1973

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Recommended Citation

Galda, Edward J., "Solidification of high speed steels: the effects of Mo and W on the freezing process and eutectic carbide morphology" (1973). *Theses and Dissertations*. 4090.
https://preserve.lehigh.edu/etd/4090

SOLIDIFICATION OF HIGH SPEED STEELS: The Effects of Mo and W on the Freezing Process and Eutectic Carbide Morphology

by
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A Thesis

Presented to the Graduate Committee

of Lehigh University

in Candidacy for the Degree of

Master of Science

in

Metallurgy and Materials Science

Lehigh University

1972

This thesis is accepted and approved in partial fulfillment of the requirements for the degree of Master of Science.

May 20 1972
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ACKNOWLEDGEMENTS

The author would like to express his appreciation to his advisor, Dr. R. Wayne Kraft, for the guidance and direction of his studies and research at Lehigh. The assistance of Dr. J. I. Goldstein and Dr. R. H. Barkalow throughout this investigation was also very valuable and appreciated.

Financial support from the American Iron and Steel Institute, the assistance of Latrobe Steel Company with chemical analyses, and the supplying of materials by Universal Cyclops Steel Corporation and Bethlehem Steel Corporation are gratefully acknowledged.

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ABSTRACT

The effects of systematic variations in Mo and/or W content upon the freezing process and as-cast carbide morphology of high speed steels were studied for four series of alloys encompassing the nominal composition ranges of AISI type M2 (6W-5Mo-4Cr-2V) and M10 (0W-8Mo-4Cr-2V) high speed steels. Thermal analysis, metallographic examination, and quantitative metallography were used to characterize these effects. The liquidus, peritectic, and eutectic reactions were similarly influenced by molybdenum and tungsten, the peritectic temperature being strongly depressed by additions of either element. The types of carbides found in the as-cast structures did not vary, but the amount of feathery eutectic carbide (a layered structure of MC and M_6C) was directly related to the total Mo plus W content. The amount of isolated vanadium-rich MC type carbide was seen to increase as the amount of feathery eutectic decreased, and also varied with the Mo:W ratio. M2 and M10 high speed steels are similarly alloyed and contain an equal atomic amount of Mo plus W. A series of alloys ranging between the M2 and M10 compositions contained similar volume percentages of feathery eutectic, but M10 had 2½ times more isolated MC in its as-cast structure than M2.

This result is in good agreement with investigations performed on annealed and hardened steels and shows that some correlation exists between as-cast and thermomechanically processed structures.

BACKGROUND

Carbides in High Speed Steels

Retention of wear resistance and hardness at high temperatures is a defining characteristic of high speed steels. A fine dispersion of hard excess carbides allows finished tools to exhibit this quality.

The three principal carbides which are present in high speed steels are the face-centered cubic M_6C, $M_{23}C_6$, and MC type carbides.[1-5] M_6C is a complex W-Mo carbide which can vary in composition from Fe_4W_2C to Fe_4Mo_2C or Fe_3W_3C to Fe_3Mo_3C; Cr and V are soluble in this phase. During hardening M_6C is partially dissolved, resulting in alloying of the austenitic matrix and the presence of excess carbides that impart wear resistance to the hardened material. In the annealed state, high speed steels contain $M_{23}C_6$. This chrome-rich carbide, which can dissolve Fe, W, Mo, and V, is readily solutioned at high temperatures and is not present in the steel after hardening. The vanadium-rich MC carbide (VC or V_4C_3), containing limited amounts of other elements, is an extremely hard carbide. It is not dissolved during austenitization and helps inhibit grain growth and impart wear resistance in high speed steels.

Since M_6C, $M_{23}C_6$, and MC each have different effects upon the heat treating response and final properties of high speed steels, the amount and morphology of these three carbides is a factor of important concern to users of tool steels. M_6C and MC are both products of the solidification reactions in high speed steels, and for this reason the as-cast structure plays a key role in the overall performance of these ferrous materials.

Solidification of High Speed Steels

The freezing process in both T (tungsten) and M (tungsten-molybdenum and molybdenum) tool steels has been the subject of previous research.[6-10] That most directly pertinent to this work is the work of Barkalow on AISI type M2 (6W-5Mo-4Cr-2V) tool steel. By means of thermal analysis and systematic metallographic observations Barkalow detected three major reactions during solidification:

1. At approximately 1435C primary crystallization of delta ferrite occurs.
2. A peritectic reaction starting at 1330C produces austenite and some carbides from the liquid and ferrite.
3. The peritectic reaction does not go to completion, and by 1240C the remaining interdendritic liquid has decomposed into a eutectic mixture of austenite, M_6C, and MC.

Any delta ferrite not consumed by the peritectic undergoes a eutectoid decomposition into austenite and M_6C below the solidus temperature.[8,11] This freezing process is consistent with the results of earlier work by Hoyle and Ineson[12] and a more recent study by Brandis and Wiebking.[13]

In addition to the three principal reactions just described, a small but obvious slope change was observed about 20°C above the solidus temperature on a cooling curve. Brandis and Wiebking interpreted this deflection as indicating a peritectic four phase reaction, whereas Barkalow, et. al., associated the slope change with the crystallization of MC carbides. The reaction which occurs at the 1240C solidus temperature would then correspond to the eutectic decomposition of the last remaining liquid into austenite and M_6C.

As-Cast Microstructure of High Speed Steels

The typical as-cast structure of a high speed steel consists of areas of delta eutectoid reaction by-products separated from interdendritic eutectic by a band of austenitic or martensitic matrix.[8,9,12] While the presence of eutectic is characteristic of these materials, its morphology is strongly influenced by the alloy composition.

Geller and Mininzon[14] have noted that three types of eutectic occur in high speed steels. The high tungsten alloys such as 18-4-1 are characterized by a skeletal or herringbone eutectic carbide morphology. Selective etching and microanalysis have identified this phase as being W-Mo-rich M_6C.[9,10] A fan-shaped or feathery eutectic is typical of the tungsten-molybdenum and molybdenum grades such as M2.[15] High magnification examination of these carbides, along with their selective etching response and microanalysis, indicates that they are a layered structure of MC and M_6C.[10] A mixture of MC and austenite or isolated particles of MC is the third morphology common to most high speed steels. The amount of this carbide present is strongly dependent upon vanadium content.

The aim of thermo-mechanical processing is to remove any remnants of the as-cast interdendritic network and to give an end structure of uniformly dispersed fine carbides. The initial eutectic morphology influences the final structure, and hence the properties, of the steel. Differences in the types of carbides present and the ease with which they can be broken up and dispersed will therefore have an effect on the quality and performance of finished tools. The feathery eutectic carbides are compositionally different from the herringbone carbides and also are known to give a more desirable final structure.[14]

Replacement of Tungsten in High Speed Steels by Molybdenum

Historically, the M grade steels were developed from the T grades when some or all of the W in these alloys was replaced by Mo. This was initially done for economic reasons, but the advent of better heat treating facilities brought wider acceptance of the M steels. At the present time, the W, W-Mo, and Mo type high speed steels are all in common usage. Being comparably alloyed on an atomic basis, these grades are similar in properties and cutting performance and often can be used in place of one another.[4,5,7,15]

This interchangeability of Mo and W can be accounted for on several bases. The Fe-Mo-C and Fe-W-C ternary diagrams are similar, and Mo and W can readily replace each other in various carbides. On an atomic basis, 1 wt. % Mo can substitute for 1.92 wt. % W, while 1% Mo is equivalent to 1.3% W in its effect on the austenite field of Fe.[4,6,7,9,16,17]

While molybdenum is used as a common replacement for tungsten in high speed steels, this substitution does result in some microstructural changes. It appears that Mo does not compete with V for C as well as W does, and as Mo replaces W the ratio of MC to M_6C type carbide increases.[1,2,15,18]

In the hardened state, AISI type M2 (6W,5Mo) and M10 (0W,8Mo) tool steels both contain MC and M_6C as excess carbides. MC comprises 39% of the excess carbide in M10 and only 15% in M2.[4] Considering the difference in the effects of MC and M_6C on the properties of high speed steels, the Mo:W ratio can have a significant bearing on the structure and performance of these alloys.

Purpose of this Research

The objective of this research is to study the effects of molybdenum and tungsten on the solidification reactions and as-cast structure of high speed steels. AISI type M2 and M10 tool steels are the alloys chosen for this study. The basis for this choice is that these two grades are very similar in composition except that the W in M2 is replaced by an equal atomic amount of Mo in M10.

By systematically varying the W and Mo contents, the individual effects of these alloying elements can be determined. These results may then be used to help understand the changes that occur as the Mo:W ratio is varied in a series of alloys between the M2 and M10 nominal compositions.

MATERIAL

The AISI type M2 high speed steel used in this work was supplied by the Universal Cyclops Steel Corporation. This alloy was in the form of 5/8" diameter bars which had been conventially processed from a commercial ingot. The heat analysis of the material was 0.82% C, 6.11% W, 4.95% Mo, 4.18% Cr, 1.88% V, 0.009% S, 0.020% P, 0.26% Mn, 0.31% Si, 0.20% Ni, 0.17% Co, 0.08% Cu, and 0.021% Al.

Homer Research Laboratories of Bethlehem Steel Corporation provided a 300 lb. heat of an alloy made to M2 specifications but without tungsten. This material, designated Alloy X, had a ladle analysis of 0.91% C, 0.0% W, 4.82% Mo, 3.91% Cr, 2.02% V, 0.017% S, 0.008% P, 0.28% Mn, 0.35% Si, 0.06% Ni, 0.04% Co, 0.02% Ti, and 0.005% Al. It was hammer forged into ½" square bars.

Some compositional variations used in this work required the addition of elemental molybdenum to M2 or Alloy X remelt stock. Compressed powder pellets of 99.9% pure Mo were used for this purpose.

EXPERIMENTAL TECHNIQUES

Compositional Variations

Figure 1 is a schematic representation of the range of alloys studied in this work. AISI type M2 and M10 high speed steels correspond to the alloy compositions in the upper left and lower right corners of the diagram, respectively. By blending various amounts of Alloy X (0W, 5Mo), M2, and/or elemental Mo, four series of alloys corresponding to lines (1), (2), (3), and (4) in the schematic were prepared. Thermal analysis and metallographic investigations were performed on all four alloy series. The results from series (1) and (3) were used to determine the effects of Mo variations on the solidification process in high speed steels. The effects of W were studied in series (2), and series (4) alloys dealt with variations in the Mo:W ratio of the M2 and M10 steels.

In order to avoid any errors due to deviations from the desired alloy compositions, all thermal analysis samples were analyzed for the major alloying elements (C, W, Mo, Cr, and V) prior to being examined metallographically.

Thermal Analysis

Thermal analysis was used to study the effects of systematic variations in W and/or Mo content on the freezing process in high speed steels. The accuracy of the technique employed was checked by determining cooling curves for materials with known solidification temperatures (pure Ni and Ni-Ni_3Nb eutectic). These results were found to be in good agreement with published data, thus implying that the results determined for the high speed steel alloys were also accurate. The procedure that was used is described below.

Samples weighing approximately 30 grams were placed in 16 mm ID alumina crucibles. The thermal analysis crucible was placed inside a larger crucible and insulated on the bottom and sides by loosely-packed Micro-Quartz felt. A boron nitride cap was placed on top of the crucible. After being flushed with argon and evacuated to about 100 microns of Hg, the sample chamber was filled to a positive pressure of argon. Induction heating was used to superheat the sample to about 1550C. Then by decreasing the inductive power, the specimen cooled through the freezing range at roughly $100^{o}C$ per minute. A silica-encapsulated 38 guage Pt-Pt10%Rh thermocouple with one wire insulated by fine alumina tubing was immersed in the sample and connected to an adjustable-range adjustable-zero strip chart recorder. By setting the recorder scale at 11-16 mV, a time-temperature chart for the entire freezing range of the alloy was determined. Samples were remelted and allowed to freeze several times, the reaction temperatures being recorded for each run. Results for different runs on the same sample and for different samples of the same composition were found to be in close agreement. Typical cooling curves are presented and discussed in a later section.

Metallography

After being sectioned and chemically analyzed, each thermal analysis sample was metallographically prepared. Polishing was done by standard techniques using 6 micron and 1 micron diamond compounds in order to avoid any severe relief effects. The selective etching techniques developed by Blickwede, et. al.,[3] were then utilized to identify the various eutectic carbides in the as-cast structure. Particular attention was paid to the amounts and types of carbides that were present.

In order to ascertain the effect of the Mo:W ratio on the relative amount of isolated MC carbide in the as-cast structures of M2 and M10 high speed steels, quantitative metallography was performed on the series (4) alloys. Similar data was also gathered for Alloy X. Using an optical metallograph and a magnification of 1600X, a nine-point grid was systematically placed on the polished surface of each sample a total of 1,600 times, care being taken to uniformly cover the entire specimen cross section. For each placement, the number of grid points falling on isolated MC carbides and the number falling on feathery eutectic colonies were noted. The volume percentages of MC and of feathery eutectic were calculated by dividing the total number of grid points landing on a given structural feature by 14,400 (the total number of points counted). The standard deviation for the data entries was calculated, and using common statistical techniques[19,20] the standard error and 95% confidence interval for each volume percentage were determined.

