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DEVELOPMENT OF ALLOYS HAVING GOOD HIGH TEMPERATURE PROPERTIES THROUGH POWDER METALLURGY TECHNIQUES

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FOREWORD

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ABSTRACT

Pure titanium carbide and titanium carbide with molybdenum carbide, vanadium carbide and chromium carbide have been alloyed with refractory binding agents such as iron-aluminum alloys with a content of 8 to 14% of aluminum as well as Fe-Al-Cr, Fe, Cr-Al and Fe-Al-Mo. The carbide phase has been varied from 5 to 35%.

The most promising alloys found out among the 12 series of alloys consisted of a binding agent of iron-aluminum with 12 or 14% of aluminum and of mixed crystals of titanium carbide - chromium carbide 90/10.

All alloys examined can be shaped to a certain extent at high temperatures.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

Richard R Kennedy

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I. Display of the problem

Among all heat and scale resistant materials examined in the last years, cemented carbides on the base of titanium carbide with binders of Ni-Cr, Co-Cr and Ni-Co-Cr have found the largest development and have shown the most favourable results. The so-called cemented carbides grade "WZ" as developed in Metallwerk Plansee are just tested in service in gas turbines. According to the results obtained hitherto it may be supposed that these cemented carbides can be used for turbine blades and other structural parts of high temperature engines working at temperatures of 950 to 1050°C. The alloys of our development contain 75 to 35% of titanium carbide and 65 to 25% of a binder, alloyed of Ni-Cr 80/20, Co-Cr 70/30 or Ni-Co-Cr 60/20/20, respectively. We are gradually producing them according to the usual methods of production of cemented carbides. We have examined very closely their properties at room temperatures as well as at elevated temperatures.*

Figure 1, left side, shows some properties of cemented carbides alloyed of TiC-Ni-Co-Cr as a function of its content of binding metal. It is obvious that the impact strength is improved by an increasing content of binder, the hardness, however, and also the modulus of elasticity are decreasing correspondingly.

The stress to rupture strength as well as the creep strength of such combined alloys depend on the high heat resistant binding alloy as well as on the carbide component. The heat resistance will be, no doubt, higher as that one of a pure binding alloy, provided that the carbide component is of sufficient importance and is forming a carbide skeleton. Due to the high hardness and the high modulus of elasticity these materials will be more brittle than the superalloys known as yet. If we diminish the content of carbide, the carbide skeleton gradually decomposes and, in materials with a content of less than 40% TiC, the carbide appears only in the shape of round single grains embedded in the binder. The reason of the greater creep strength of these materials is no longer the reinforcing effect of the carbide skeleton but, presumably, it is caused by the embedded carbides obstructing the slide of the binding alloy in hot condition. The influence of the grain size, the grain shape and the dispersion on the creep has not yet been investigated.

The idea of the present investigation was the production of materials with a carbide content of less than 35% consisting of pure titanium carbide or mixed crystals of titanium carbide with molybdenum carbide, or vanadium carbide with chromium carbide and using as binding agents alloyed heat resistant steels, alloyed

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* P. Schwarzkopf and R. Kieffer: Refractory Hard Metals, Macmillan New York 1953, pp. 395 etc.; R. Kieffer and P. Schwarzkopf: Hartstoffe and Hartmetalle, Springer Verlag Vienna 1953, pp. 662 etc.; R. Kieffer and F. Kolbl: Z.anorg.allg.Chem. 262 (1950) pp. 229/47; Plansee-Berichte 1, (1952) pp. 17/35.

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especially with aluminium, chromium and nickel instead of the usual super alloys. We, consequently, are entering in the field illustrated in figure 1, right side, Provided that these materials would be scale resistant up to temperatures of about 1100°C they could show, as stated above, both a good stress rupture strength and creep strength. As the intended binding alloys, partly well known alloys for heating elements, are also hot-workable, we can presume that such compound carbide alloys will be both to mill and to forge. Contrary to the known cemented carbides grade "WZ" it may be possible to produce semi-finished products of these alloys. When sintering the proposed compositions as usually in hydrogen or in vacuum, we obtain relatively porous sintered compacts and it may even be necessary to compress them by a subsequent working. Only largely dense materials will show a favourable heat resistance.

Attention had of course also been paid to economical reasons as well as to considerations concerning the raw materials, when choosing the project of the research.

II. Accomplishment of investigations

As explained in the introduction, the task of the investigations was the production of high heat and scale resistant sintered materials on the base of titanium carbide with binding agents of an iron alloy, heat and scale resistant as well. Pure titanium carbide and mixed crystals of titanium carbide and molybdenum carbide and vanadium carbide, and titanium carbide and chromium carbide to an extent of 5 to 35% served as carbide components. The technical titanium carbide as used in the production of cemented carbides contains only 18 to 19% of combined carbon and a few tenths of free carbon. There was a danger of a reaction of the free carbon on the iron binder thus forming brittle phases (bicarbides etc.), when using pure titanium carbide which is very difficult to produce in its theoretical composition due to the well known difficulties. We therefore thought to investigate the use of titanium mixed crystals instead of pure titanium as, according to experience, they are much easier to produce pure. When making use of mixed crystals containing chromium carbide, we thought to support the formation of a stable film during the development of scale by the chromium present in the carbide phase.

There were many possibilities in choosing a binding alloy on the base of iron. We first tested the behaviour of an iron aluminium binder containing 8, 10, 12 and 15% of aluminium respectively. Pure iron aluminium alloys, sintered in vacuum, show rather good hot forming properties and are materials of an excellent scale resistance& properties, use of which has already been made practically with alloys for heating elements. Alloys with a high content of aluminium show very favourable properties; the workability, however, leaves just a great deal to be desired. As these alloys are ferritic ones they have a good creep strength. Contents of Al_2O_3 added intentionally or produced by an adequately handled sintering procedure can essentially improve the creep. It was also to presume, that additions of carbides and carbide mixed crystals are very much improving the creep strength of such compound alloys because of the deposits contained, producing an obstruction against the slide effect.

A technically good control of the sintering process of alloys sensible to oxidation, together with metals forming oxides difficult to reduce, is only possible in vacuum. On account of the favourable experiences made with the vacuum sintering process, when sintering permanent magnets with additions of boron, the influence of an addition of ferro-boron corresponding to a content of about 0.5% of boron in the resulting alloy, was investigated in further series of tests. (See: F. Frehn and W. Hotop: Effect of Small Boron Contents on the Properties of Sintered Bodies Prepared by Vacuum Sintering. Symposium on Powder Metallurgy London 1954).

Boron dissolves oxide skins during the sintering process, because of the occurance of a liquid phase, thus producing sintered compacts of greater density. This liquid phase, containing boron accelerates the diffusion thus facilitating the homogenization of the sintered alloy. Further, the sintering temperature can be lowered essentially which is a great advantage of the proposed materials usually sintered at 1300 to 1400°C. For the boron containing alloys sintering temperatures of only 1200 to 1250°C were sufficient.

We know of the alloys for heating elements that an addition of chromium is prolonging their life essentially. The behaviour of these alloys with respect to the scale is far better as compared with chromium free alloys, but their workability is somewhat poorer. Therefore, further alloys with additions of 3% of chromium to the 12% iron aluminium binder were produced. In order to facilitate the sintering process 0.5% of boron was added, consisting of ferro-boron.

Further compositions were made in order to investigate the properties of the usual iron chromium aluminium alloys used for heating elements with binders consisting of 30% Cr and 5% Al. The same was done with an alloy of iron nickel chromium with 20% Ni and 25% Cr.

First of all alloys containing mixed crystals of titanium carbide with molybdenum carbide, vanadium carbide and chromium carbide, respectively, instead of pure titanium were alloyed only with binders consisting of an iron aluminium alloy with 12 and 14% of aluminium. The titanium carbide mixed crystals contained 10% of molybdenum carbide, vanadium carbide or chromium carbide, respectively. Only for one series of tests a titanium-chromium carbide mixed crystal 80/20 was used.

By using NiAl as binder to titanium carbide, no good materials were obtained under the given conditions.

In one of the last series of tests an iron aluminium molybdenum alloy 81/14/5 was used as binder to the TiC/Cr_3C_2 mixed crystal 90/10. A similar alloy was recently suggested for heat resistant materials, which seems to be better than a pure iron aluminium alloy.

On principle, only *very fine component powders* were used as it is not at all easy to homogenize the proposed sintered alloys, consisting of many materials, despite of the liquid phase. The very fine, pure and easy sintering carbonyl iron powder served, therefore, as iron base. All the other additions were applied milled to powder.

In order to improve the distribution as well as the homogenization of the powders the mixture Fe-Al-Mo-TiC/Cr_3C_2 90/10 was *wet milled* during a sufficient long period. This is a process as applied in the manufacture of cemented carbides.

The *specimens were manufactured* according to the usual methods of the Powder Metallurgy i.e. *single pressing* and *sintering in vacuum.* The sintered compacts were expected to remain considerably porous despite of the formation of a liquid phase, thus reducing their properties. In order to investigate the properties of dense alloys some compositions were manufactured by *hot pressing* and examined after having homogenized them by annealing.

III. Composition and manufacture of specimens

Summarizing the statements in article II the following series of alloys were investigated with regard to their composition:

1. Table 1: Fe-Al-TiC (for tensile test specimens) (No. 59, 2-8, 49, 9-15, 50, 16-22)
2. Table 2: Fe-Al-TiC (for hot pressed pieces) (No. 45, 24-30, 46, 31-37, 47, 38-44)
3. Table 3: Fe-Al-TiC-B (No. 60, 52-58)
4. Table 4: Fe-Al-Cr-TiC-B (No. 61-68)
5. Table 5: Fe-Cr-Al-TiC-B (No. 69-76)
6. Table 6: Fe-Cr-Ni-TiC-B (No. 77-84)

7. Table 7: Fe-Al-TiC/Mo_2C-B (No. 85-94)
8. Table 8: Fe-Al-TiC/VC-B (No. 95-104)
9. Table 9: Fe-Al-TiC/Cr_3C_2, 90/10-B (No. 105-114)
10. Table 10: Fe-Al-TiC/Cr_3C_2, 80/20-B (No. 115-124)
11. Table 11: NiAl-TiC/Cr_3C_2, 90/10B (No. 125-131)
12. Table 12: Fe-Al-Mo-TiC/Cr_3C_2, 90/10-B (No. 132-138)
13. Table 13: Fe-Al-Mo-TiC/Cr_3C_2, 90/10-B (wet milled) (No. 139-145)

As to the manufacture of the specimens the following can be said: The investigation of the technological properties of the sintered bodies are intended were made with flat tensile strength test bars. (See: R. Kieffer and W. Hotop: Sintereisen and Sinterstahl, Springer Verlag Vienna 1948, pp. 323/24).

A carbide lined die was used to press the very fine grained mixtures acting as an abrasive. The powder components were intimately mixed in a wing mixer (Lodige mixer) during half an hour. Some comphor-ether solution was added and rods of 5 to 6 mm in height were pressed by an uniform pressure of 6 t/cm^2. No difficulties were met in pressing and the green bodies showed relatively stable edges without slip cracks. The green bodies were put in a vacuum furnace with molybdenum heating elements, embedding the bodies as several separated layers in aluminium oxide powder in boats (Figure 2 and 3.) They were always sintered during 1 hour in a slight vacuum of 10^{-2} to 10^{-3} mm Hg. The sintering temperatures of the Fe-Al-TiC specimens were 1300 and 1350°C, respectively. All specimens containing boron were sintered at 1250°C; some of them at only 1200°C. After the sintering procedure, most specimens showed a clean metallic surface and a metallic surface of fraction. With increasing addition of carbide the surface showed a dull gray and the surface of fraction was somewhat dull as well.

The equipment as shown in Figures 4 and 5 was used for the production of hot pressed compacts made of mixtures Fe-Al-TiC in order to investigate the properties of largely non porous bodies. An amount of the mixture, determined by weight was put in a graphite shell and heated under pressure to a temperature of 1200 to 1250°C. This was continued until the readings taken of the recording instrument showed no reduction of the volume. The specimens of a diameter of 15mm and about 10mm in height were then thoroughly cleaned of the remainders of graphite and were again sintered afterwards, like the tensile strength bars, 1 hour at 1300°C and 1350°C, respectively, in slight vacuum.

IV. Examination

1. Density

The density of the tensile strength test bars either green or sintered was determined after having covered them with paraffin according to the buoyancy method. The indicated values are averages of 2 measurements.

2. Shrinkage

Only the shrinkage in length was determined and stated in percents of the original length of the green body. The indicated values are averages of 10 measurements.

3. Hardness

We have determined the Vickers hardness with a load of 20 and 30 kgs. The samples were ground by a fine grained grinding wheel before the test. The indicated values are averages of 10 measurements made of 2 rods. The values differ greatly especially concerning the samples with high hardness.

4. Tensile strength and elongation

The specimens were marked in a distance of 50 mm and torn by a tensile strength machine of 10 tons load using shoulder jaws. Though very carefully clamped it was unavoidable that the relatively brittle samples broke partly untimely due to the bending stress. Such values were not taken into consideration. With exception of the carbide free samples no measureable elongation was found. The indicated values are averages of 2 measurements.

5. Impact transverse strength

The samples, without notch, were smashed by a small hammer with an impact energy of 150 cmkg. The distance of the jaws was 40 mm. The hammer was touching the broad side of the specimen. The indicated values are averages of 2 measurements.

6. Scaling

A prismatic specimen of about 5 x 10 x 25 mm was cut out of each rod and heated in a muffle furnace in slight moving air during 2, 4, 8, 16, 32 and 64 hours at 800 to 900°C. A scaling time of only 2 to 4 hours was applied at a temperature of 1100°C, because most of the samples showed so much scale after this period that the oxide film partly scaled off. The hot pressed samples, which were very dense, mostly showed badly adhering layers of scale. After each annealing operation the specimens were weighed and the augmentation of weight was referred to 1 cm^2 of the surface. The values as indicated are individual ones.

7. Hardness at high temperatures

We have manufactured equipment of our own design similar to the apparatus of F.P. Bens (Trans.Am.Soc.Met. 38/1946, Figures 6 and 7, 105/16). Specimens cut to suitable size were heated in this equipment in vacuum to temperatures of 200, 400, 500, 600, and 700°C, respectively. Three Vickers measurements were made by means of a diamond in a special holder. The indicated values are averages of 3 measurements made of each specimen.

