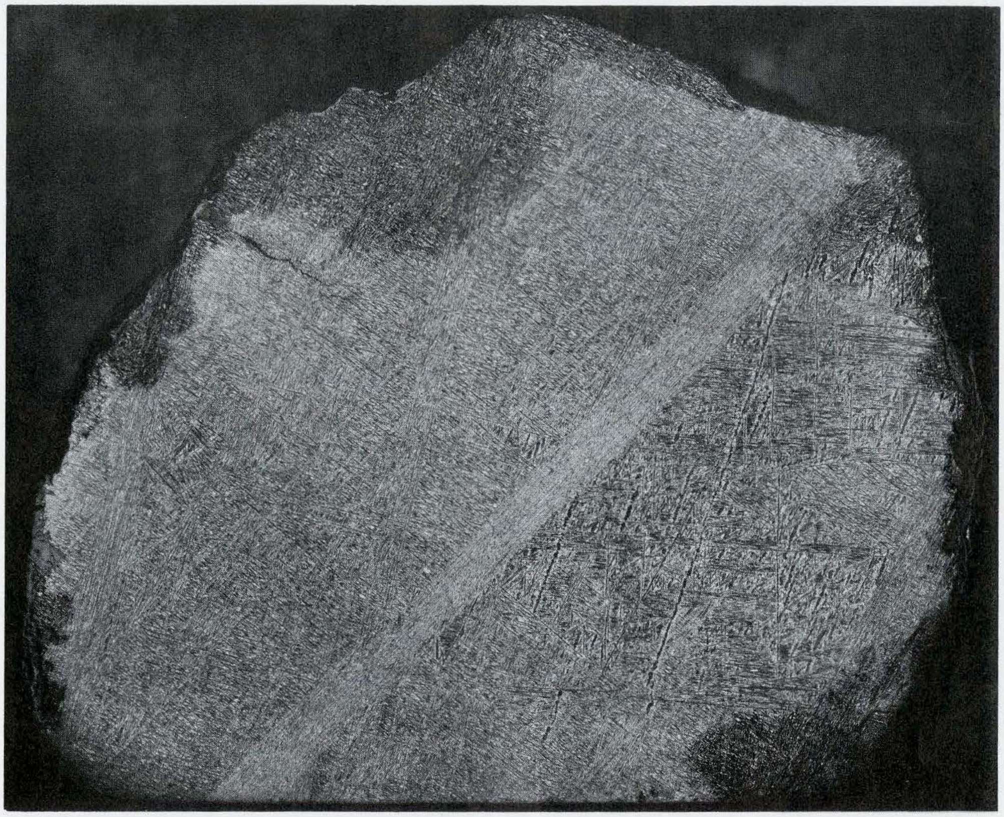

Figure 1

Figure 2

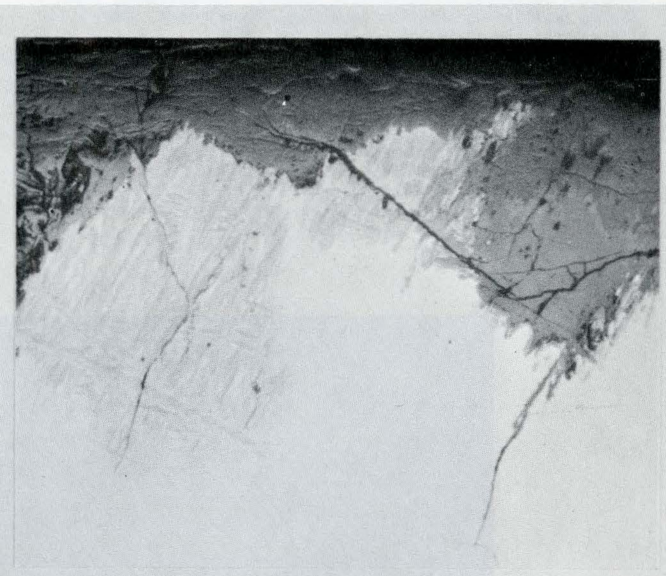

Figure 4

Figure 3

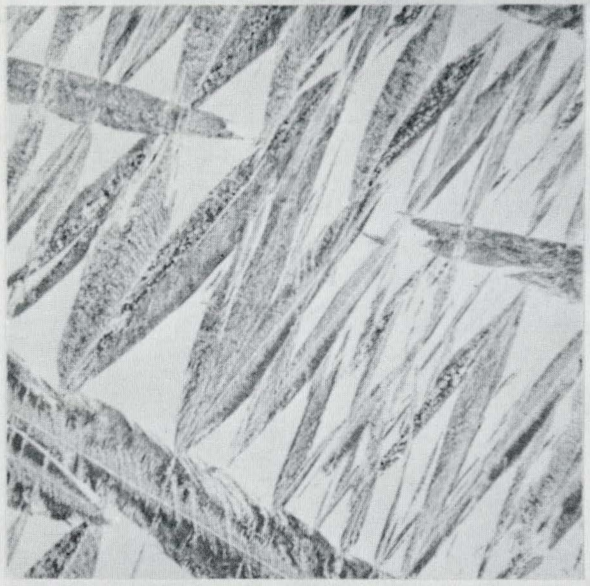