PRESENTATION AND DISCUSSION OF RESULTS

Thermal Analysis

Employing thermal analysis techniques described in the preceding section, effects of Mo and/or W variations upon the solidification process in high speed steels were investigated. Cooling curves were determined for samples from the four alloy series studied in this work, and a pseudo-binary phase diagram was plotted for each series. These results were also of use in interpreting the as-cast microstructures of thermal analysis samples.

M2, Alloy X, and M10 Cooling Curves

The three principal materials whose compositions are end points for the four alloy series under consideration are M2 (6W,5Mo), Alloy X (0W,5Mo), and M10 (0W,8Mo material artificially prepared by adding molybdenum to Alloy X). Thermal analysis results indicate that the freezing process is essentially the same for all three alloys.

A cooling curve typical of nominal composition M2 high speed steel is presented in Fig. 2a. Four solidification reactions, as determined by Barkalow, et. al.,[9,10] are evident in the figure. Clearly defined breaks in the cooling curve at 1425C, 1325C, and 1242C correspond to primary crystallization of delta ferrite, peritectic reaction of liquid and ferrite to form austenite, and eutectic decomposition of the last-remaining liquid, respectively. The slope change which occurs about 20°C above the eutectic break marks the precipitation of vanadium-rich MC type carbides from the melt.

The same four reactions are evident in cooling curves for Alloy X and M10 (Fig. 2b and 2c) and occur in the same order as they do for M2. The primary difference between M2 and Alloy X is that, for the latter, the peritectic reaction temperature is 60°C higher than that of M2 and the eutectic temperature is 52°C lower. (Reasons for this difference will be discussed when the series (2) pseudo-binary phase diagram is presented.) The only difference between the M2 and M10 cooling curves appears to be that the four reaction temperatures are lower for M10.

Series (1) Alloys

In series (1), systematic additions of pure molybdenum to M2 remelt stock were used to determine the effects of this element upon the solidification process. Referring to Fig. 3, it can be seen that increasing the Mo content from 4.95% (nominal M2) to 7.64% results in only a slight depression of the liquidus but causes a marked decrease in the peritectic reaction temperature (1325C in Fig. 3a and

1251C in Fig. 3b). In fact, at higher Mo contents, the peritectic reaction (barely visible in Fig. 3b) is seen to occur between the slope change and eutectic, the latter two reaction temperatures having remained relatively constant. A further increase in Mo content to 8.08% results in a continued depression of the liquidus temperature to a final value of 1408C (see Fig. 3c). The peritectic reaction appears to be eliminated due to ferrite stabilizing effects of Mo, and the slope change and eutectic temperatures are depressed slightly.

A pseudo-binary phase diagram summarizing thermal analysis data for the series (1) alloys is presented in Fig. 4. The following trends should be noted:

1. The major effect of additions of Mo to M2 remelt stock is a strong depression of the peritectic reaction temperature (L+F→A). The peritectic decreases 28°C per % Mo added and seems to be eliminated at about 8% Mo. This result would be expected since molybdenum has a b.c.c. structure and would tend to stabilize ferrite while retarding the formation of f.c.c. austenite.

2. Mo additions slightly depress the liquidus temperature (L→F), but primary crystallization of

delta ferrite still occurs in all series (1) alloys.

3. The other two main steps in the freezing process, L→MC at the slope change and L→A+M_6C at the eutectic temperature, appear to be essentially unaffected, and the temperature gap between the two reactions is about 20°C for all of these samples.

Series (2) and (3) Pseudo-Binaries

The series (2) and series (3) pseudo-binary phase diagrams will be presented and discussed together. Each series contains the 0% W, 5% Mo Alloy X which can be thought of as either M2 without tungsten or a low-molybdenum M10 alloy. Molybdenum and tungsten, both being b.c.c. transition elements in the Cr subgroup of the periodic table, should on an atomic basis be similar in their effects upon the solidification process of Alloy X.

The series (2) pseudo-binary, determined from thermal analysis results for samples that were a mixture of M2 and Alloy X remelt stocks, is presented in Fig. 5. By mixing pure Mo and Alloy X, analogous results were determined for the series (3) alloys (see Fig. 6). From these two graphs the effects of Mo and of W are seen to be both qualitatively and quantitatively similar:

1. The liquidus temperature is not strongly altered by

additions of either element. In series (2) L→F stays constant at 1430C, while in series (3) it decreases gradually as the % Mo increases (1432C for Alloy X and 1413C for M10).

2. In a manner similar to that seen for Mo in the series (1) alloys, both Mo and W additions cause a strong lowering of the peritectic reaction temperature. Quantitatively, this ferrite stabilizing effect is a depression of 9°C per wt. % W and 20°C per wt. % Mo. Accounting for the large difference in the atomic weights of W and Mo (a factor of 1.92), a given Mo addition decreases the peritectic reaction temperature only 10% more than an equivalent atomic amount of W.

3. From Fig. 5 and 6 it can be seen that additions of either Mo or W increase the eutectic temperature. Since these two metals are predominant elements in the M_6C carbide, it seems logical that their increased presence would tend to raise the temperature at which the eutectic reaction ($L \rightarrow A+M_6C$) occurs.

4. The slope change temperature is decreased by adding Mo, but remains constant as % W is varied.

5. An overall effect of Mo or W additions is to decrease the temperature difference between the L→MC

and L→A+M_6C reactions. This gap is about 50°C greater for Alloy X than it is for either M2 or M10 (a fact that will later be used to help interpret differences in the as-cast microstructures of these samples).

Series (4) Pseudo-Binary

The series (4) alloys were studied to determine the effects of replacing tungsten in nominal composition M2 with molybdenum. When W is totally replaced by Mo, the resulting alloy falls in the nominal composition range of AISI type M10 high speed steel. The parameter (wt. % Mo) ÷ (wt. % Mo + wt. % W) is used as a measure of the extent of substitution, a value of 1 signifying total replacement of W.

Since primary interest in the series (4) alloys was in their as-cast structures, and since cooling curves for M2 and M10 have been presented (Fig. 2), there is no need to discuss these thermal analysis results in any detail. The solidification process is alike for M2 and M10, and the only effect of increasing the relative amount of molybdenum appears to be slight downward shifts in each of the four reaction temperatures. The reader is referred to Fig. 7 for a summary of this data.

Metallography

All thermal analysis samples were metallographically examined to determine how compositional variations affect the as-cast microstructure. No marked changes in interdendritic spacing were evident, so particular attention was paid to the amount and morphology of eutectic carbides. Quantitative metallography was performed on the series (4) alloys and Alloy X.

Series (1) Alloys

The typical as-cast structure of M2 high speed steel is seen in Fig. 8a. Small amounts of delta eutectoid reaction by-products (not evident in the picture because of the type of etchant used) are contained in an austenitic or martensitic matrix. Two types of interdendritic carbides are evident in the structure. Several isolated MC particles (denoted by arrows) are dispersed in a larger amount of darkly-stained feathery eutectic carbides.

Molybdenum is a major element in both the M_6C carbide formed by eutectoid decomposition of delta ferrite and the feathery eutectic carbide typical of as-cast M2. In the series (1) alloys the type of interdendritic eutectic does not vary, but from the photomicrographs in Fig. 8 it is apparent that the feathery carbides become finer with greater Mo additions. It also seems that the amount of eutectic increases slightly, less isolated MC particles are noticeable, and there is a substantial rise in the amount of dendritic precipitation. Thermal analysis results showed Mo to be a ferrite stabilizing element, so the samples of higher alloy content are expected to contain more matrix carbides resulting from eutectoid decomposition of delta ferrite.

The fact that extensive dendritic precipitation is seen in Fig. 8c implies that a peritectic reaction did occur during solidification of the 8.08% Mo material. A surrounding envelope of high carbon austenite is necessary to supply carbon to decomposing delta ferrite.[10,11] Although thermal analysis of this sample did not reveal a peritectic break in the cooling curve (Fig. 3c), this solidification reaction may have occurred so close to the eutectic or may have involved so little material that it was not evident in thermal analysis results.

Series (2) and (3) Alloys

As opposed to the series (1) study, which deals with alloy additions to M2, the series (2) samples range from nominal composition M2 to an M2 alloy with the tungsten totally removed. Thermal analysis results show that the gap between the slope change and eutectic temperatures is much greater for 0% W material (Alloy X) than it is for nominal

M2 (see Fig. 5). For any given cooling rate, the size of this gap is related to the time available for MC carbides to form before the L→A+M_6C reaction consumes the last-remaining interdendritic liquid.

Microstructures of three series (2) samples are shown in Fig. 9. The amount of feathery carbides decreases as lower tungsten contents retard the formation of M_6C. The MC particles normally in the feathery eutectic thus become visible in the structure. The resultant trend is a decrease in the total carbide volume but an increase in the amount of vanadium-rich MC as the alloy composition varies from M2 (6W,5Mo) to Alloy X (0W,5Mo). From quantitative metallography, nominal composition M2 (Fig. 9a) was found to contain 8.25±0.63 vol. % feathery eutectic. (Volume percentages are given with 95% confidence limits.) Isolated MC carbides, which were not stained by alkaline $KMnO_4$ and thus appear lighter than the feathery carbides, comprised only 0.21±0.07 vol. % of the sample. The most apparent change brought about by decreasing the W content from 6.35% to 2.10% is a large increase in the amount of MC in the as-cast material and a tendency for this carbide to be in a eutectic structure of its own (Fig. 9b). In Alloy X (Fig. 9c), the amount of feathery eutectic is 3.39±0.36 vol. %, and there is 1.21±0.20 vol. % MC. The result of removing tungsten from M2 is thus a large increase in the amount of isolated MC (0.21 vs. 1.21 vol. %), a reduction in the volume fraction of feathery eutectic (8.25 vs. 3.39 vol. %), and an accompanying decrease in the amount of feathery carbides and M_6C.

Comparing Fig. 9 and 10, microstructural trends in the series (2) samples appear to be very similar to those for series (3). Since Mo and W supposedly are interchangeable in high speed steels, increasing the molybdenum content of Alloy X from 5.08% to 8.26% amounts to a replacement of the tungsten in M2 with an equal atomic amount of molybdenum. Quantitative data shows that M10 contains 7.98±0.60 vol. % feathery eutectic and 0.54±0.12 vol. % MC. Recalling that Alloy X has 3.39 vol. % feathery eutectic and 1.21 vol. % MC, it is clear that these two elements, at least in this particular case, are alike in their effects upon the as-cast structure of high speed steels.

Series (4) Alloys

Conclusions regarding microstructural effects of molybdenum and tungsten have to this point been derived solely from results for samples in which total alloy content varies. The series (4) samples were prepared by mixing various proportions of M2 and M10. In this manner, the atomic amount of molybdenum plus tungsten is kept constant, and structural trends can be determined for samples having equivalent alloy contents. Since it is known that the ratio of MC to M_6C type carbides in annealed or hardened high speed steels increases as W is replaced by Mo,[1,2,4,15,18] a similar trend should be seen in the as-cast microstructures of series (4) alloys. Due to the fact that the feathery eutectic carbides are a mixture of MC and M_6C and they had too fine a structure to be counted by the quantitative metallography method employed in this work, the actual MC:M_6C ratio could not be determined for these samples. Instead, volume percents were established for isolated MC carbides and feathery eutectic colonies. This data in itself should be helpful in understanding the source of various carbides in commercially processed tool steels.

Microstructures for M2, M10, and two alloys of intermediate composition are presented in Fig. 11. There appears to be no difference in interdendritic structure except that as the Mo:W ratio increases more isolated MC carbides are present. Results of quantitative metallography show no statistical difference in the amount of feathery eutectic. M2 contains 8.25±0.63 vol. %, and M10 has

7.98±0.60 vol. %. There is a significant variation in the amount of MC. Data presented in Fig. 12 shows that, as the amount of Mo relative to the total amount of Mo and W increases from a value of 0.44 for M2 to a value of 1.0 for M10, the amount of isolated vanadium-rich MC carbides in the as-cast structure increases by a factor of 2½ (from 0.21±0.07 vol. % in M2 to 0.54±0.12 vol. % in M10).

Due to carbide formation during solid state transformations, annealed high speed steels contain much more MC and M_6C than the as-cast material.[5] Although the quantitative results of this work do not account for all of the carbides in commercially processed M2 and M10, they at least show that some correlation exists between trends seen in these solidification structures and those that were determined by other investigators for thermo-mechanically processed material.

SUMMARY AND CONCLUSIONS

All the high speed steel alloys whose compositions fall within the range demarcated by 0% W-5% Mo, 6% W-5% Mo (AISI type M2), 6% W-8% Mo, and 0% W-8% Mo (AISI type M10) exhibit basically the same freezing process and as-cast microstructure.

Mo and W were found to have similar effects upon the solidification process in high speed steels. The four main freezing reactions and the order in which they occur for most of the alloys are:

1. Liquid→Ferrite
2. Liquid+Ferrite→Austenite
3. Liquid→MC
4. Liquid→Austenite+M_6C

The peritectic reaction (number 2) is strongly depressed by an increase in either W or Mo content and will occur at temperatures below that of the third reaction in highly alloyed samples (6% W and greater than 7% Mo). The temperature gap between the third and fourth reactions is related to the time available for formation of MC carbides and is much greater in the low alloy content samples such as the 0% W-5% Mo material than it is for the other compositions.