8. Transverse rupture strength at high temperatures

In order to find out the transverse rupture strength both at room temperature and elevated temperature equipment of our own design was used (Figures 8 and 9.) As working temperatures up to 900°C. were planned it was necessary to develop a special construction for both the support and the pressure bar. They were made of sintered aluminium oxide. The rollers of sintered aluminium oxide of the support were mounted in a shaped piece of cemented carbide, grade "WZ" (an alloy of TiC-Ni-Co-Cr). Slots in the end in which guide pins were done, avoided a displacement of the specimens. A 10 tons tension test machine applied the pressure. We examined always 2 specimens at 20, 500, 700 and 900°C, respectively. The following formula served for the calculation of the values:

$$B = \frac{P \cdot 7.5}{b.h^2}$$

P = total load
b = width of the specimen
h = height of the specimen
l = distance of the supports (= 50 mm)
B = transverse rupture strength

9. Tensile strength at high temperatures

We used equipment of our own design (Figures 10 and 11). Special attention should be drawn to the supports which were also made of cemented carbide, grade "WZ" (TiC-Ni-Co-Cr alloy). We determined the tensile strength during a short period at 500, 700 and 900°C, respectively, using always 2 specimens. The indicated values are averages of these measurements.

10. Forgeability tests

In order to examine the forgeability of the tested materials the specimens were heated in a carbon tube furnace with alumina insert at 1150°C under hydrogen and forged by hand on the one end of the specimen.

The forgeability of the specimens can be determined after finding out whether the end is deformed or whether cracks or breakage occurred. A shaping without cracks could even be attained with materials which got cracks or even broke by doing the forging at higher temperatures.

V. Discussion of the results

The technological properties of materials examined at room temperatures are compiled in tables 14 to 30.

We shall now discuss a single property by comparing all materials.

1. Pressed density

The series of alloys (1) to (2) (for details see page) show a distinctly decreasing density if the addition of Fe-Al as well as of titanium carbide is increasing. Generally speaking, the density of all series of alloys is decreasing with an increasing content of carbides. An addition of ferro boron barely influences the density of series No. (3). An addition of chromium is causing the somewhat worse compressibility of series No. (4).

The alloy No. (5) show the same compressibility compared to the alloys No. (2). Higher densities are obtained with series No. (6) due to their higher content of nickel and chromium.

The compressibility of the alloy series No. (7) to (10) is nearly not influenced by an addition of mixed crystals compared to that one of pure titanium carbide.

Series No. (12) show a worse compressibility due to the wet milling and a considerably reduced pressed density because of the very fine powdered starting mixtures.

2. Sintering density and shrinkage

The carbide free samples of series (1) to (2) are shrinking relatively considerably. This effect is strongly reduced by an addition of 5% of titanium carbide; the sintering density and the shrinkage, however, are greatly increasing with additions exceeding the a/m 5%. In fact, the shrinkage of some alloys containing titanium carbide is more than the double of that one of titanium carbide free alloys, a phenomenon which is again increased by the use of binders with an increased content of aluminium. If the specimens are sintered at 1350°C. instead of sintering them at 1300°C they are showing a similar behaviour with exception of the absolute values of the sintering density and the shrinkage, which are considerably higher. Comparing the density of the normally sintered specimens to these produced by hot pressing, but made of the same pre-material, the density of the latter is considerably higher. Presuming a porosity of the hot pressed specimens of less than 2% we can say that the porosity of the normally sintered specimens is of about 8 to 14%. It is, however, possible to obtain an essentially improved sintering density, neighbouring largely to that one of the compact body, by using suitable methods of which we shall report later on.

An addition of 0.5% of boron as ferro boron to series No. (3) causes a very increased sintering density and shrinkage as compared to series No. (2), a fact which indicates that the boron alloy, acting as liquid phase, is largely instrumental to dense sintering. These samples show practically the same density as the hot pressed ones.

The addition of chromium to series No. (4) hinders the sintering process probably due to the formation of non-reduceable oxide skins. The density and the shrinkage are lower than these of series No. (3).

The raise of the sintering temperature to 1300°C. made it only possible to obtain somewhat dense and metallic alloys of series No. (5). Series No. (6), however, could just be sintered satisfactorily at 1200°C but with a relatively great shrinkage.

The series of alloys No. (7) to (10) show, especially as to the series (7) to (9), both a very high sintering density and shrinkage, which are of higher values than with the series with pure titanium carbide. The effect of dense sintering is intensified by an increase of the content of aluminium on the binder. There is only one exception: series (9) containing a mixed crystal $TiC-Cr_3C_2$ 80/20 with an inferior shrinkage and a lower sintering density. Presumably this is effected by non-reducible chromium oxide skins.

Series (12), worked normally, showed no essential difference compared to series No. (9) though being of a somewhat changed composition. Is the mixture however wet milled, the shrinkage is nearly the double but the structure of the surface of fracture is of a specially metallic aspect and very fine grained. Both series are, however, dense to a large extent.

3. Hardness

It goes for all series of alloys that an increasing content of carbides improves their hardness very strongly. A material containing 30 to 35% of carbide will have a hardness of about a hardened steel. The hardness of sintered materials depends largely on its density like, by the way, all their stress properties, a fact, which is illustrated very distinctly by comparing series (1) and (2), sintered either at 1300 or 1500°C.

The hardnesses of the corresponding hot pressed specimens are nearly of the same value as these of the specimens sintered at 1350°C.

The additions of boron to the series No. (3) are effecting an increased density and, parallel to it, a distinctly improved hardness. The addition of chromium to series No. (4) which, as already pointed out, hinders slightly the sintering process, results in a somewhat lower hardness. An incomplete sintering process is proved by the relative low hardness of the series No. (5), whereas the series No. (6) are of a better hardness and are easier to sinter. The series of mixed crystals No. (7) to (10) are of materials of an exceptionally high hardness. Series (9), containing TiC/Cr_3C_2 90/10, is of special prominence. A distinct improvement of the hardness is caused by an increase from 12 to 14% of the content of aluminium of the binder. There is only series No. (10) with a content of TiC/Cr_3C_2 80/20 which is worse, even as to its hardness. A fine milling of the series No. (12) does not cause any increase in hardness compared to the samples made in normal production which is presumably due to a somewhat greater micro porosity (see also sintering desnity).

4. Tensile strength at room temperature

Though the determination of the tensile strength of brittle material is very difficult and does not always give reproducable values, it is, however, an indication, in connection with hardness and impact flexure strength, concerning the ductility and the presumable hot stress properties. Contrary to the increase in hardness with increasing content of carbides, the tensile strength of all series of alloys is diminishing very distinctly with an increasing content of carbides. This is presumably due to the fact that we are obviously measuring too low values of tensile strength when testing hard and brittle materials of a high content of carbides. An increase of the aluminium content of the binder of the series (1) to (2) causes a lower tensile strength, a fact, which is presumably in accordance with brittleness. The tensile strength is obviously secured by the addition of boron to the series No. (3) especially when comparing it to the values of series (2).

The series of alloys No. (4) shows a good tensile strength, series No. (5) is not as good. Series No. (6) shows average values.

The mixed crystal series No. (7) to (10) are of a good tensile strength and series No. (9) containing TiC/Cr_3C_2 90/10 is of an outstanding quality. The addition of TiC/Cr_3C_2 80/20, on the other hand, results in a clear deterioration of the tensile strength.

The tensile strength of the wet milled specimens of series (12) is clearly better than of the samples produced in the normal way, though the hardness is somewhat lower. This is presumably caused by the somewhat higher ductility and the fine grain of the wet milled materials.

5. Elongation

Only the carbide free sintered alloys of the series No. (1), (5) and (6) show a clear elongation. The values of all other alloys containing between 5 to 35% of carbides are undeterminable without a precise equipment to find out elongation (dilatometer). This effect proves, that the ductility of the generally used Fe-Al binder with a content of 8 to 14% of Al does not allow a plastic deformation at room temperature. Also the binding agents Fe-Cr-Al and Fe-Ni-Cr, though rather ductile, are getting brittle at room temperature by infiltration of carbides.

6. Impact flexure strength

The impact flexure strength of all alloys is strongly reduced by an increasing content of carbides due to the notch effect of the infiltrated carbide grains. Series (1) to (2) illustrate the fact that also an increase of the aluminium content of the binder is reducing the toughness.

The addition of boron to series No. (3) results in an improved impact flexure strength. Series No. (4) does not show any influence exerced by the addition of chromium. Series No. (5) is bad, but series No. (6) is moderately good.

Among all series of mixed crystals the alloys containing the mixed crystal TiC/Mo_2C are the toughest ones followed up by TiC/Cr_3C_2 and TiC/VC. Series TiC/Cr_3C_2 80/20 is bad again.

There is no essential difference between the normal and the wet milled specimens of series of alloys No. (12) as to its impact flexure strength. The wet milled specimens are even somewhat more brittle but are of a better tensile strength.

7. Warm hardness

The values of the warm hardness allow to draw certain conclusions from the mechanical resistance at elevated temperatures. An increasing addition of carbides is strongly improving the warm hardness as well as the hardness at room temperature. The warm hardness of the series No. (1) to (2) is diminishing with an increasing aluminium content of the binder, but this is only true for alloys with a low content of TiC. A high content of TiC, however, is increasing the hardness due to the influence of the carbides even at elevated temperatures (see figures 12, 13, 14).

The addition of boron to series No. (3) is increasing the warm hardness as well (see figure 15). The addition of chromium to series No. (4) does not influence greatly the warm hardness (see figure 16). The series of alloys No. (5) though being of a relatively low hardness at room temperature and series No. (6) are hard in warm state (figures 17, 18).

The mixed crystal alloys (7) to (10) show a very improved warm hardness according to an increasing carbide phase; an increase of the aluminium content of the binder increases the warm hardness. The best alloys in this respect are those with a content of TiC/Mo_2C (figure 19) followed up by TiC/Cr_3C_2 90/10 (figure 21). The alloys TiC/VC and TiC/Cr_3C_2 80/20 are only satisfactorily down to bad. A wet milling process (figure 20, 22) of series (12) does not influence their warm hardness in any decisive manner (figure 23).

8. Hot transverse rupture strength

Though an increasing addition of carbides is generally diminishing the transverse rupture strength at room temperature, this addition is strongly improving the transverse rupture strength at elevated temperatures, say at 700 to 900°C. Low values of hot transverse rupture strength are mostly shown by specimens, which do not break at a certain temperature during the test and which, of course, are so very plastic and are, therefore, bending strongly. Such materials are not to be applied at elevated temperatures and which have to undergo a stress at the same time. At a testing temperature of 500°C, the series No. (1) to (2), especially as to the specimens with a higher content of carbides, showed an increasing transverse rupture strength compared to the same property at room temperature. (Figures 24, 25, 26). Some other alloys showed the same effect as well, which is probably due to the better toughness at elevated temperatures. A further increased testing temperature, however, reduces the transverse rupture strength but the percentage of this reduction is smaller for samples with a higher content of carbides. These samples are, therefore, much more rigid and show a better resistance at elevated temperatures. The rigidity is also increased by an increasing content of aluminium of the binder which is probably due to the influence of most finely divided aluminium oxide.

The addition of boron to series No. (3) is improving the hot transverse rupture strength, but only the specimens with a high content of carbides are of a sufficient rigidity to break by brittleness. The samples containing 30 to 35% TiC show even better values of transverse rupture strength at 700°C than at room temperatures (figure 27).

An addition of chromium to series No. (4) is very profitable and the values of the specimens of a high content of carbides are better at 700°C than at 20°C. (Figure 28).

The series No. (5) does not show very good values (figure 29). The alloys of the series No. (6) however are very rigid (figure 30).

The carbide mixed crystals show outstanding values and they are to classify as follows: Series (9), (8), (7) and (10) (figures 31, 32, 33, 34). The alloys containing 35% of mixed crystals and partly the alloys with a content of only 25% are even better at 700°C than at 20°C.

The values obtained with the wet milled specimens of series No. (12) are slightly inferior to that ones of the samples made by the normal process (figure 35).

9. Hot tensile strength

When judging the results of the hot tensile strength, the same point of view can be applied as for the results obtained at room temperature. It is very difficult to apply the charge just in the axial direction of the specimens, and a prematurate break of the brittle sample is often unavoidable. The results obtained, however, allow certain conclusions concerning the admissible charge during a short time at elevated temperatures.

Similar to the hot transverse rupture strength we can observe an increase of the hot tensile strength according to an increasing addition of carbide. At room temperatures, however, we can observe just the inverse effect. Many of the specimens show values of the hot tensile strength which are higher at 500°C and even at 700°C than at 20°C. This effect is already noticeable with the alloys of the series No. (1) to (2) (figure 36) and their hot tensile strength is also improved by a higher aluminium content of the binder.

An addition of boron to series No. (3) is improving the hot tensile strength as well (figure 37).

Series No. (4) and (6) show also a good hot tensile strength (figures 33, 39) but series (5), being of a low tensile strength at room temperature, is accordingly of a reduced not tensile strength.

Series (7) to (10), with a content of mixed crystals, show again the best properties. Considered on the whole, the materials containing 35% of TiC/Mo$_2$C (figure 40) or TiC/Cr$_3$C$_2$ 90/10 (figure 41) and with a content of 12% binder are the best ones. Series No. (10) is bad again.

In spite of the relatively high tensile strength at room temperature the series No. (12), wet milled, does not show a better hot tensile strength than the similar materials of series No. (9) (figure 42). The values are not essentially higher than those of the specimens of the same composition and manufactured in the normal way.

10. Scale resistance

In spite of the very ample material examined, it is not always simple to determine the influence of the compositions of the alloy on the scaling properties. Besides the increase in weight after having fired the specimens in open air during various periods and at various temperatures, we must also consider the aspect of the specimens, i.e. the formation of the scale layer, in order to form an opinion.