Figure 5

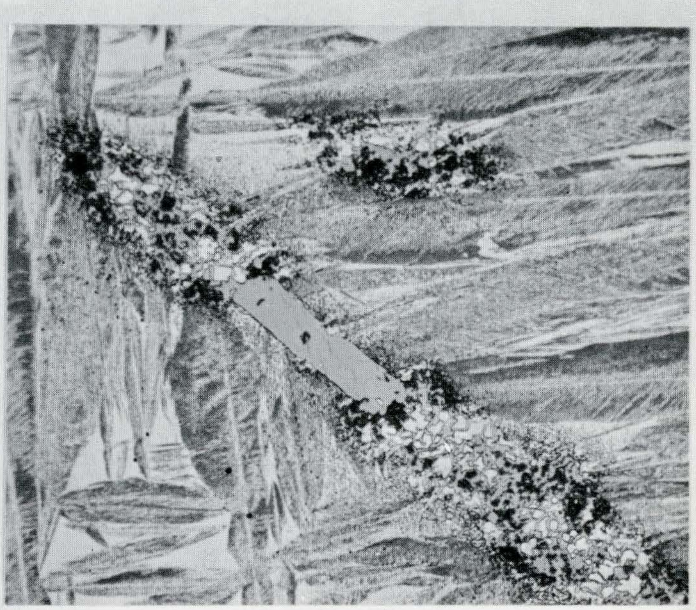

Figure 6

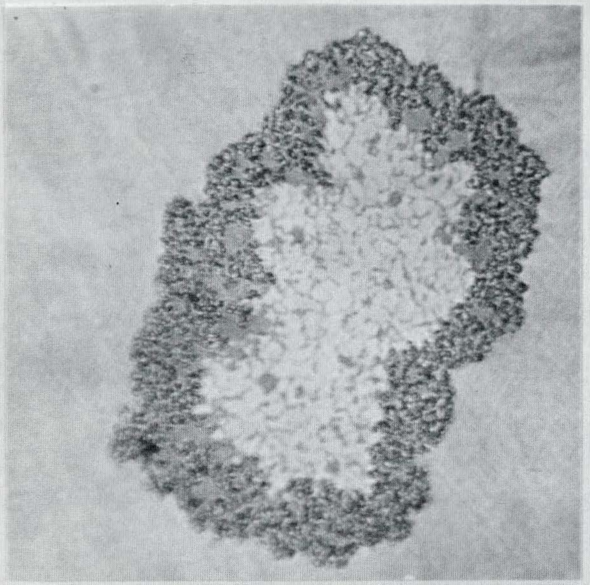

Figure 7

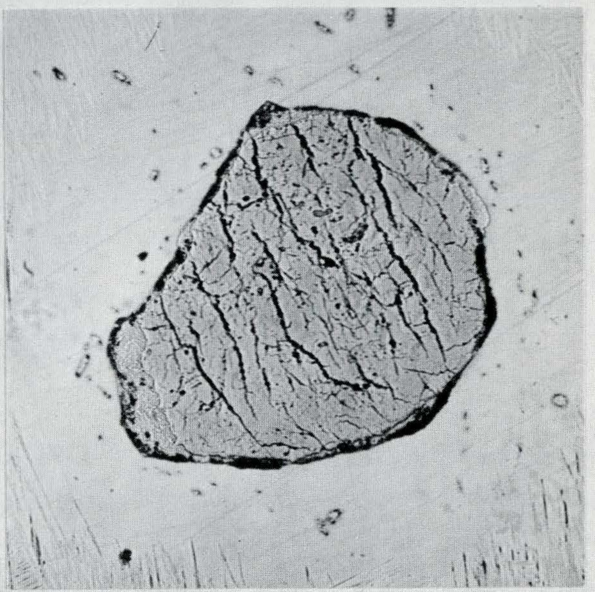

Figure 8