The feathery eutectic morphology typical of as-cast M2 was found to be typical of the other alloy compositions. Since these carbides contain MC and W-Mo-rich M_6C, increasing the amount of either alloying element increases the amount of feathery eutectic, and at low W plus Mo contents vanadium-rich MC type carbides are much more evident in the as-cast structure. Replacing the W in M2 with an equal atomic amount of Mo to make M10 does not change the amount of feathery eutectic, but the amount of isolated MC particles in the as-cast structure of M10 is more than twice the amount found in M2. Molybdenum is thus seen not to compete for carbon with vanadium as strongly as tungsten does, resulting in more VC forming in the presence of high Mo than high W.

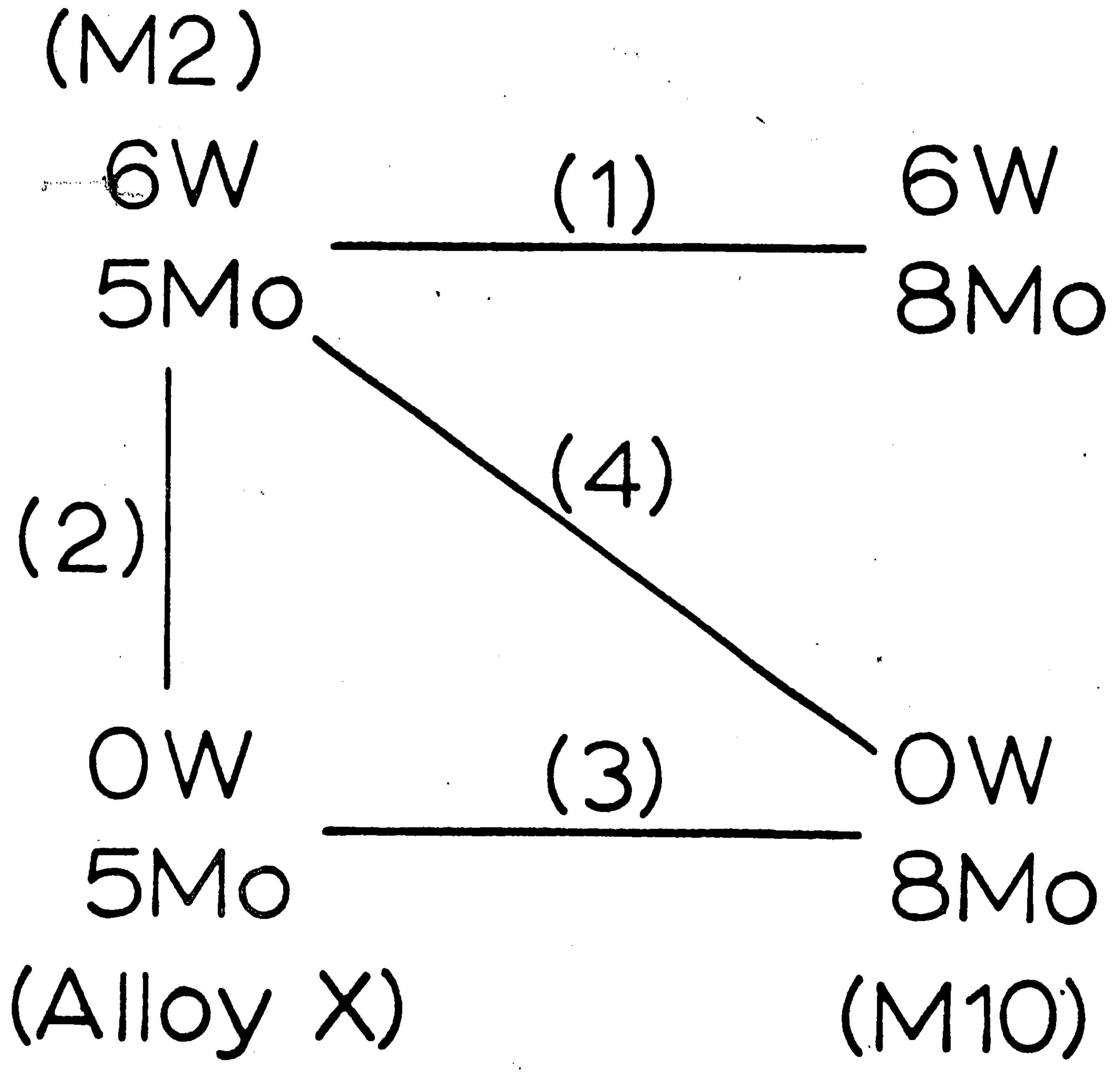
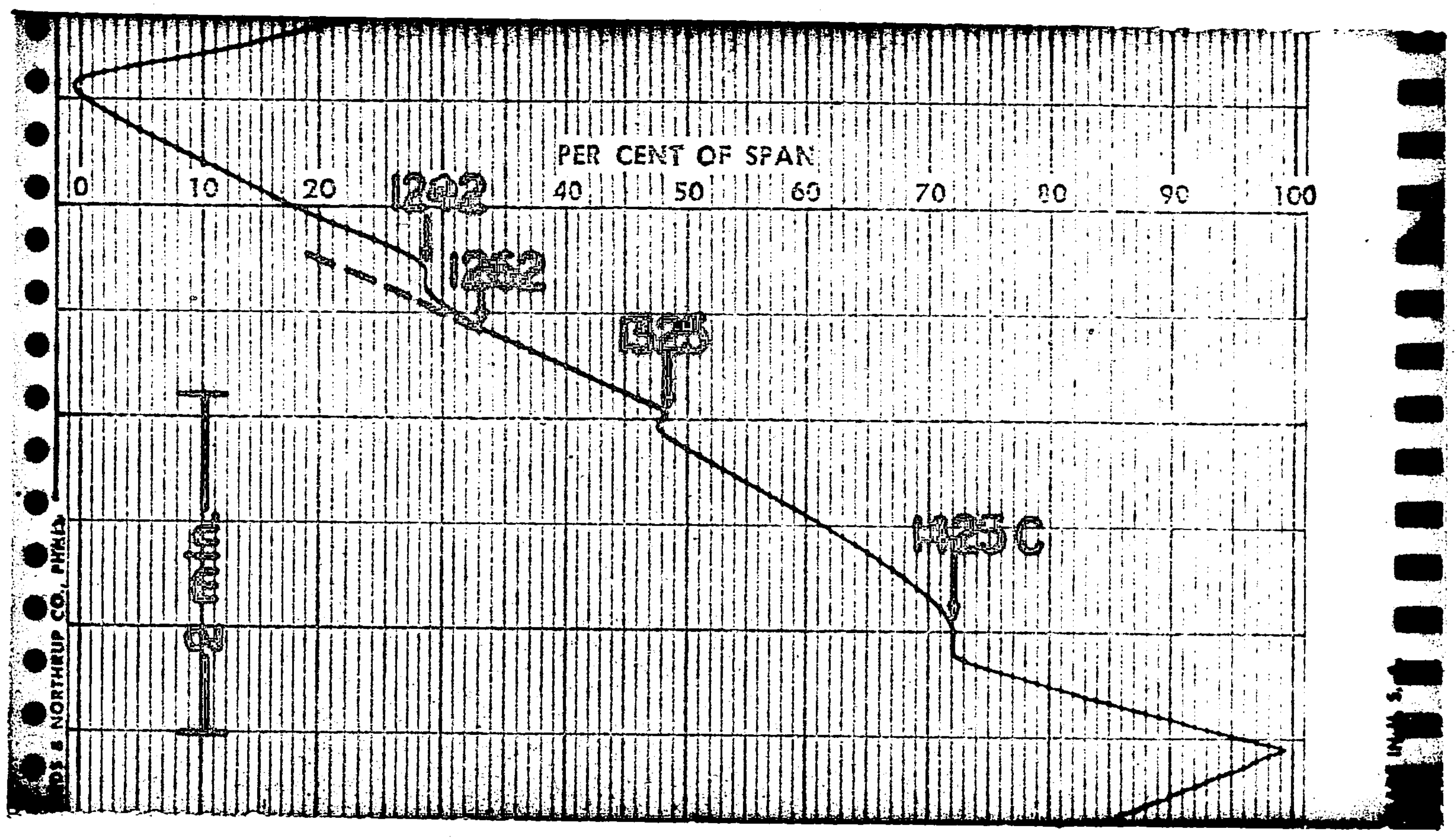
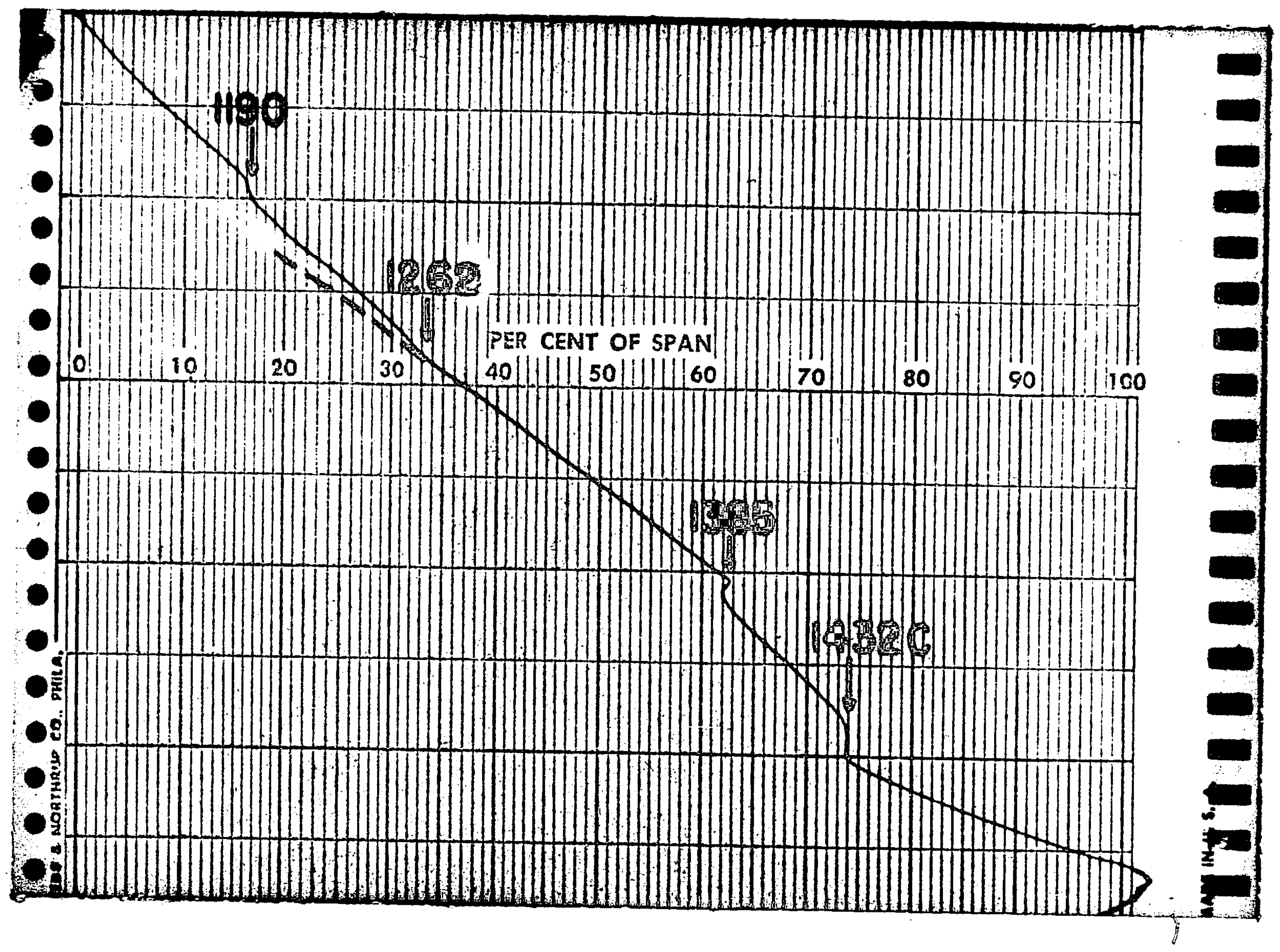