At first, the pure iron aluminium alloy of the series (1) to (2) is very stable, but when adding only 5% of TiC a thick and even strongly adhering scale layer is formed. This effect is proved very distinctly by specimens oxidized at 900 and 1100°C. When alloying the binding agent with more titanium carbide again, the scale layer is getting more and more thin, down to rather insignificant oxide layers, if a content of 30 to 35% is reached. (Figures 43, 44). We can say that the alloys No. (21) and (22), especially if they were sintered at higher temperatures (1350°C) show an outstanding scale resistance even at a temperature of oxidation of 1100°C. The aluminium content of the binder is improving the scale resistance, a fact which is illustrated in figure 43 and 44. The scaling isotherms as shown in these figures follow to a parabolic law, i.e. the strongly adhering oxide layer which is gas tight acts largely as a protection of the alloy below.

We should like to draw the attention to another fact. Comparing the tight, hot pressed samples to the porous ones, manufactured in the normal way and being of the same composition, we note the stronger oxidation of the hot pressed specimens and, especially, at higher temperatures of oxidation, that the scale layer is not of a good adherence.

We think that this effect is due to the more porous and course surface of the normally sintered samples, which causes the scale layer to adhere in a much better way than on the smooth and nearly non-porous surface of the hot pressed samples. As already pointed out, it is also the surface which is to be considered when forming an opinion as to the scale resistance of a specimen.

The addition of boron to the series No. (3) causes an inferior scale resistance, which is especially proved by the alloys with a high content of titanium carbide and at oxidizing temperatures of 900°C (figure 45). The increase in weight is, on the whole, very low again and we are permitted indeed to speak of very good scale resistant materials up to a temperature of 900°C.

The small addition of chromium to series No. (4) is nearly not influencing the scaling properties (figure 46). Some specimens oxidized at high temperatures show a very particular papillary shape of the scale layer which is reduced to some places only.

The series of alloys No. (5) containing an Fe-Cr-Al binder and which is, as already mentioned, difficult to sinter, show a very poor scaling property (figure 47). We believe, that the diffusion of the components was so poor that the Fe-Cr-Al alloy which is of very good scale resistance, failed to materialize its good effect.

Though showing a somewhat higher increase in weight, the series No. (6) can be characterized as of a good scale resistance - especially those alloys with a higher content of titanium carbide - due to their thin and strongly adherent scale layer. (See figure 48).

The series (7) to (10) with additions of mixed crystals are materials of a very good scale resistance because of the addition of the TiC/Mo_2C mixed crystal and of the use of a binder containing 12% as well as 14% of aluminium. The increase in weight is very low, especially for the materials of a high content of mixed crystal (figure 49). When judging these values we have to take the fact into account that a part of the MoO_3 which is formed during the oxidation is vaporizing and therefore the low increase in weight is only apparent. The scale layer is, however, strongly adherent and we can characterize the materials of a high content of carbide as of a good scale resistance even at 1100°C

The increase in weight of the alloys containing TiC-VC mixed crystals is also low (figure 50) but the scale layers formed are not adherent and especially, if the binder contains 14% of aluminium, local patches are formed in the scale layer which crack off easily.

The series of alloys No. (9) containing mixed crystals TiC-Cr_3C_2 90/10, especially with large additions of mixed crystals, are materials of an outstanding scale resistance (figure 51). These materials are of the same outstanding property even at 1100°C, provided a content of mixed crystals of more than 15%. If we increase the content of the mixed crystal Cr_3C_2 up to 20%, the alloys made with this mixed crystal are remarkably worse (figure 52).

The wet milled, fine grained specimens of series No. (12) containing the mixed crystal TiC-Cr_3C_2 90/10 and also a binder with molybdenum and aluminium are of an outstanding scale resistance as well (figure 53), though the addition of molybdenum to the carbide free mixture or to the mixtures of a low content of carbide deteriorates somewhat the scale resistance. The alloys, however, with a content of 20 to 30% of mixed crystals are of an outstanding scale resistance up to 1100°C.

11. Forgeability tests

These tests are only permitting a mutual comparison of the quality of the different alloys. Such tests enabled us to find out whether a certain alloy can be densified by hot coining. Forgeability is uniformly decreasing according to an increasing addition of TiC. At a temperature of 1200°C the specimens of a content of up to 20% TiC can be forged rather well. If the content is exceeding to 20% the forgeability is bad. Heated again to higher temperatures, the specimens, no doubt, would become forgeable. If we compare the binders, we find that the pure Fe-Al alloy with 8, 10 or 12% Al respectively and, if necessary, alloyed with chromium are best forgeable. Additions of carbide mixed crystals turn the alloys into very hard ones and consequently they are very difficult to forge. These alloys would even need higher forging temperatures. The alloy Fe-Al-Mo-TiC/Cr_3C_2 90/10 wet milled and subsequently sintered to high density is very difficult to forge as well. The specimens of this composition produced in the usual way, being even more porous, are good forgeable.

Summarizing, we can say that all materials are forgeable and that a hot coining of porous shapes is possible at suitable temperatures.

SUMMARY

The aims of the research were the further development of the idea to alloy titanium carbide and titanium mixed crystals with well known scale resistant and refractory alloys, i.e. alloys which are already in use as "WZ" cemented carbides" containing 35 to 90% TiC and binders of Ni-Cr or of Ni-Cr-Co. It was intended to produce and to examined alloys with a carbide phase of less than 35% and containing various refractory binders on the base of iron.

The carbide components consisted of pure titanium carbide and of titanium carbide with molybdenum carbide, vanadium carbide and chromium carbide. We made use of refractory binding agents like iron aluminium alloys with a content of 8 to 14% of aluminium as well as of the classic alloys for heating elements on the base of Fe-Al-Cr, Fe-Cr-Al and Fe-Al-Mo. We further examined a recently recommended alloy Fe-Al-Mo. The specimens were produced according to the usual procedure of the Powder Metallurgy by mixing the components which were, partly, prealloyed. The resulting powder was cold or hot pressed and sintered in vacuum. In a special series we examined the very promising process of wet milling. The sintered test bars were examined to find out the hot and cold tensile strength, the forgeability and the scaling properties.

The most promising alloys found out among the 12 series of alloys were consisting of a binding agent of iron-aluminium with 12 or 14% of Al and of mixed crystals of titanium carbide - chromium carbide 90/10. A wet milling process applied for a similar alloy containing again some molybdenum brought also materials of very favourable properties which would be recommendable for further investigations.

All alloys examined can be shaped to a certain extent at high temperatures. This property, however, does not change the fact that an addition of carbides to the scale resistant and partly refractory alloys on the base of iron, as examined, is creating materials relatively brittle in cold state but which, on the other hand, are of a good heat resistance.

VI. Suggestions for further investigations

The results of the present investigations show the direction in which we have to proceed with further research work. First there is the wet milling procedure which should be used more in the manufacture of the mixtures. Finely divided components are facilitating the diffusion and result in very dense materials of a high shrinkage. The finely divided carbide phase is presumably also instrumental to the heat resistant properties. The very promising alloys with a binding agent of Fe-Ni-Cr and Fe-Al-Cr should be examined in this respect.

We think we could counteract the brittleness in cold state presumably by varying the composition of the binder as well as of the carbide phase and the wet milling process will be, as already mentioned, of importance for the production of the powder mixtures. As the mixed crystal $TiC-Cr_3C_2$ 90/10 is most favourable in every respect it should be submitted to a close examination, testing contents of chromium carbides of 3, 5 and 15%. The alloys acting as binding agents offer many possibilities. Special attention should be paid to forgeable alloys like a nickel cobalt chromium alloy (Timken), the alloy nickel chromium titanium (Tinidur) and the alloy nickel chromium vanadium titanium (Vanidur) as well as Kanthal alloys with 5 or 10% of Al and 30% of Cr. An addition of 0.5 to 5% of silicon to an iron chromium binder with 20 to 30% would be of interest. Further, the influence of additions of oxides on the refractory properties of the alloys with a content of iron aluminium binders should be examined.

As to the examination of the materials, we think that it would be advisable to determine, besides the usual methods to find out the properties in cold and warm state, the endurance limit as well as the creep of at least of some most promising alloys.

Further, it should be advisable to be more exact when making tests like hot forging, hot rolling and hot recompressing and it is especially recommendable to examine the mechanical properties of the compacted materials both in cold and hot state.

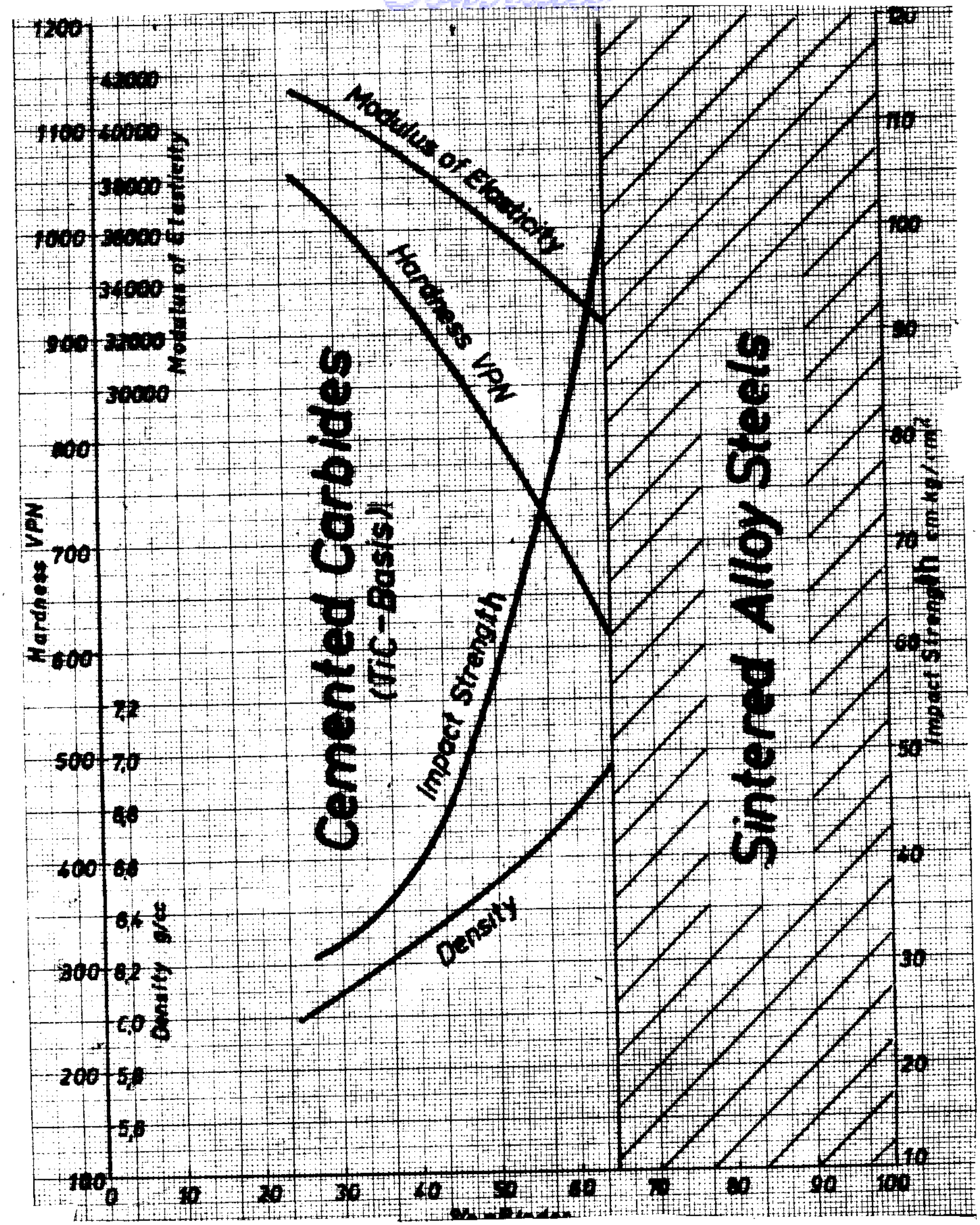

Figure 1. Properties of WZ alloys (TiC with Ni-Co-Cr binder)

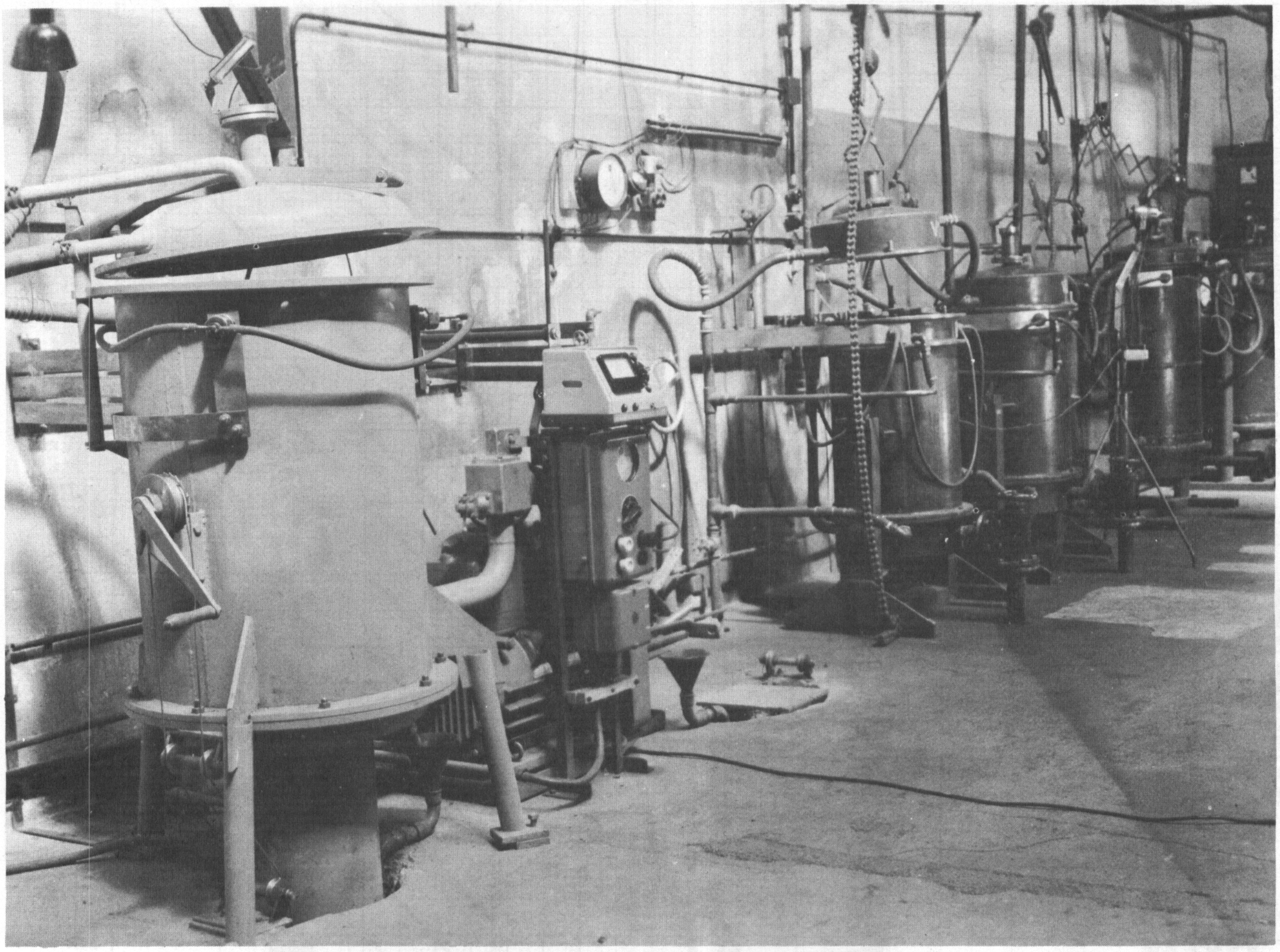

Figure 2: Vacuum furnaces with molybdenum heating elements up to 1400°C. Vacuum pumps and transformers are below the furnaces.