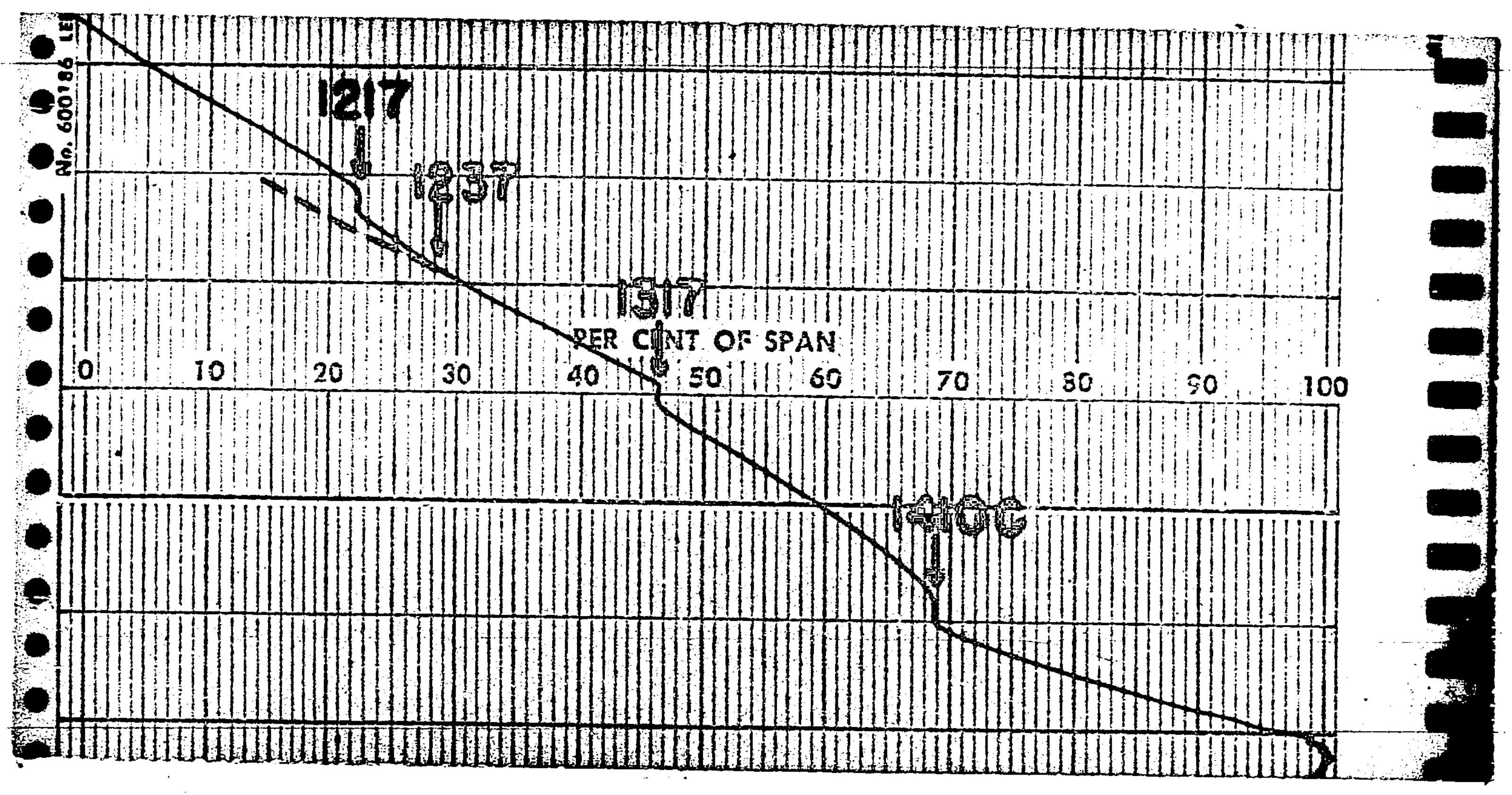
Fig. 1: Schematic of the alloy compositions that were investigated.



2a: Nominal M2
(4.95% Mo
6.35% W)

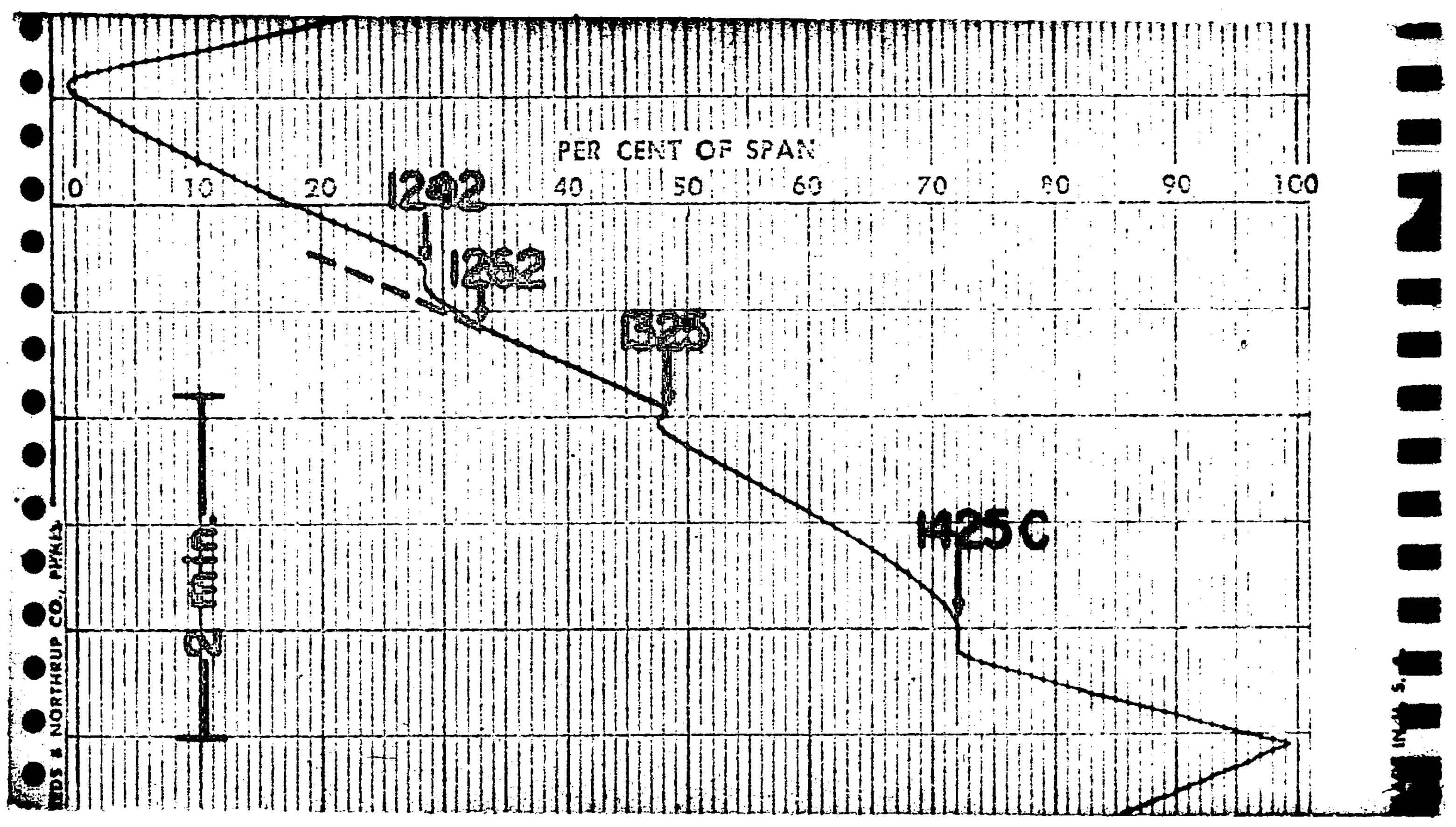


2b: Alloy X
(5.08% Mo
0.0% W)

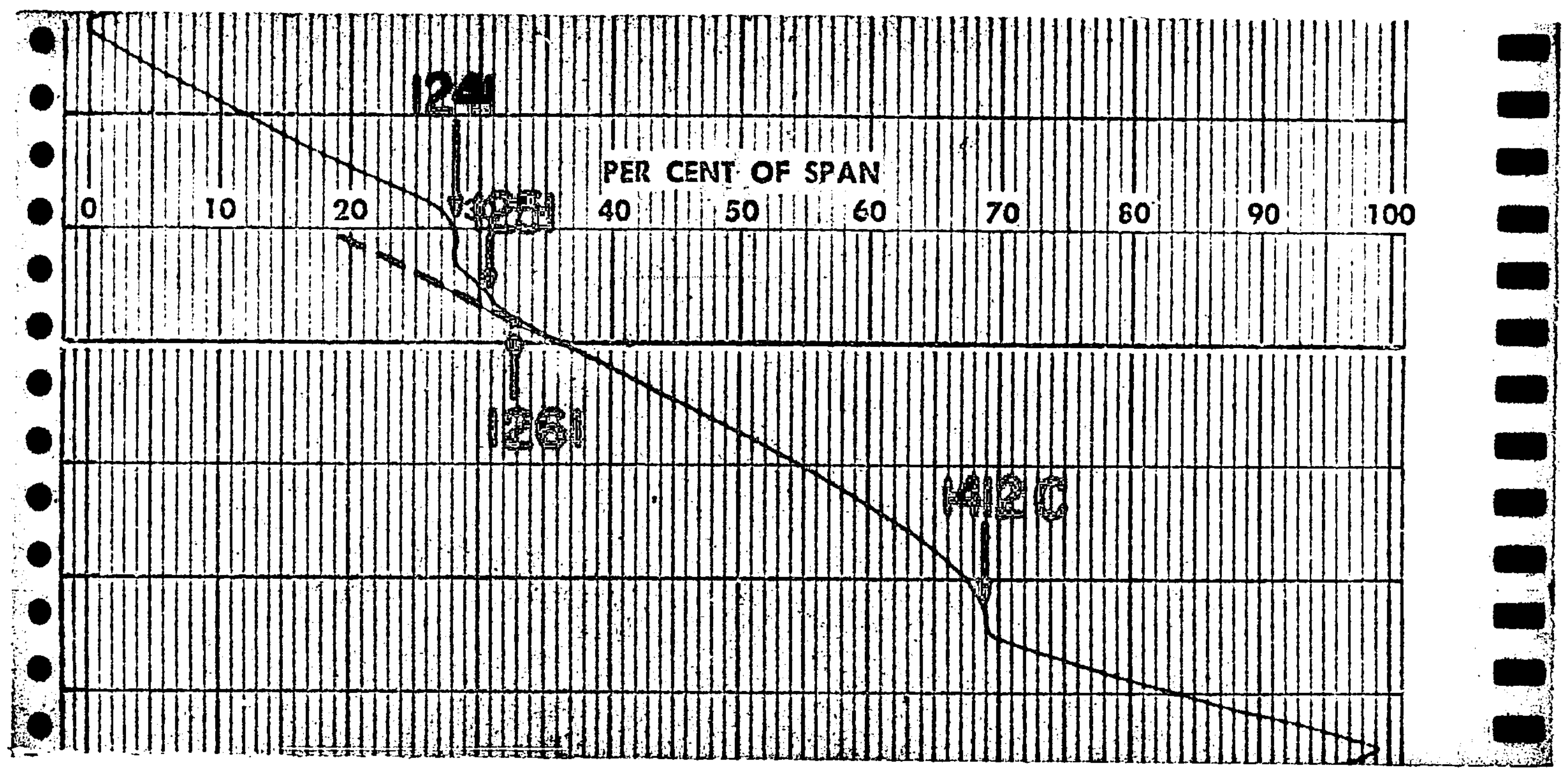


2c: Nominal M10
(8.26% Mo
0.0% W)

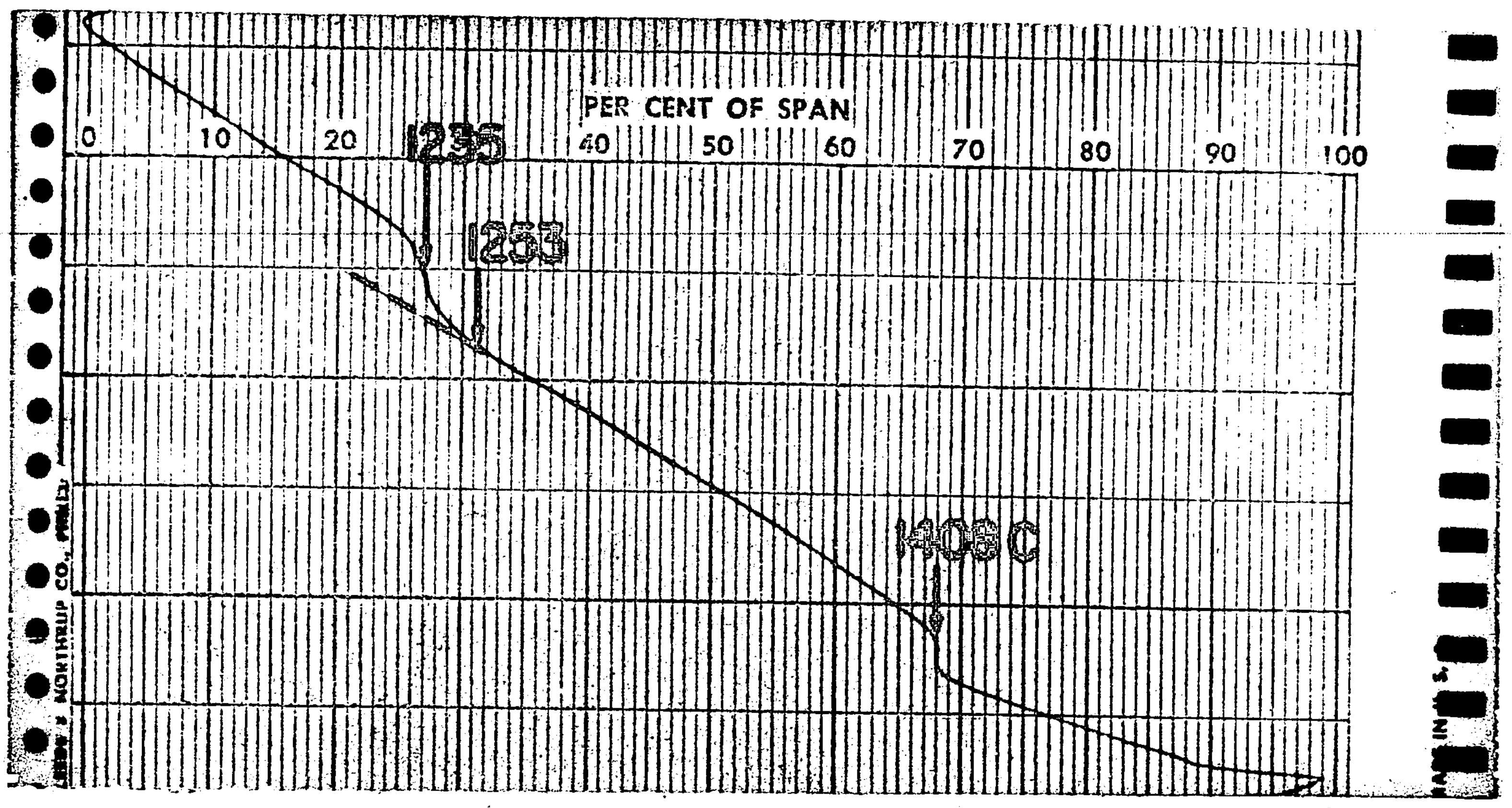
Fig. 2: Cooling curves for M2, Alloy X, and M10.