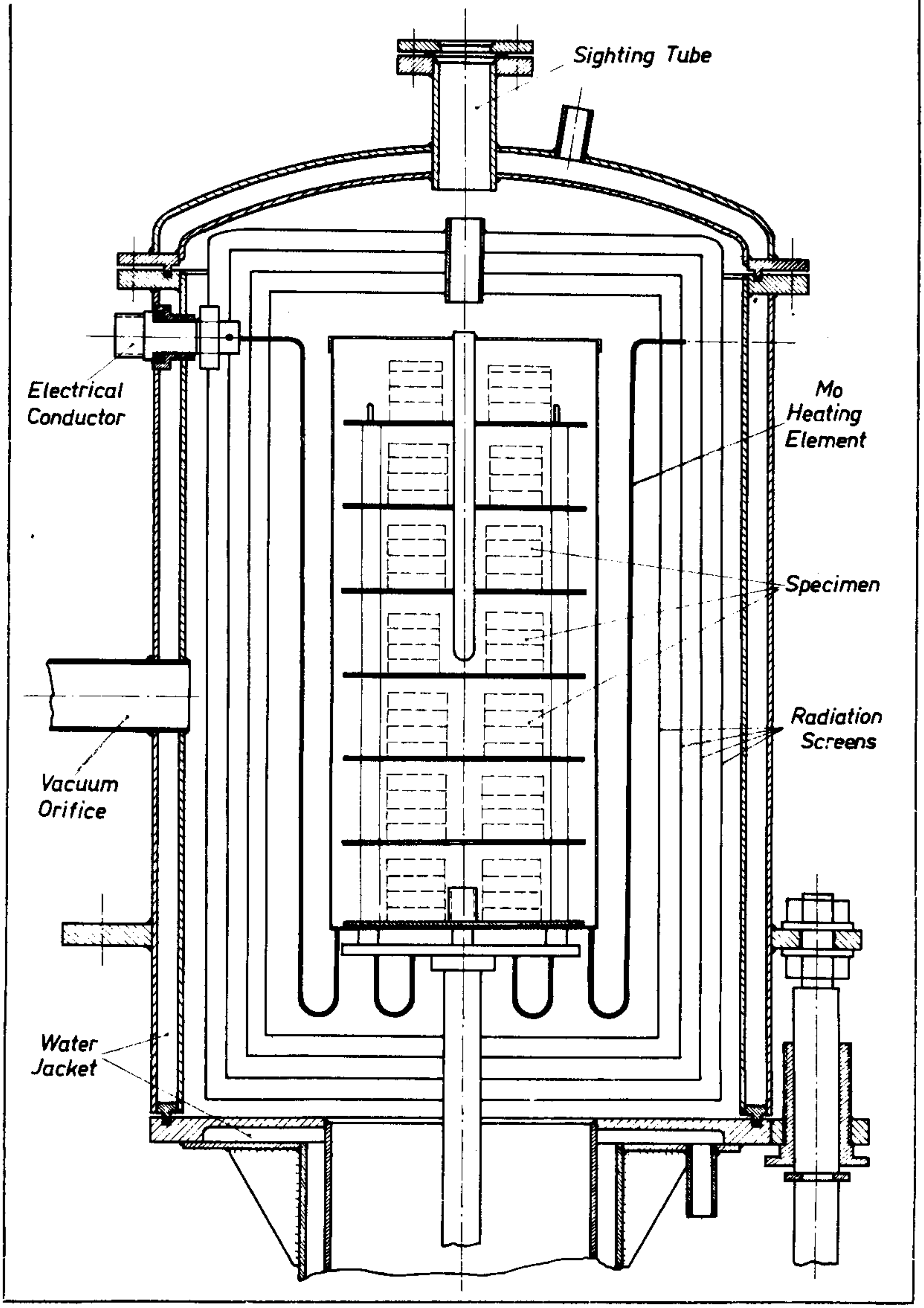

Figure 3. Vacuum sinter furnace with molybdenum heating element, diagrammatic view.

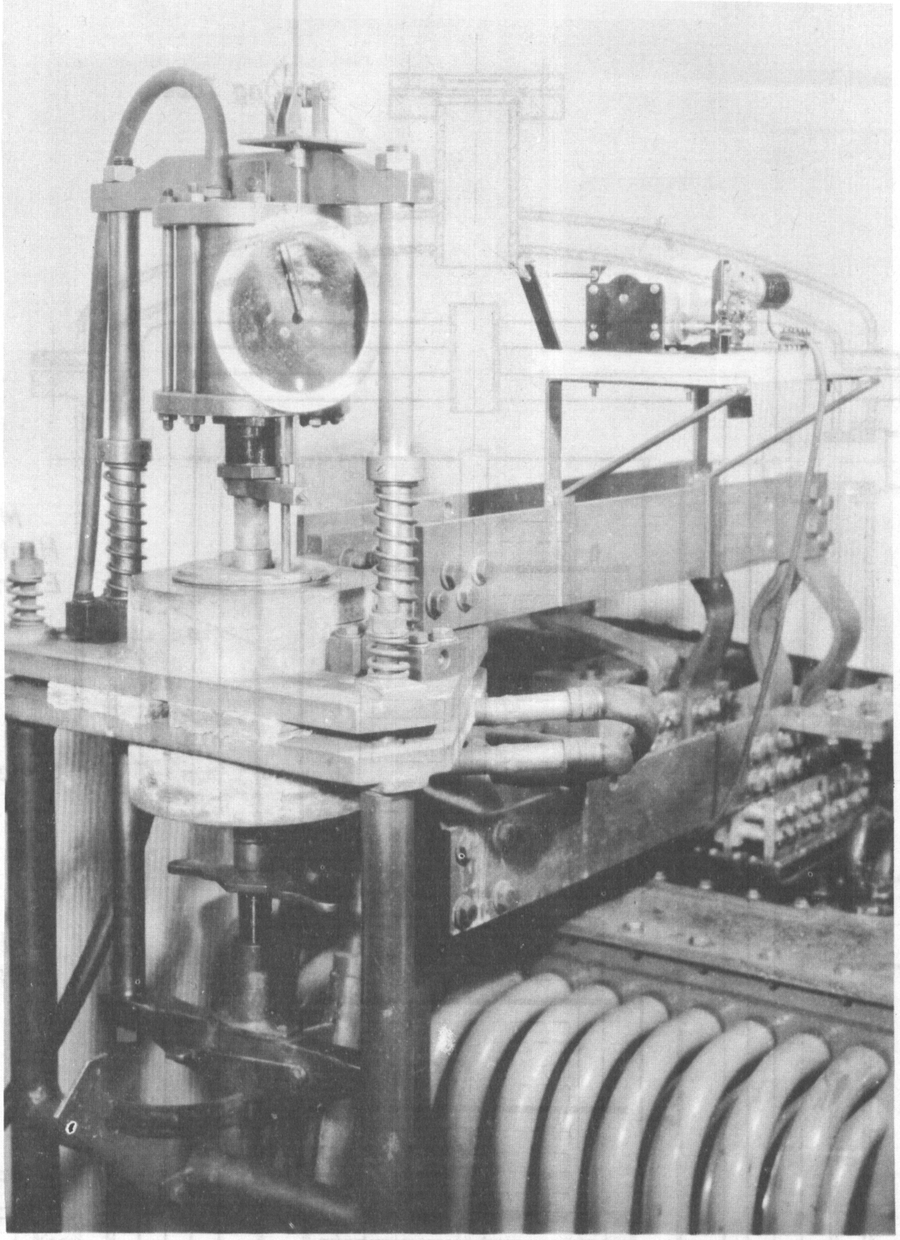

Figure 4: Equipment for hot pressing

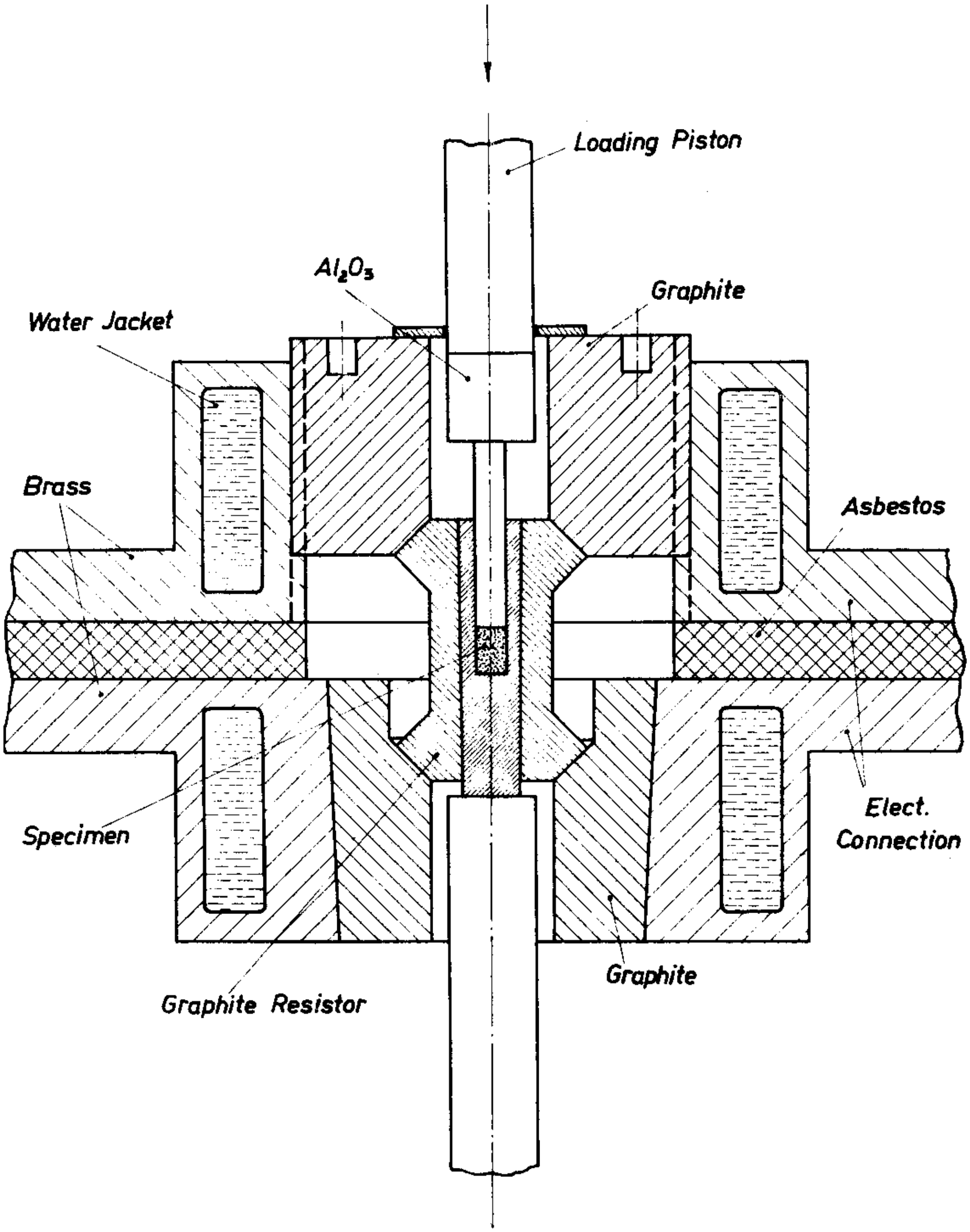

Fig. 5: Equipment for hot pressing, diagrammatic view.