3a: Nominal M2
(4.95% Mo
6.35% W)



3b: 7.64% Mo
6.26% W



3c: 8.08% Mo
6.23% W

Fig. 3: Cooling curves for three series (1) alloys.

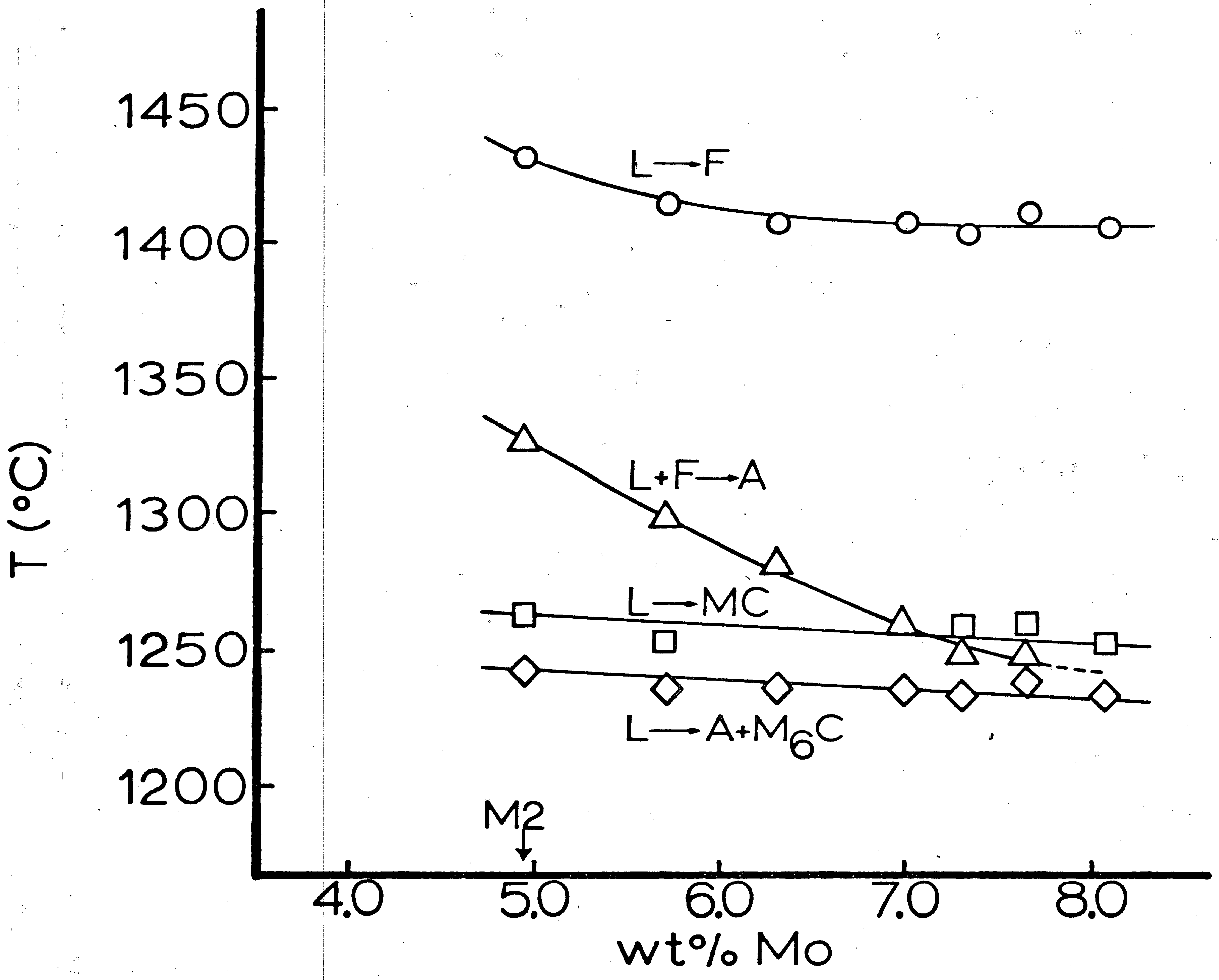


Fig. 4: Pseudo-binary for series (1) alloys.

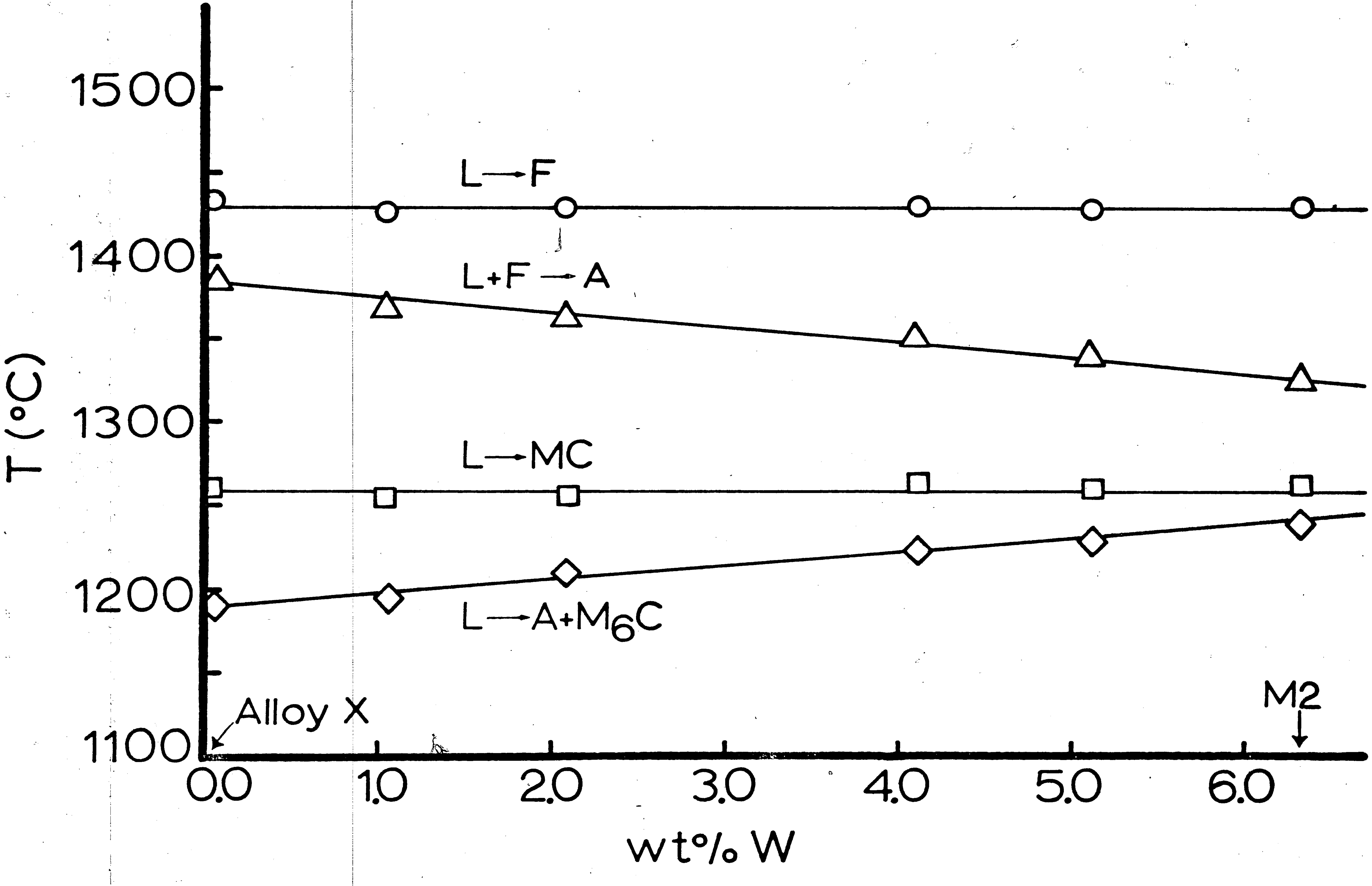


Fig. 5: Pseudo-binary for series (2) alloys.

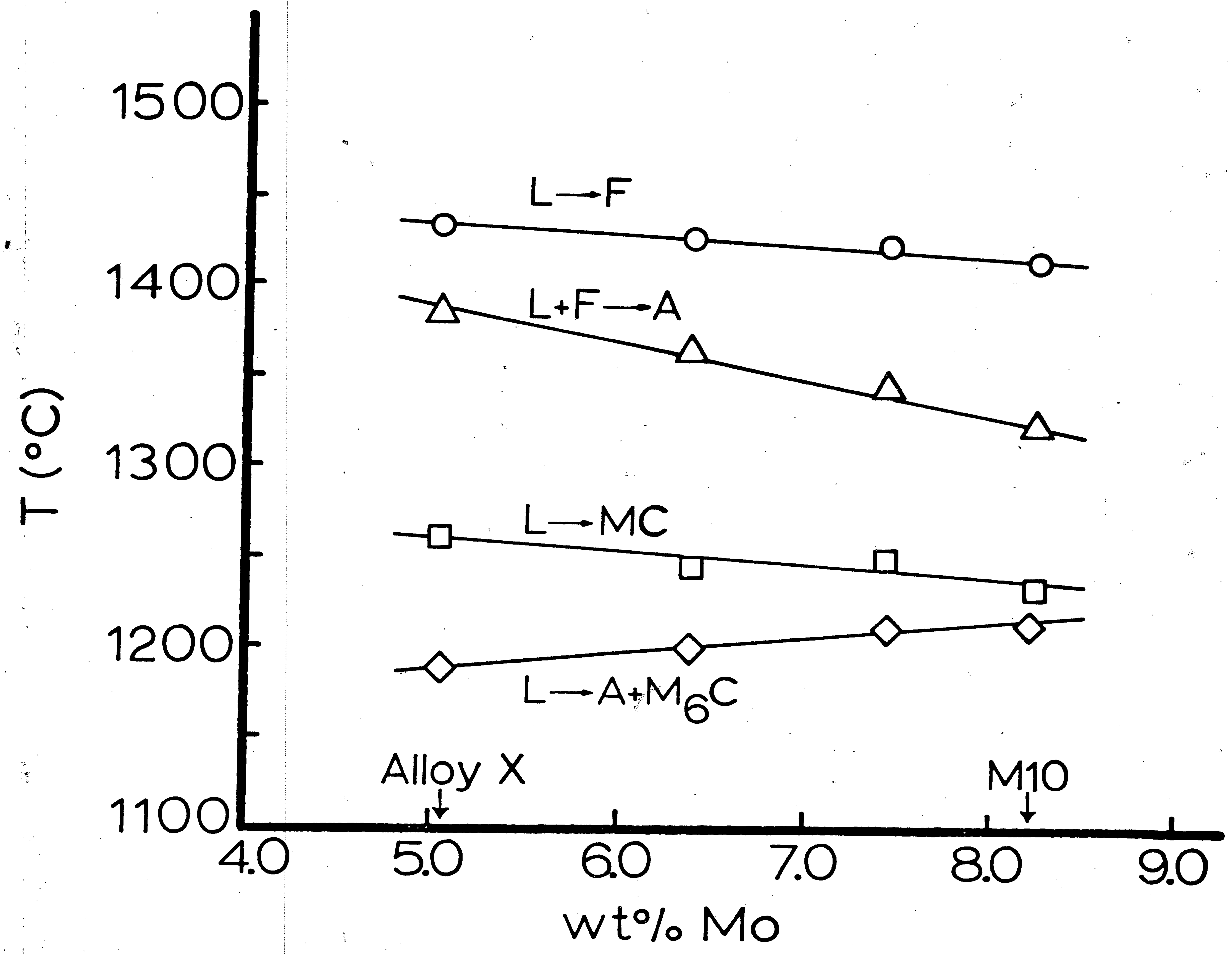


Fig. 6: Pseudo-binary for series (3) alloys.