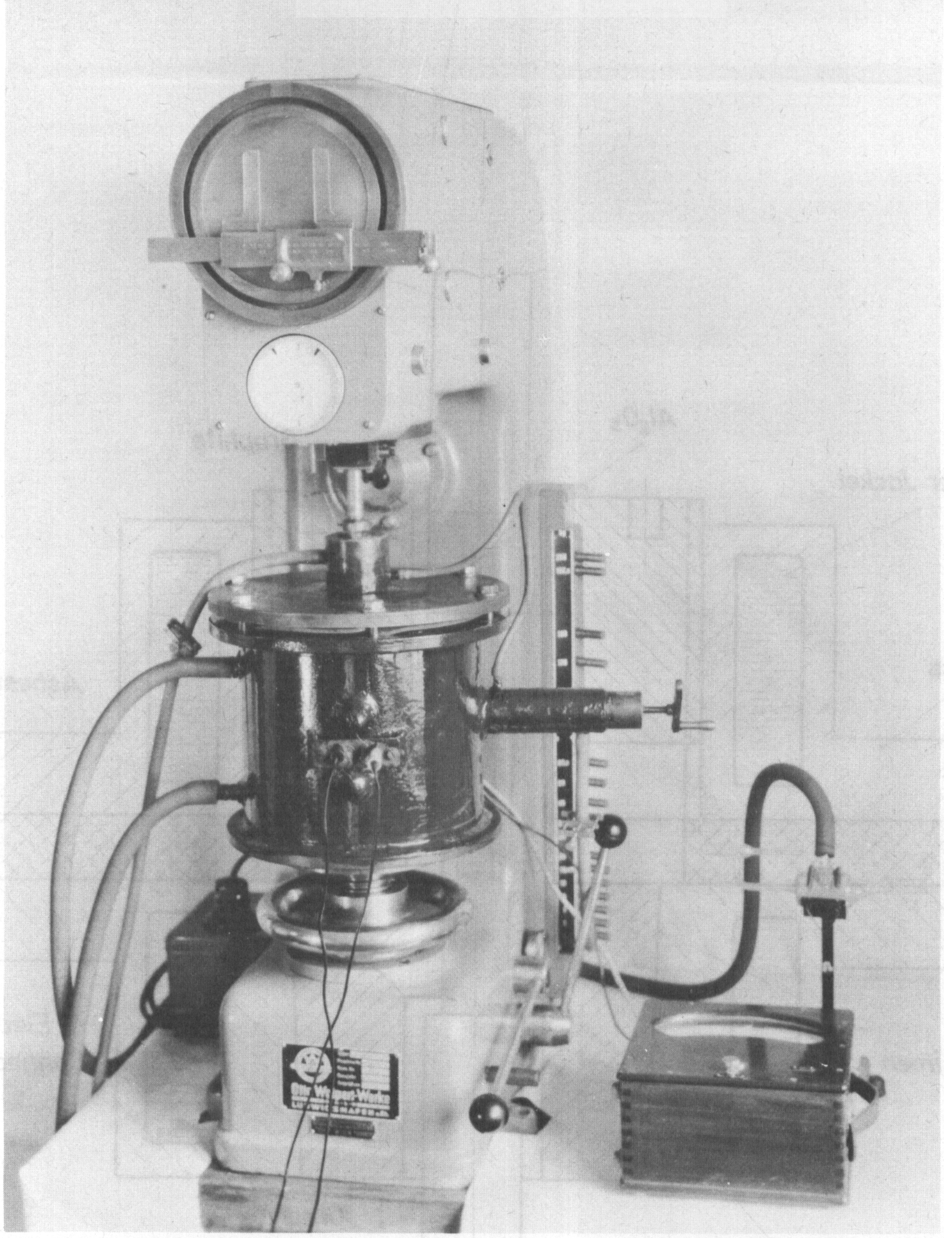

Figure 6: Apparatus for hardness tests at high temperatures

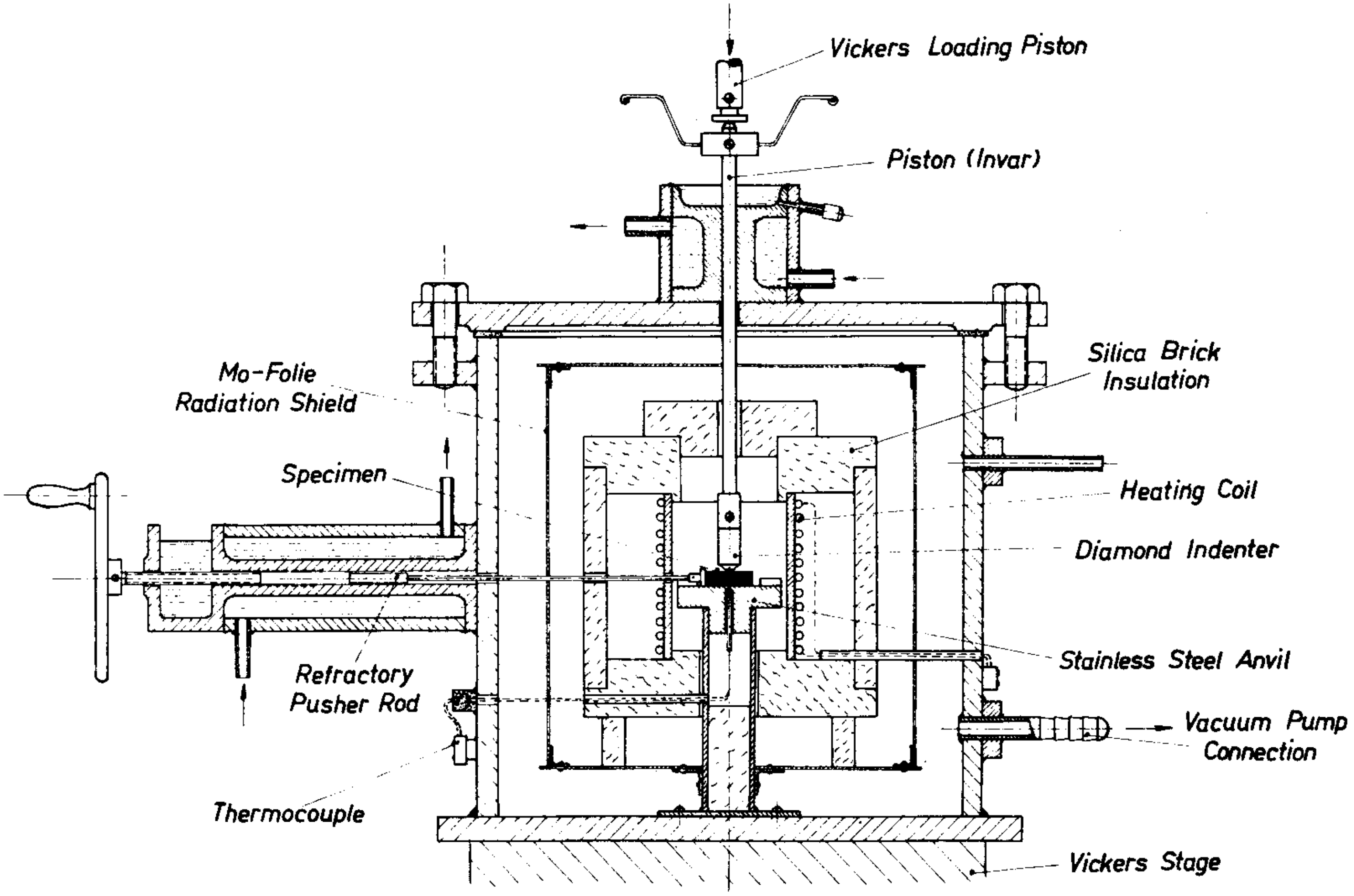

Figure 7. Apparatus for hardness tests at high temperatures, diagrammatic view

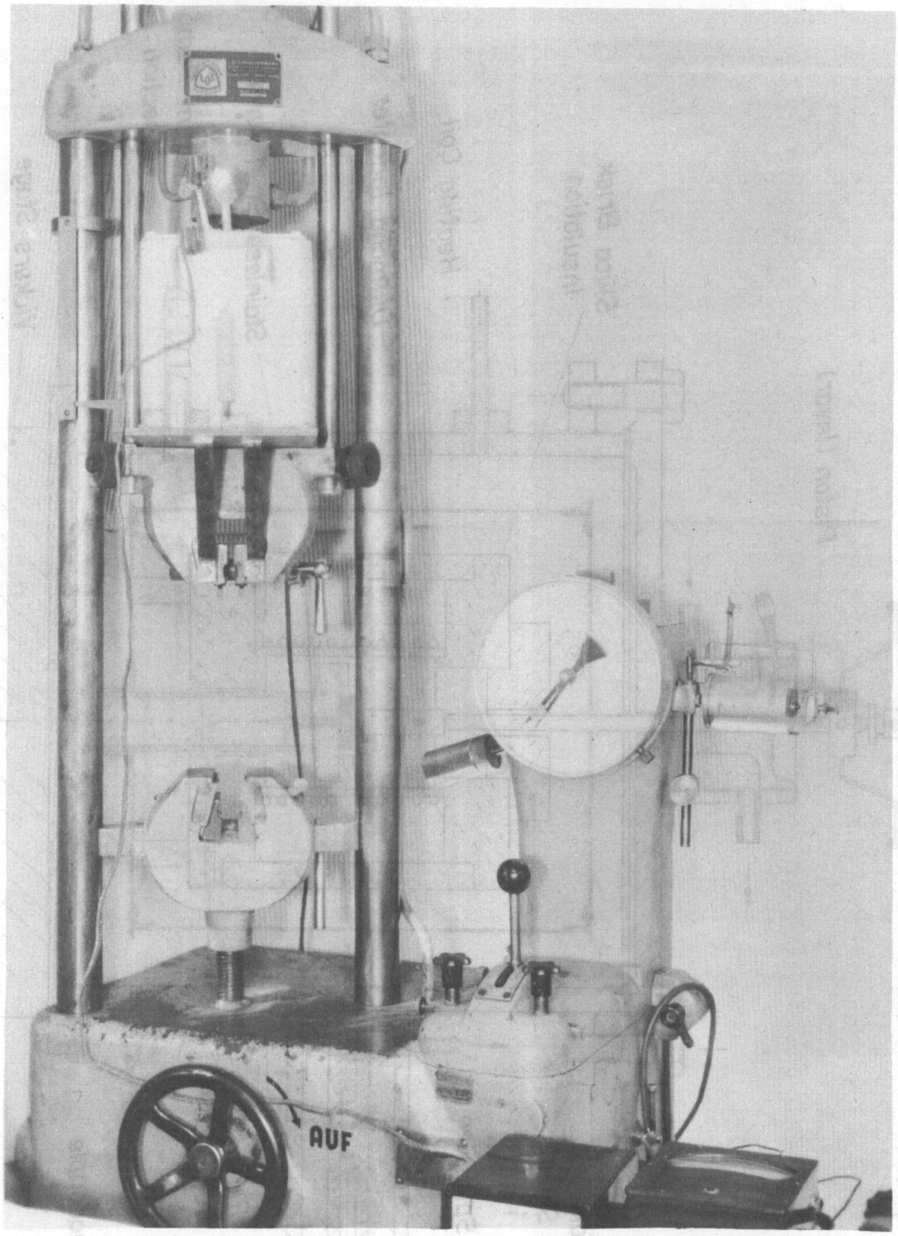

Figure 8: Equipment for determining the transverse rupture strength at high temperatures

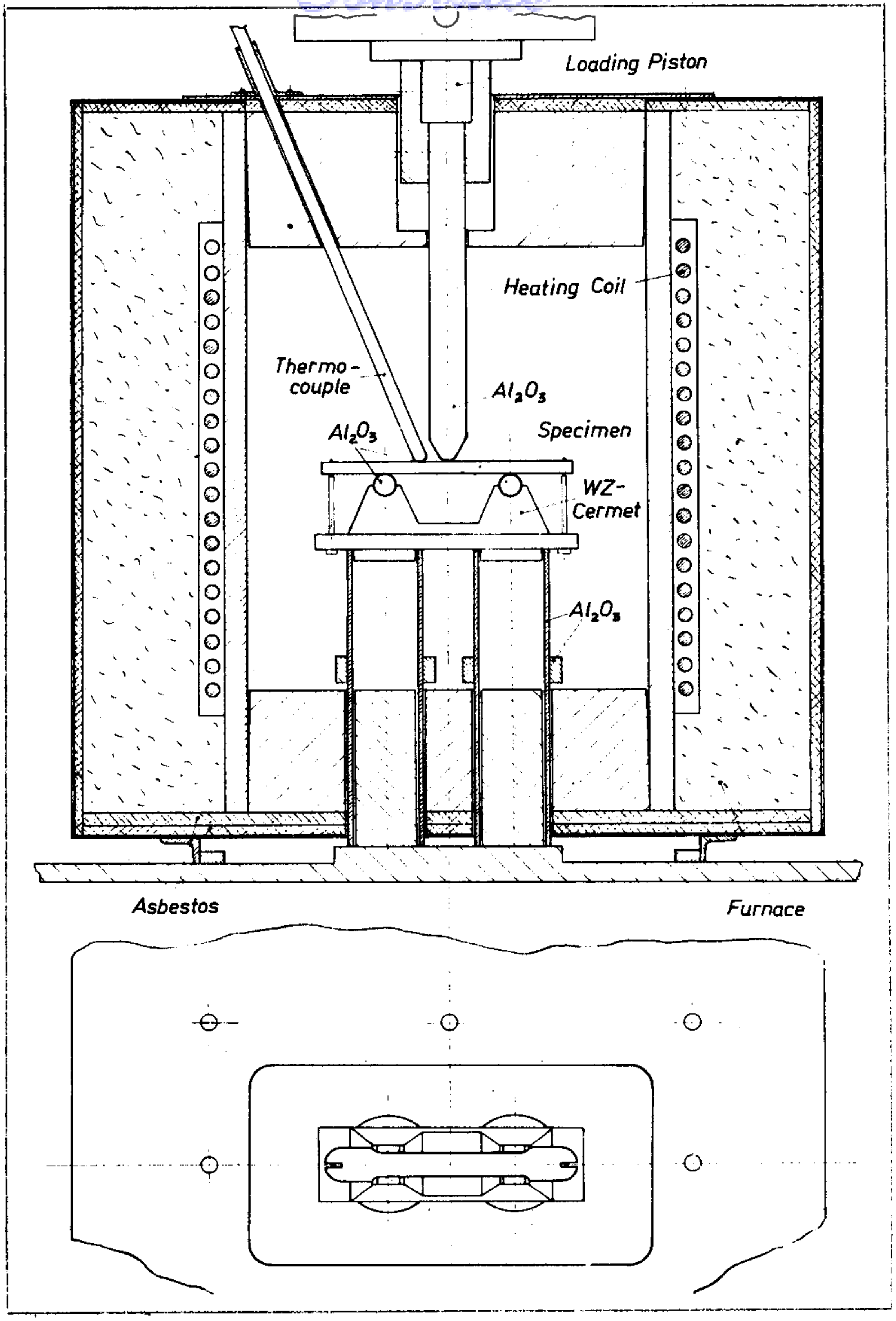

Figure 9. Equipment for determining the transverse rupture strength at high temperatures, schematic