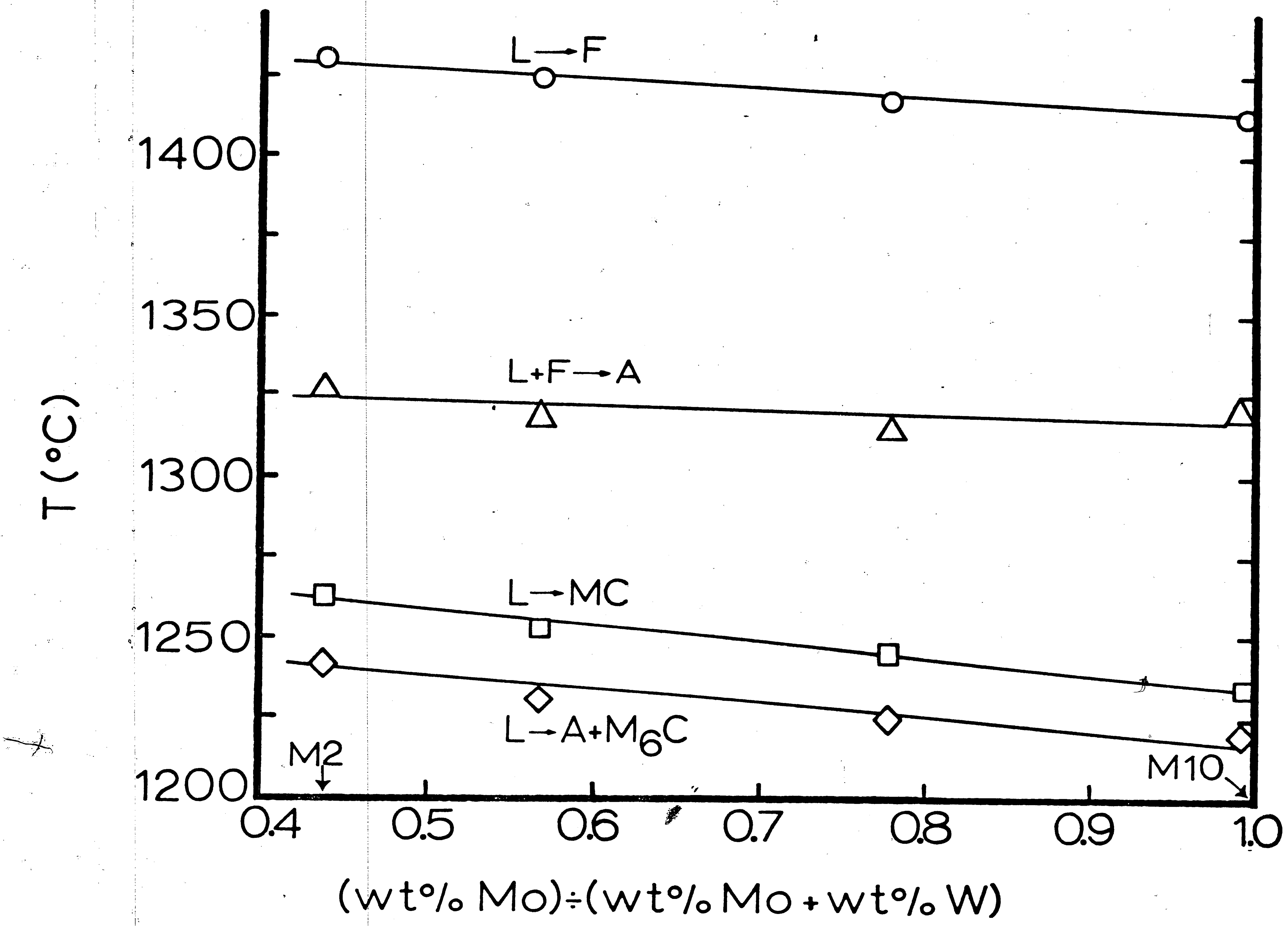
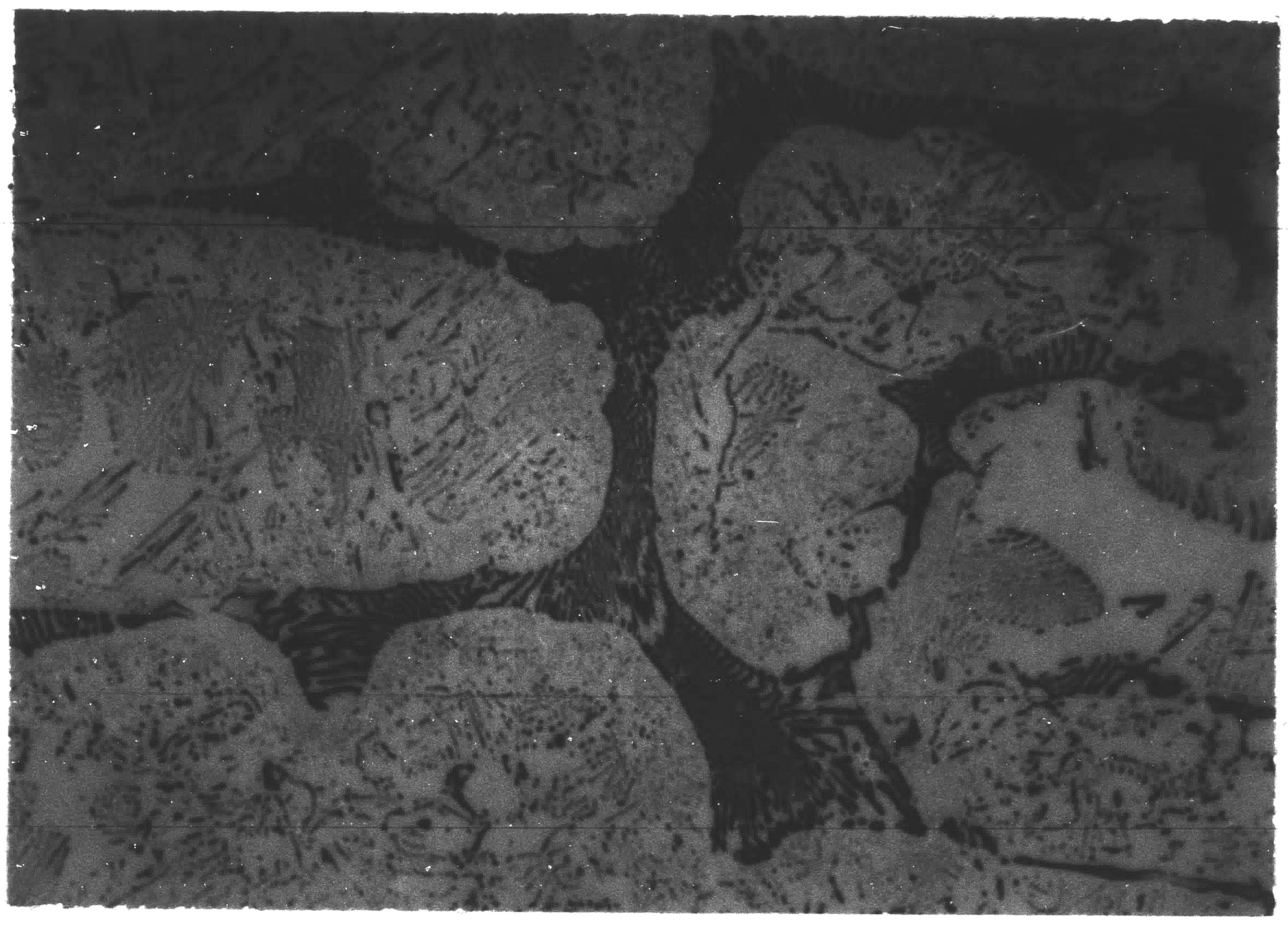


Fig. 7: Pseudo-binary for series (4) alloys.

8a: Nominal M2
(4.95% Mo
6.35% W)

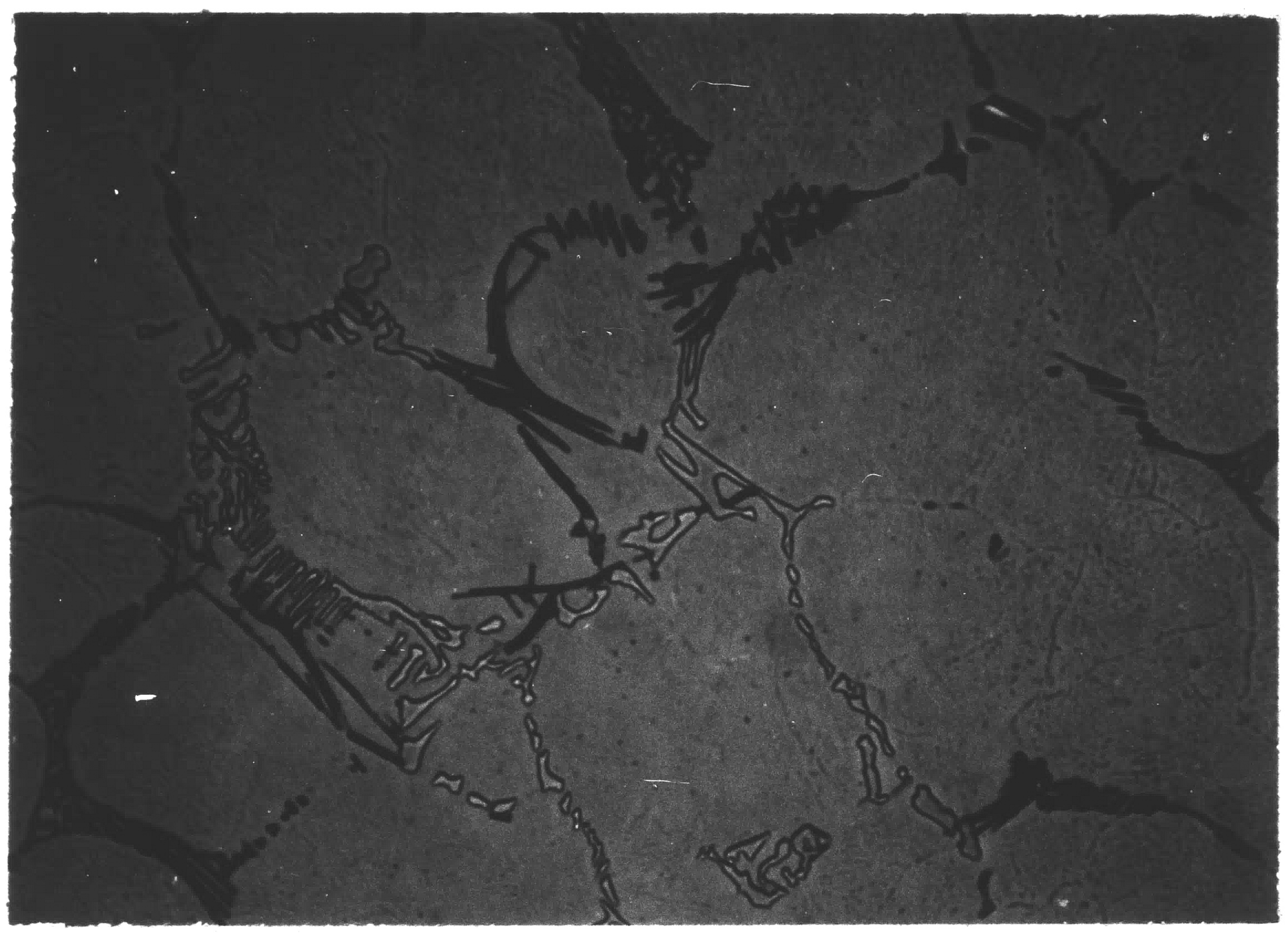
8b: 7.30% Mo
6.26% W



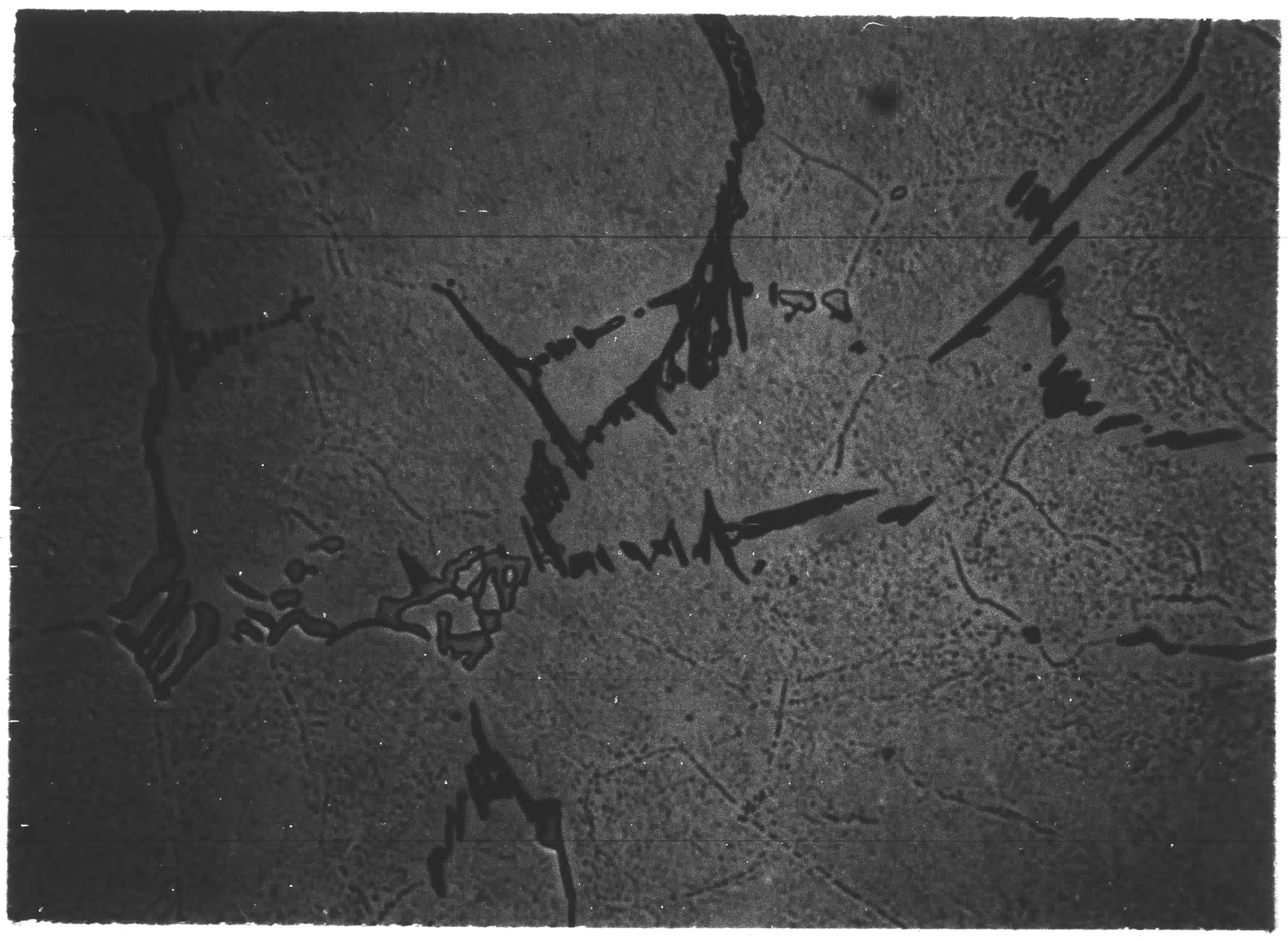
8c: 8.08% Mo
6.23% W

Fig. 8: As-cast structures of series (1) alloys. Alkaline $KMnO_4$ stain. 500X.

9a: Nominal M2
(4.95% Mo
6.35% W)
0.21 vol. % MC
8.25 vol. %
feathery
eutectic

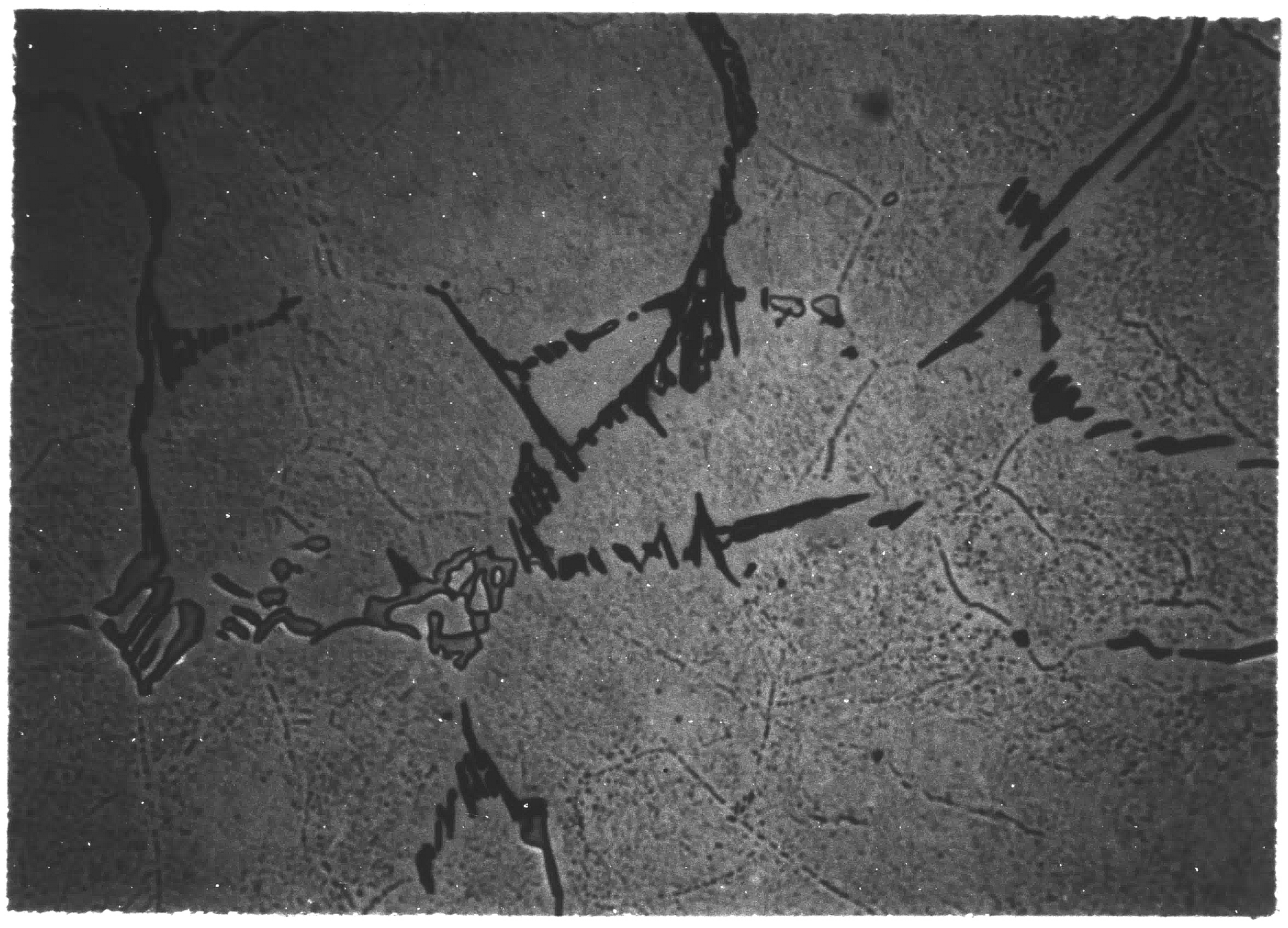


9b: 4.90% Mo
2.10% W

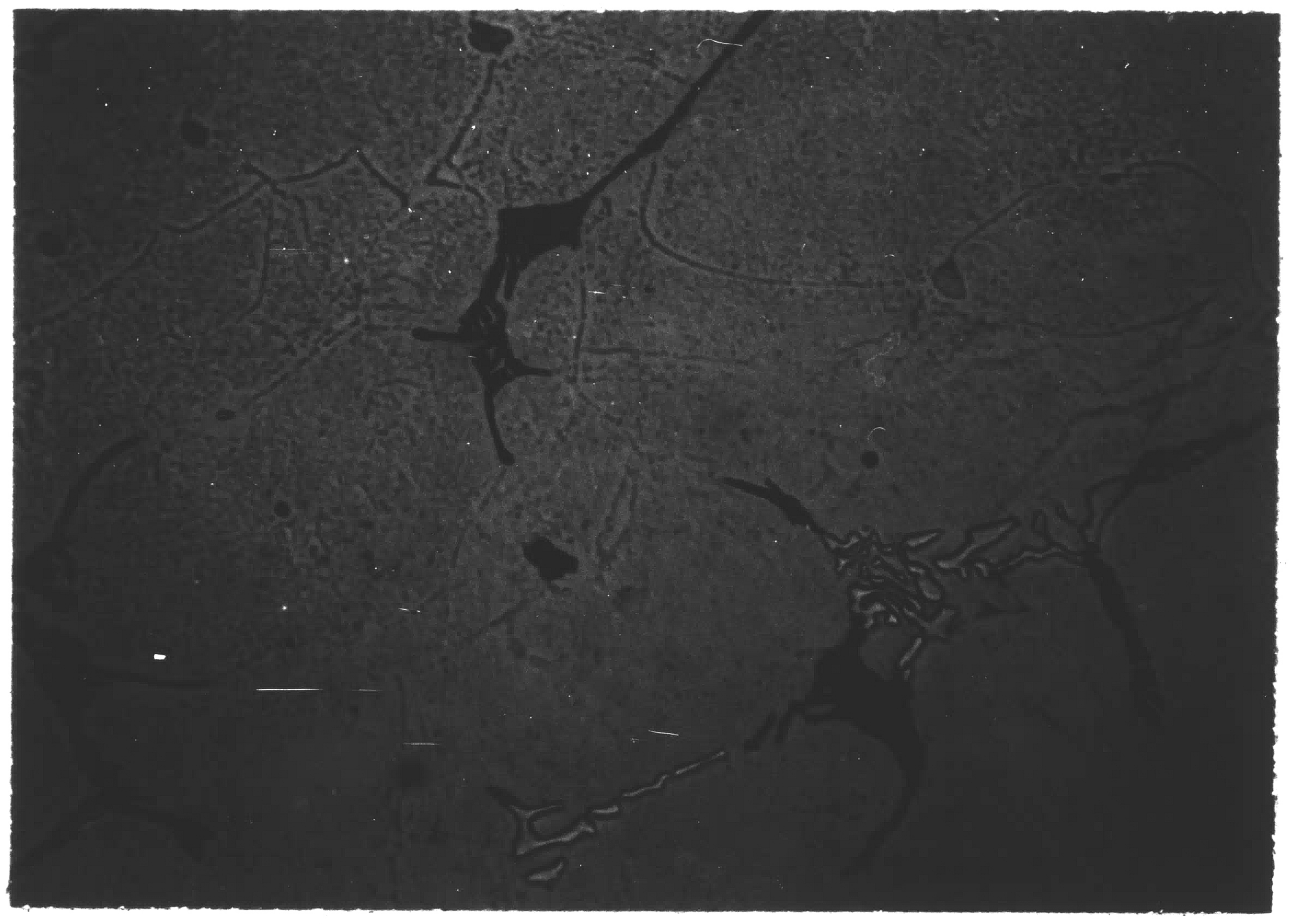


9c: Alloy X
(5.08% Mo
0.0% W)
1.21 vol. % MC
3.39 vol. %
feathery
eutectic

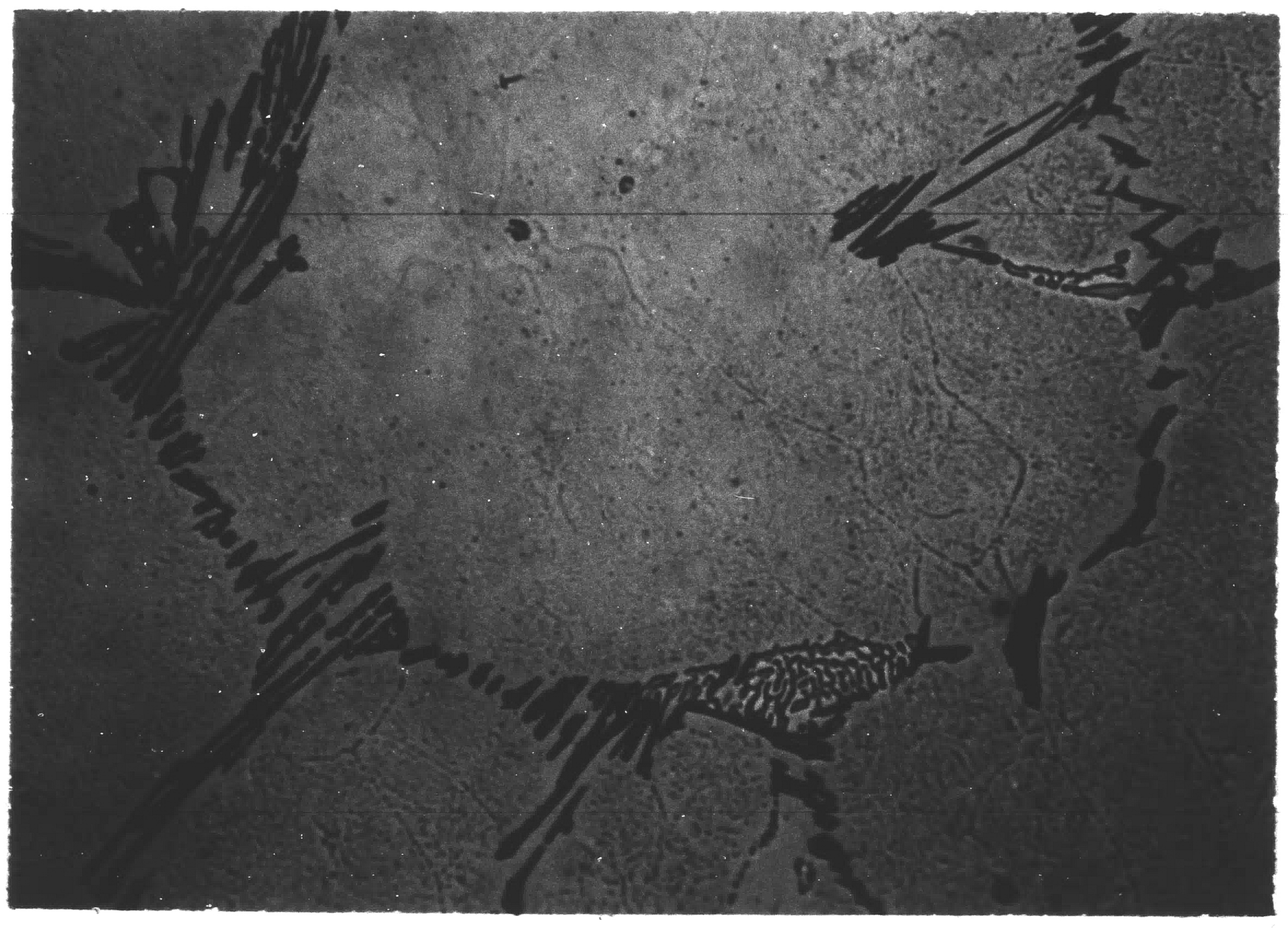
Fig. 9: As-cast structures of series (2) alloys. Alkaline $KMnO_4$ stain. 500X.