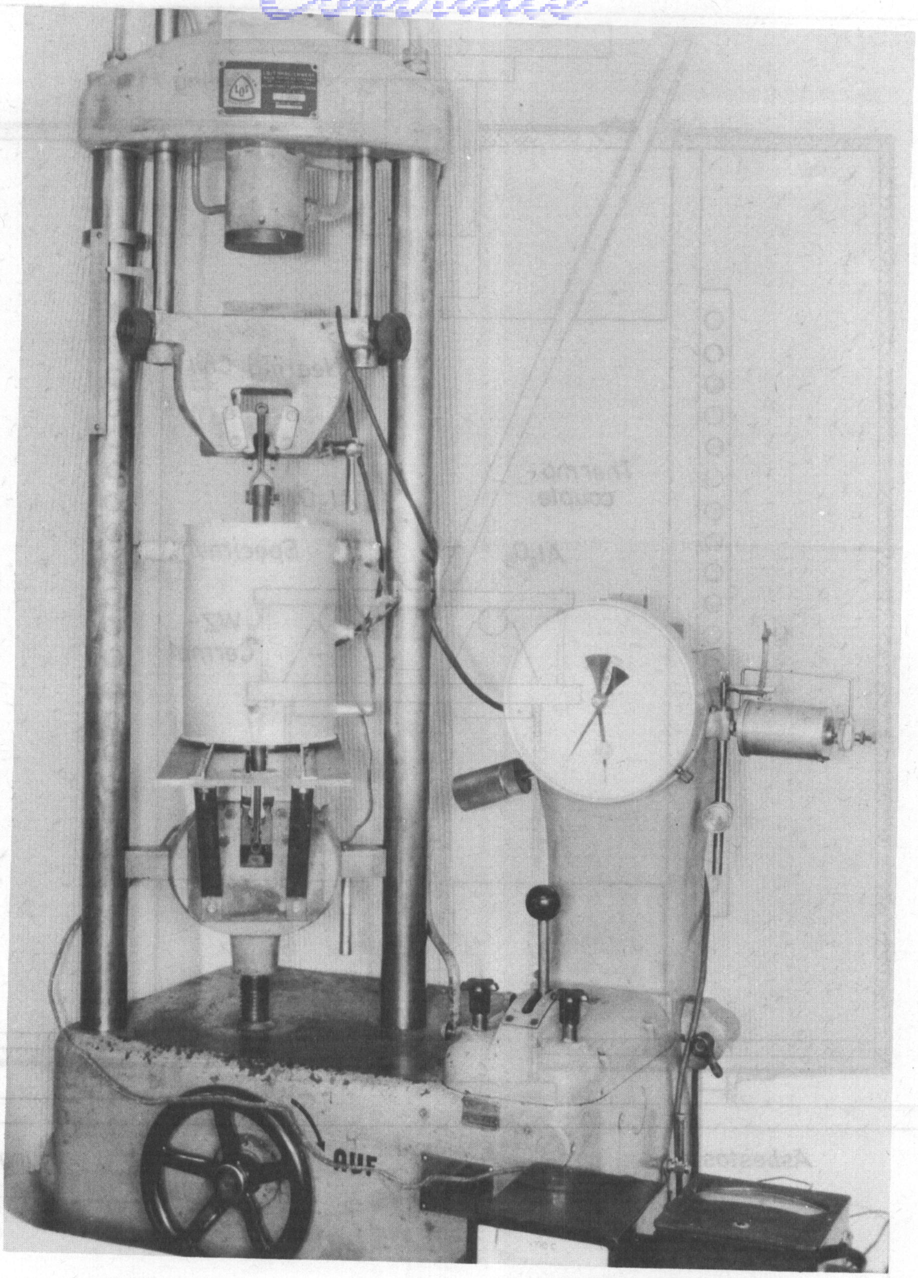

Figure 10: Equipment for determining the tensile strength at high temperatures.

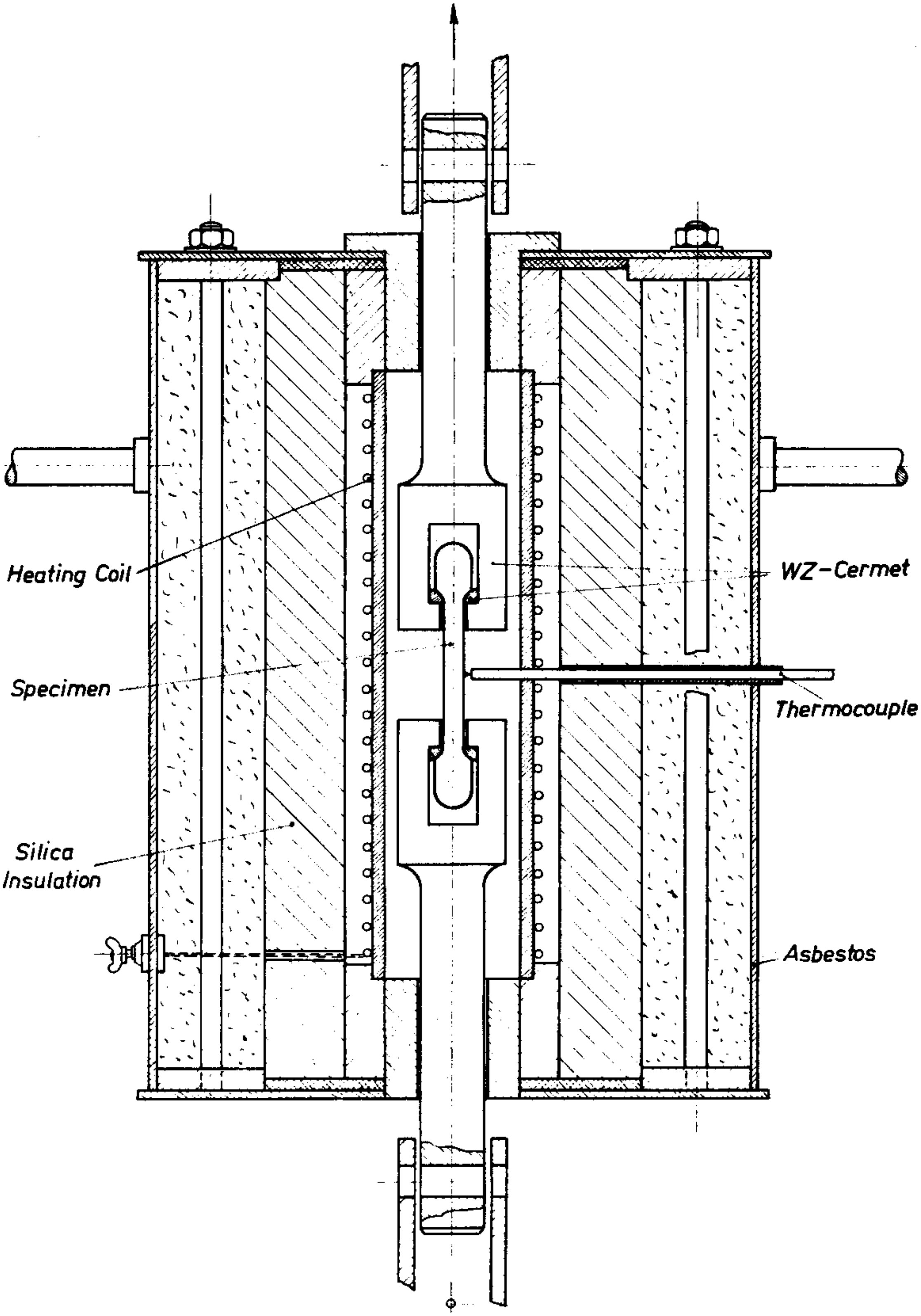

Figure 11. Equipment for determining the tensile strength at high temperatures, schematic

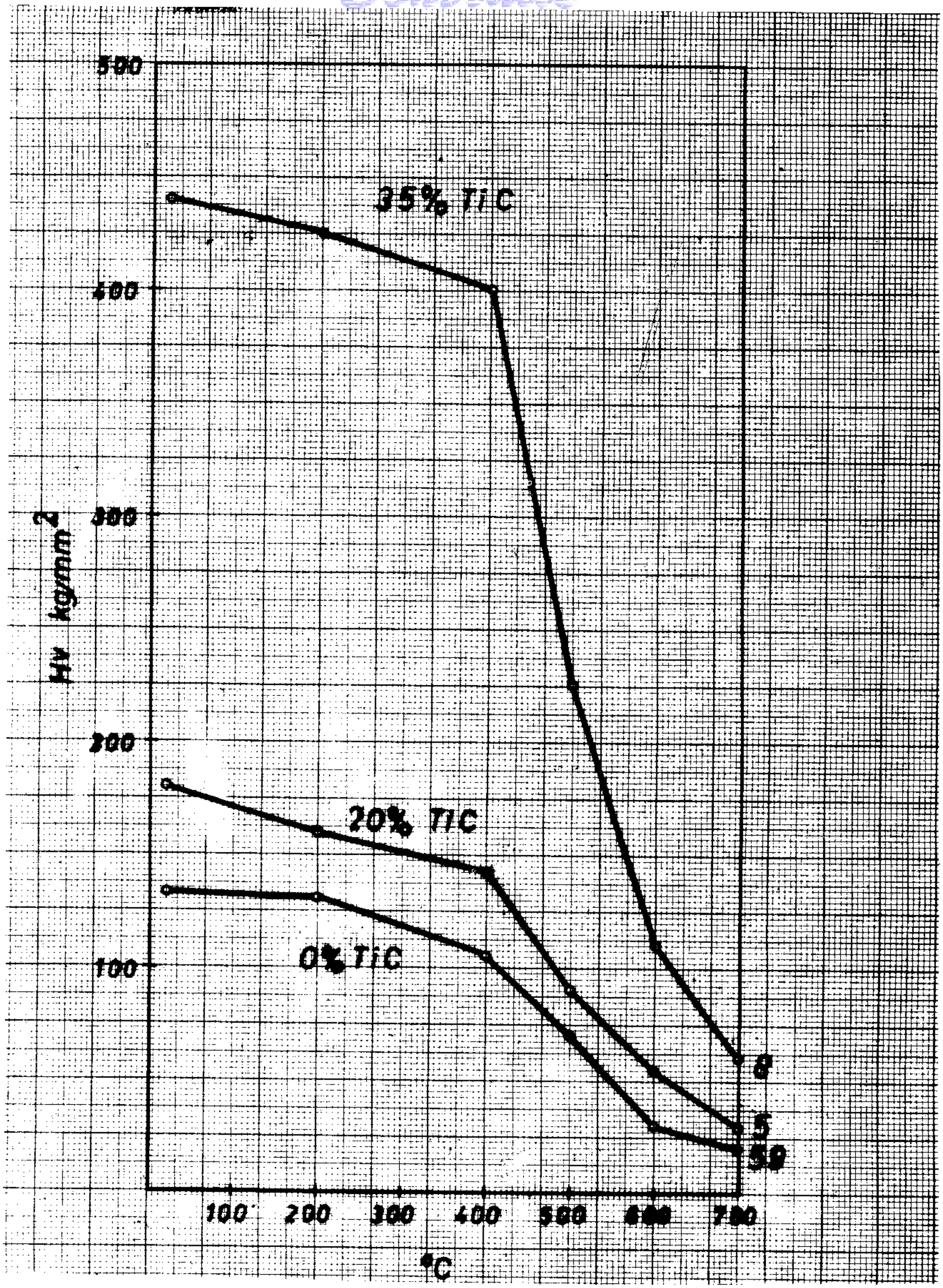

Figure 12. Hot hardness Fe-8Al-TiC (1)

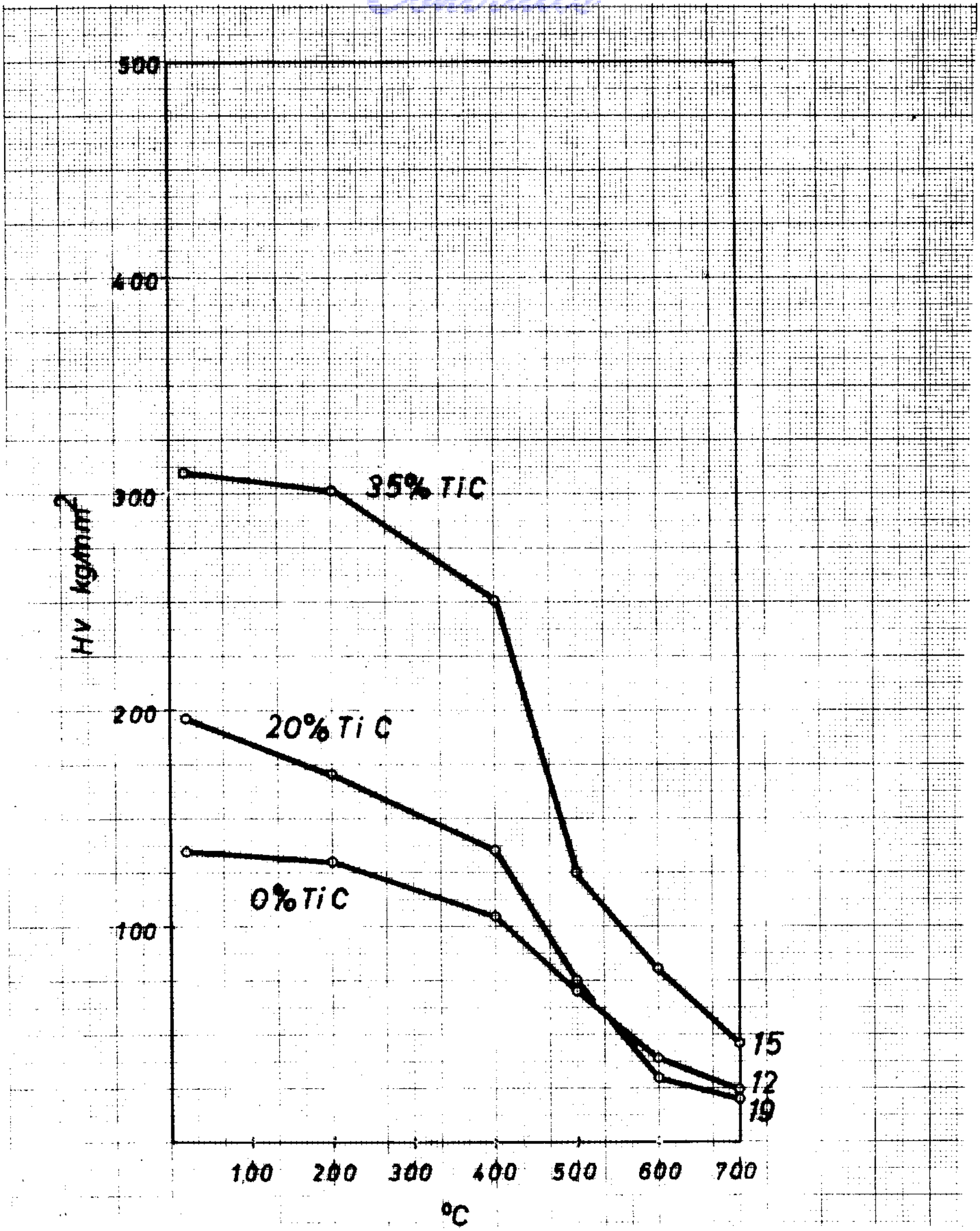

Figure 13. Hot hardness Fe-10Al-TiC (2)