10a: Alloy X
(5.08% Mo
0.0% W)
1.21 vol. % MC
3.39 vol. %
feathery
eutectic

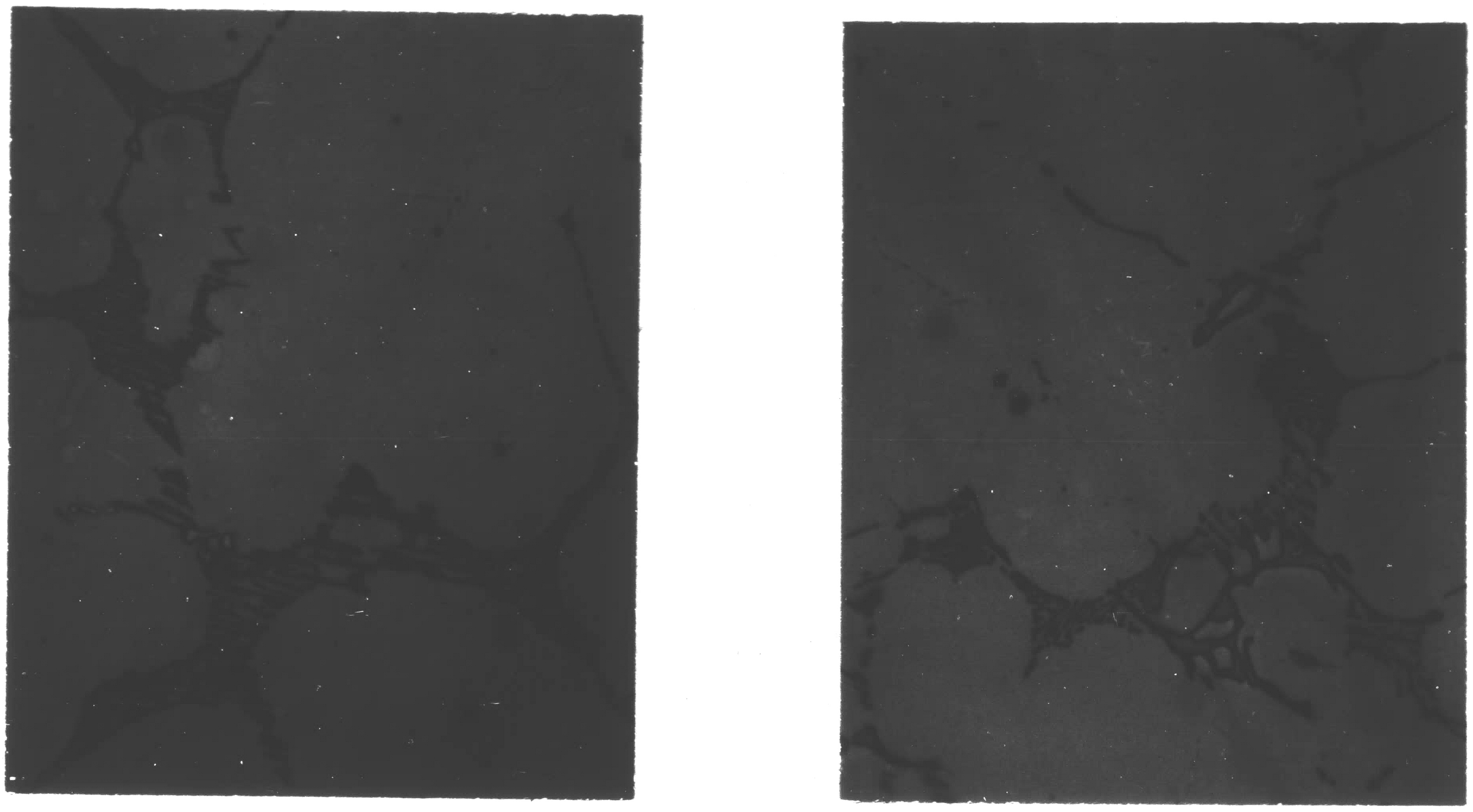


10b: 6.40% Mo
0.0% W



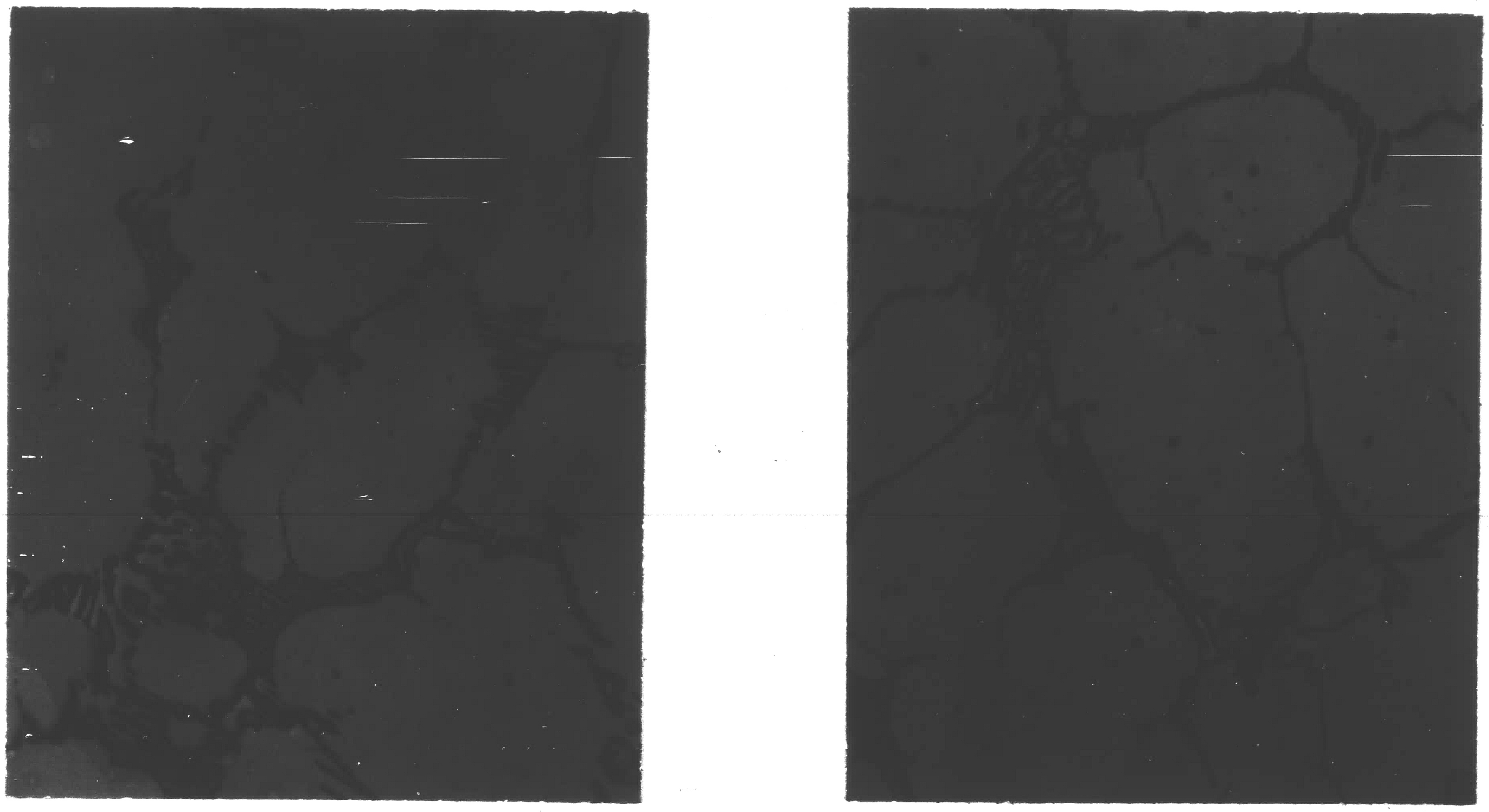
10c: Nominal M10
(8.26% Mo
0.0% W)
0.54 vol. % MC
7.98 vol. %
feathery
eutectic

Fig. 10: As-cast structures of series (3) alloys. Alkaline $KMnO_4$ stain. 500X.



11a: Nominal M2
(4.95% Mo, 6.35% W)
%Mo/(%Mo+%W)=0.44
0.21 vol. % MC

11b: 6.24% Mo, 4.70% W
%Mo/(%Mo+%W)=0.57
0.29 vol. % MC



11c: 7.36% Mo, 2.09% W
%Mo/(%Mo+%W)=0.78
0.41 vol. % MC

11d: Nominal M10
(8.26% Mo, 0.0% W)
%Mo/(%Mo+%W)=1.0
0.54 vol. % MC

Fig. 11: As-cast structures of series (4) alloys. Alkaline $KMnO_4$ stain. 500X.

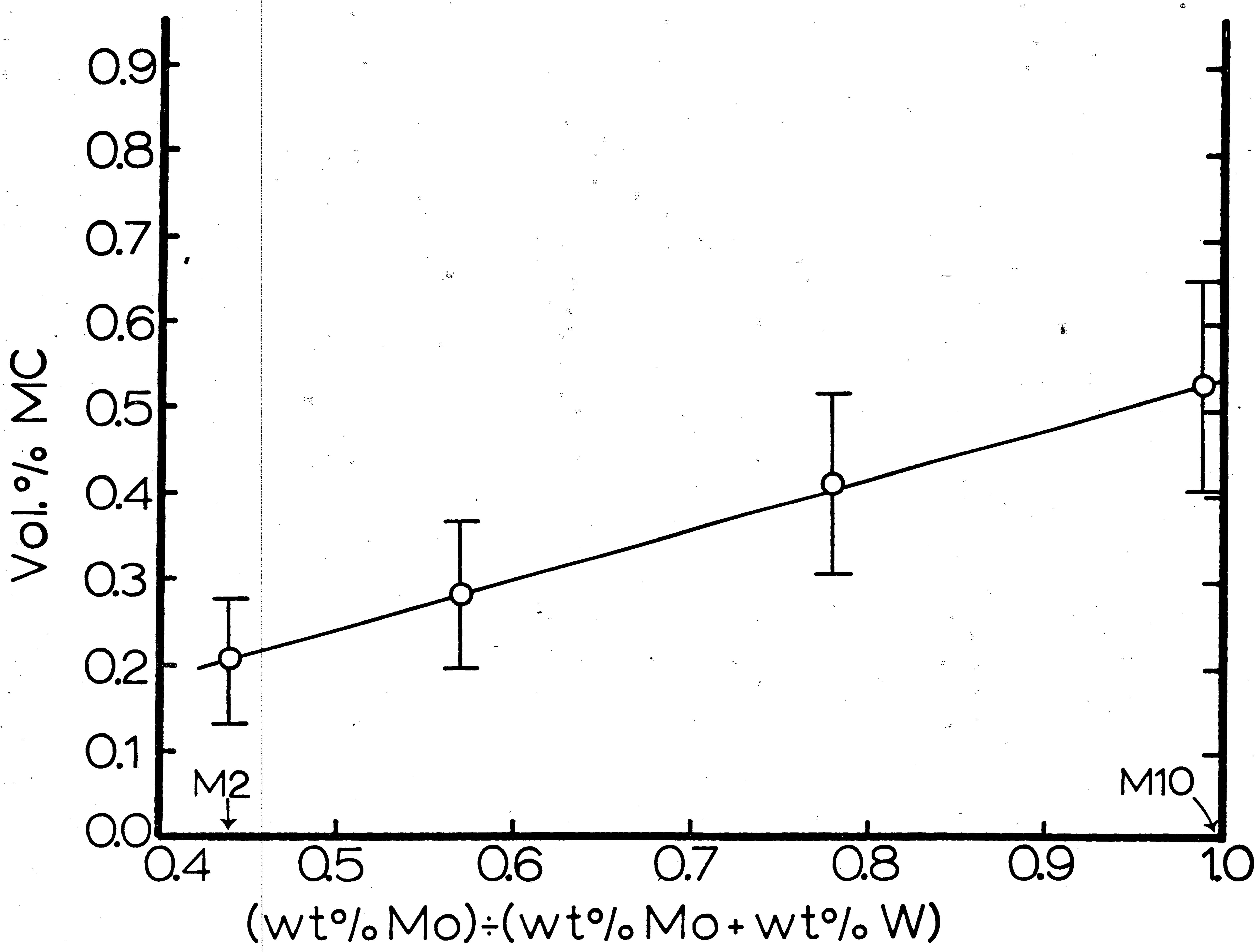


Fig. 12: Effect of the Mo:W ratio upon the amount of MC in as-cast structures.

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