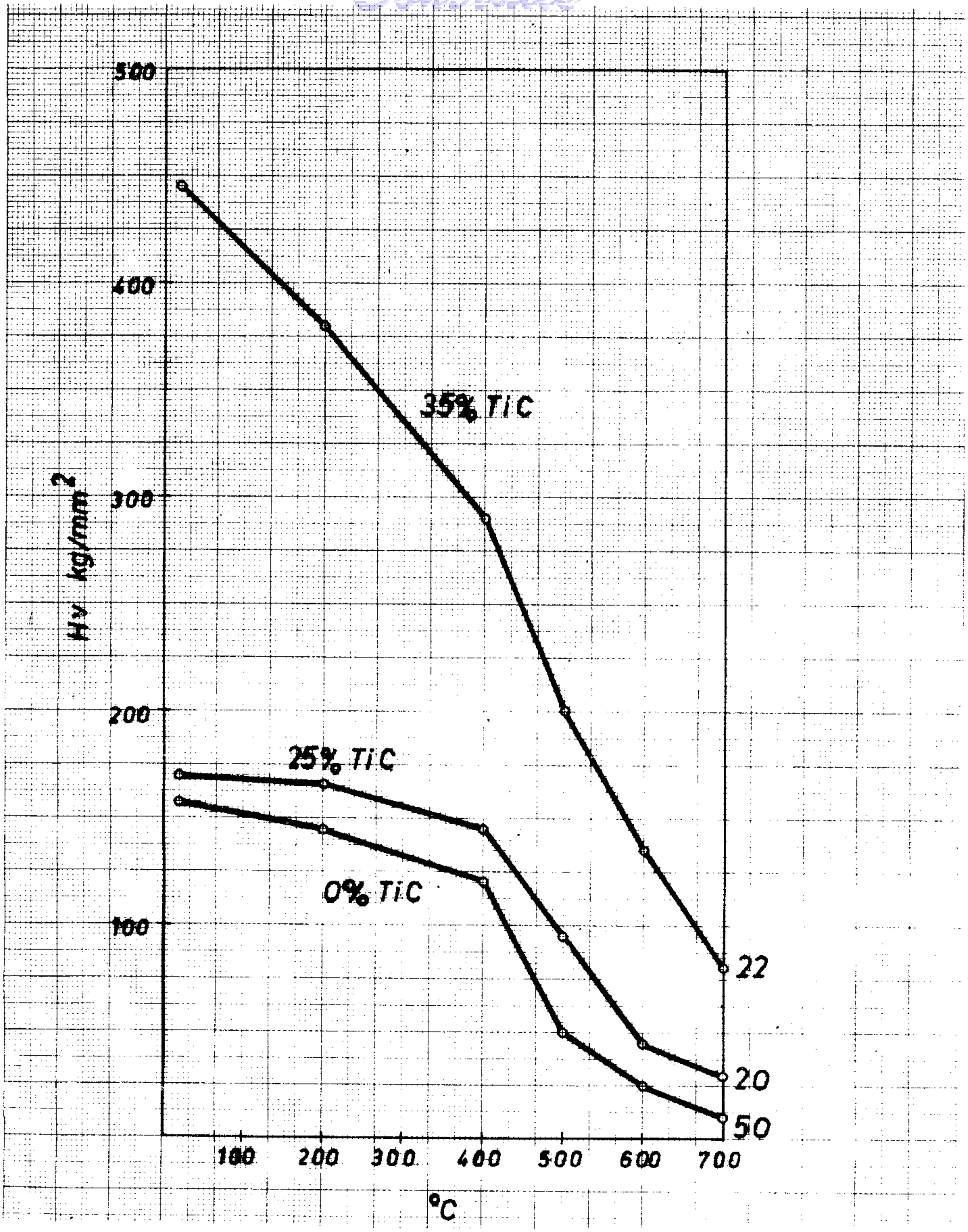

Figure 14. Hot hardness Fe-12Al-TiC (3)

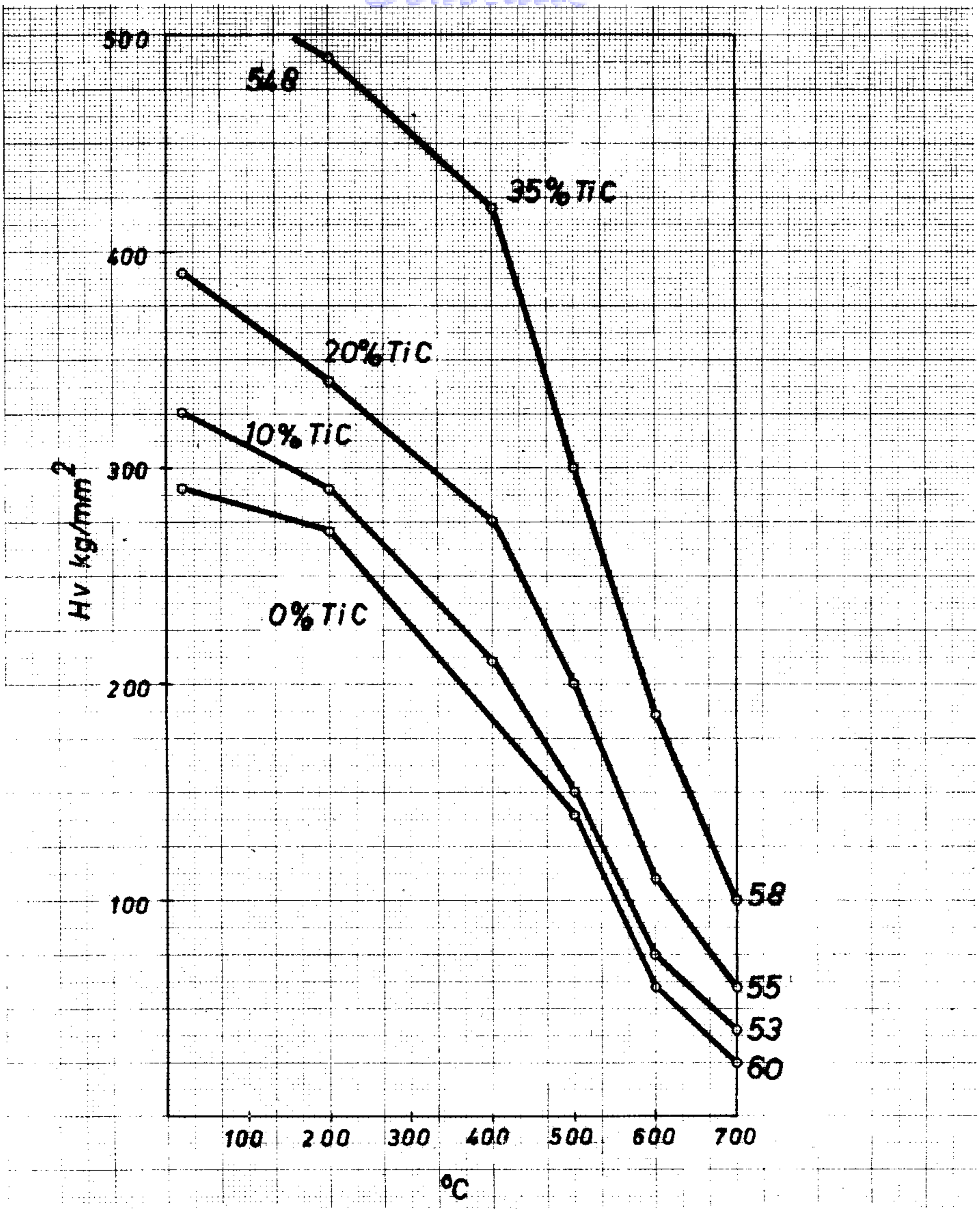

Figure 15. Hot hardness Fe-12Al-TiC-B (4)

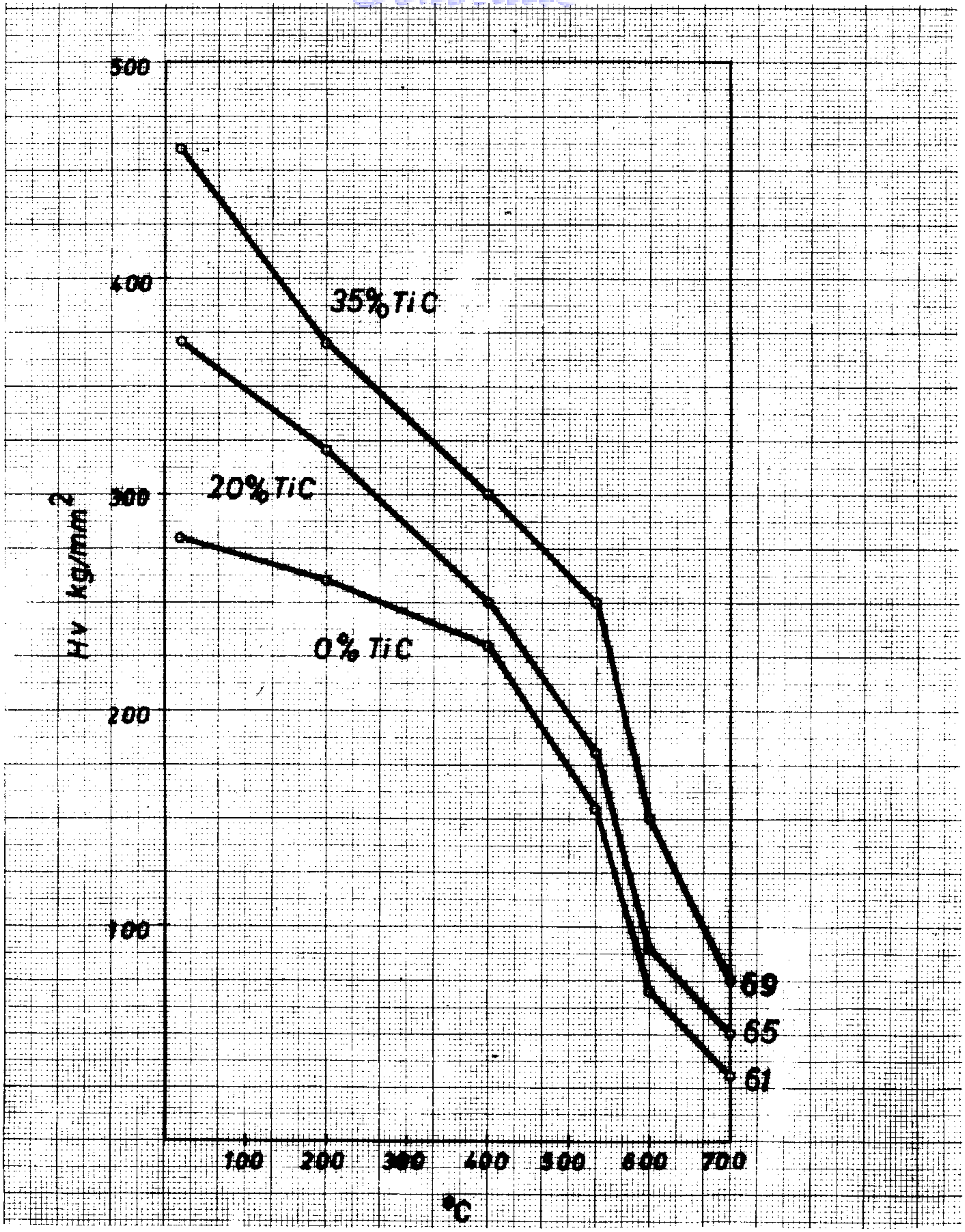

Figure 16. Hot hardness Fe-Al-Cr-TiC-B (5)

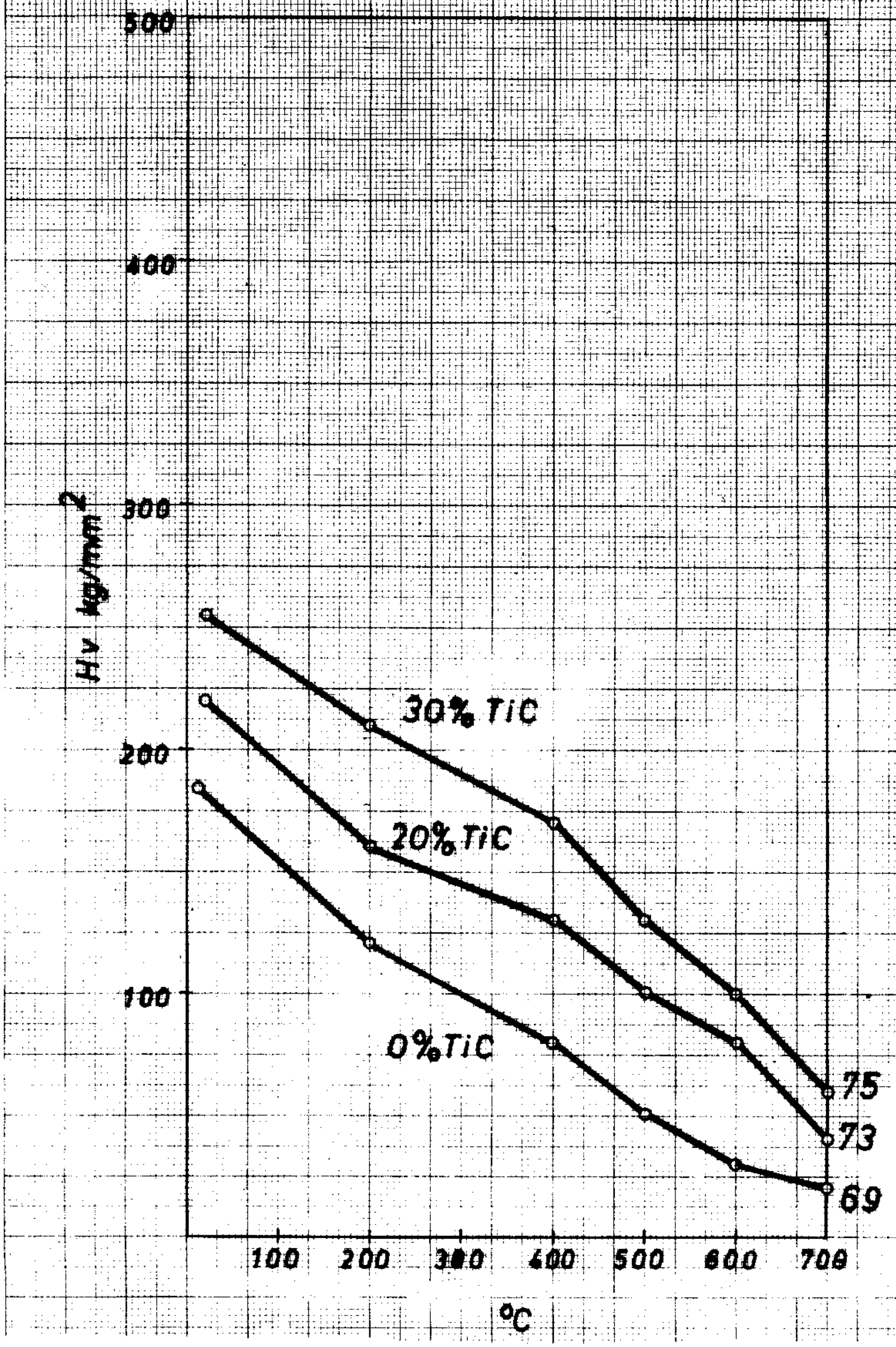

Figure 17. Hot hardness Fe-Cr-Al-TiC-B (6)

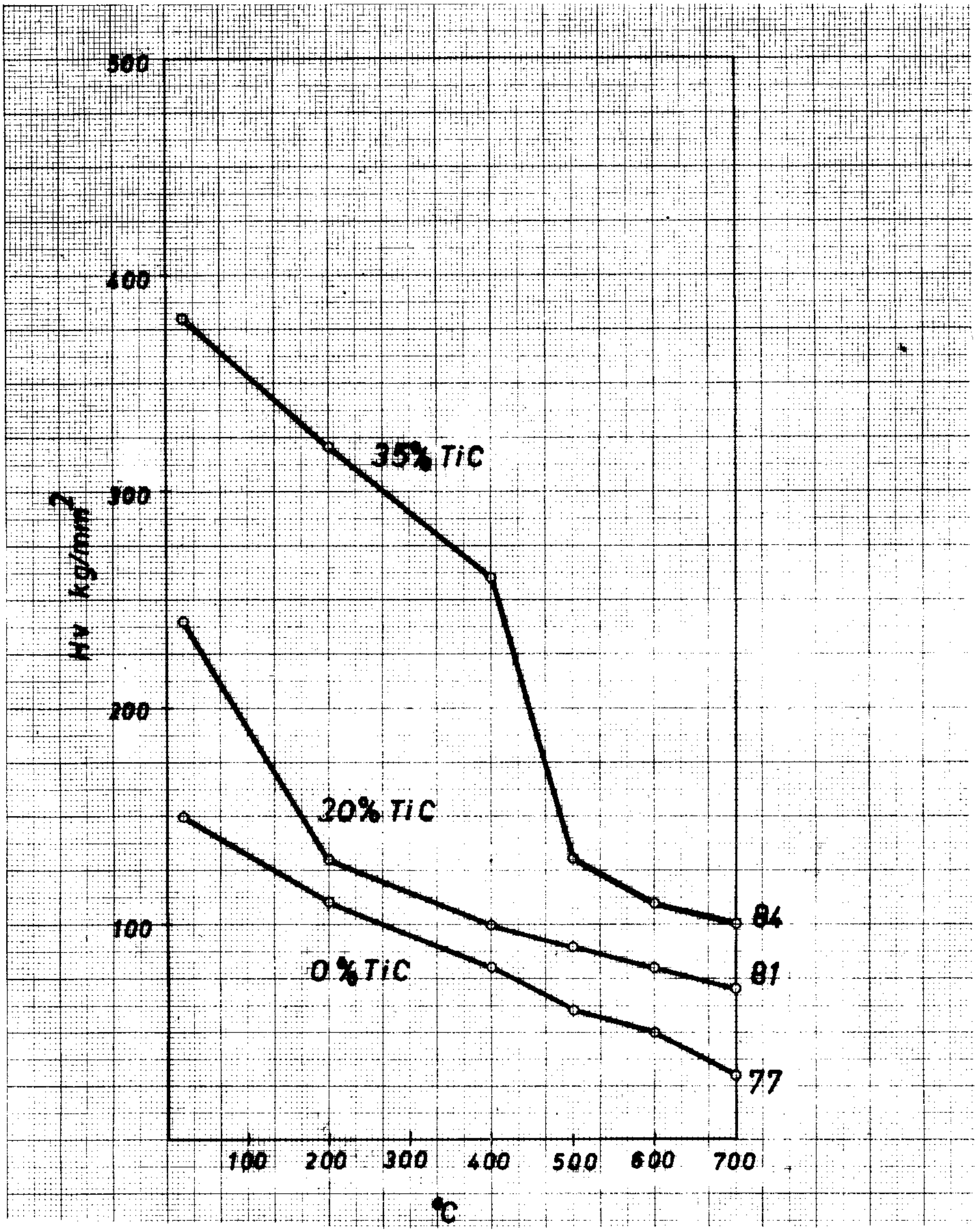

Figure 18. Hot hardness Fe-Ni-Cr-TiC-B (7)

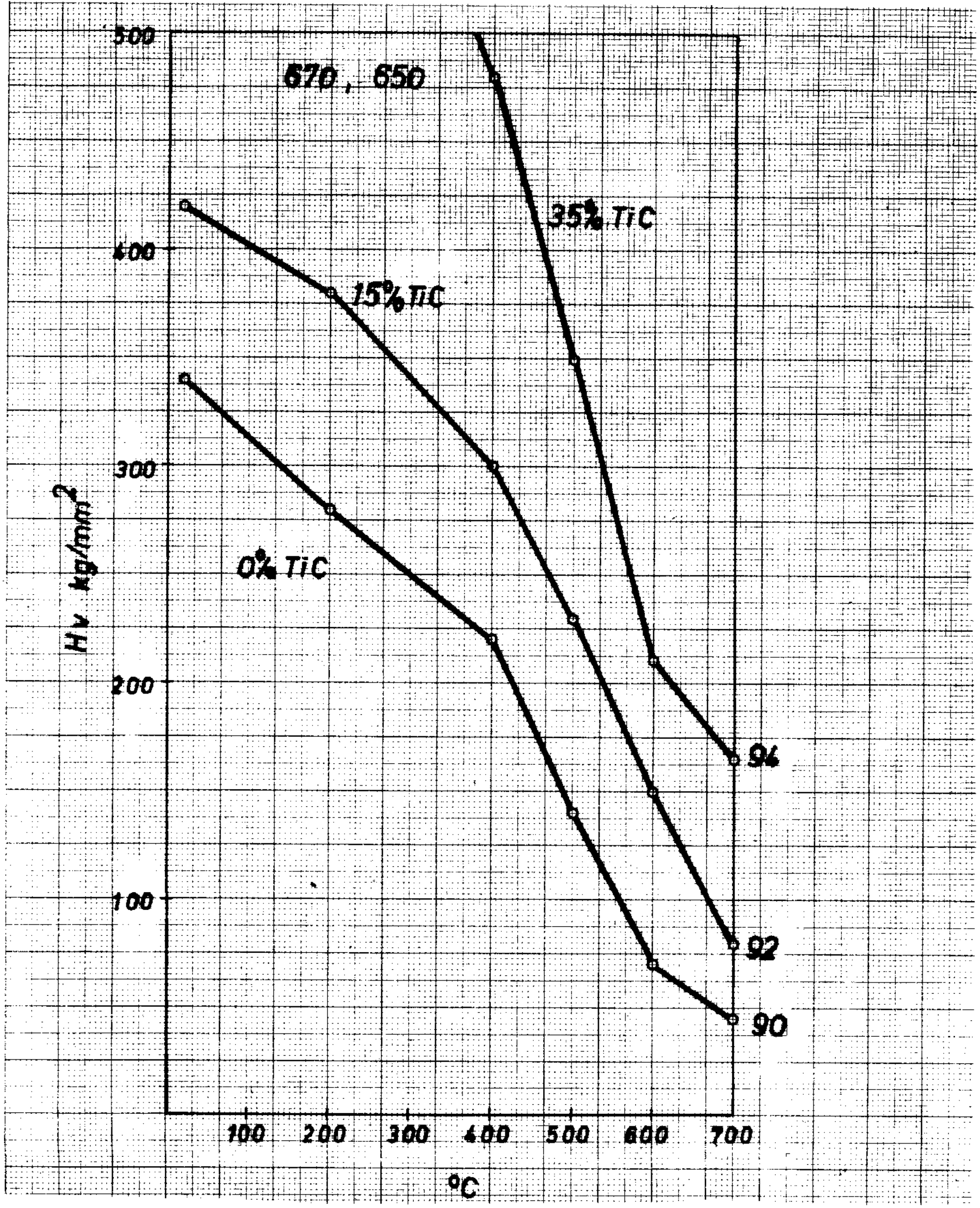

Figure 19. Hot hardness Fe-14Al-TiC/Mo_2C-B (8)

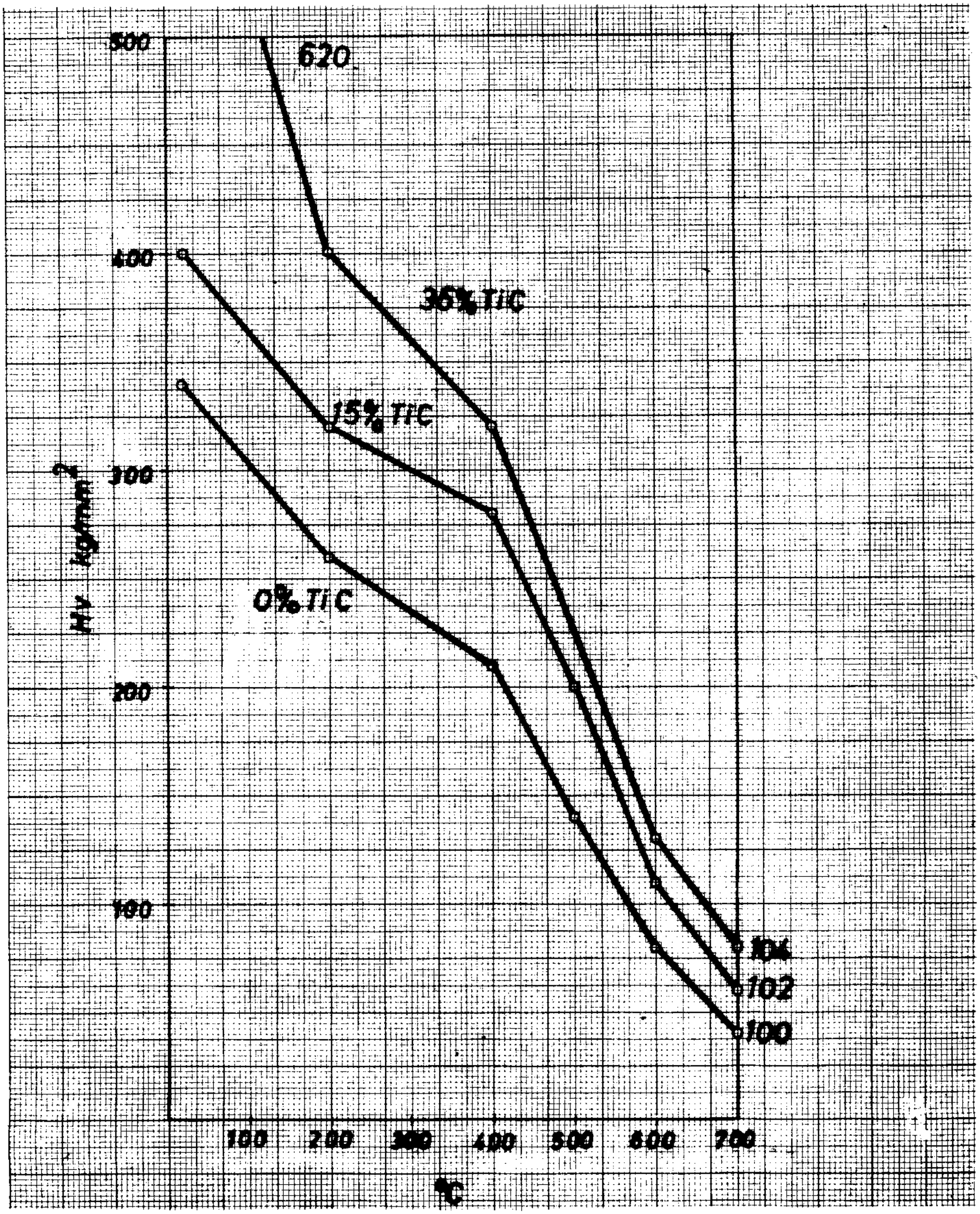

Figure 20. Hot hardness Fe-14Al-TiC/VC-B (9)

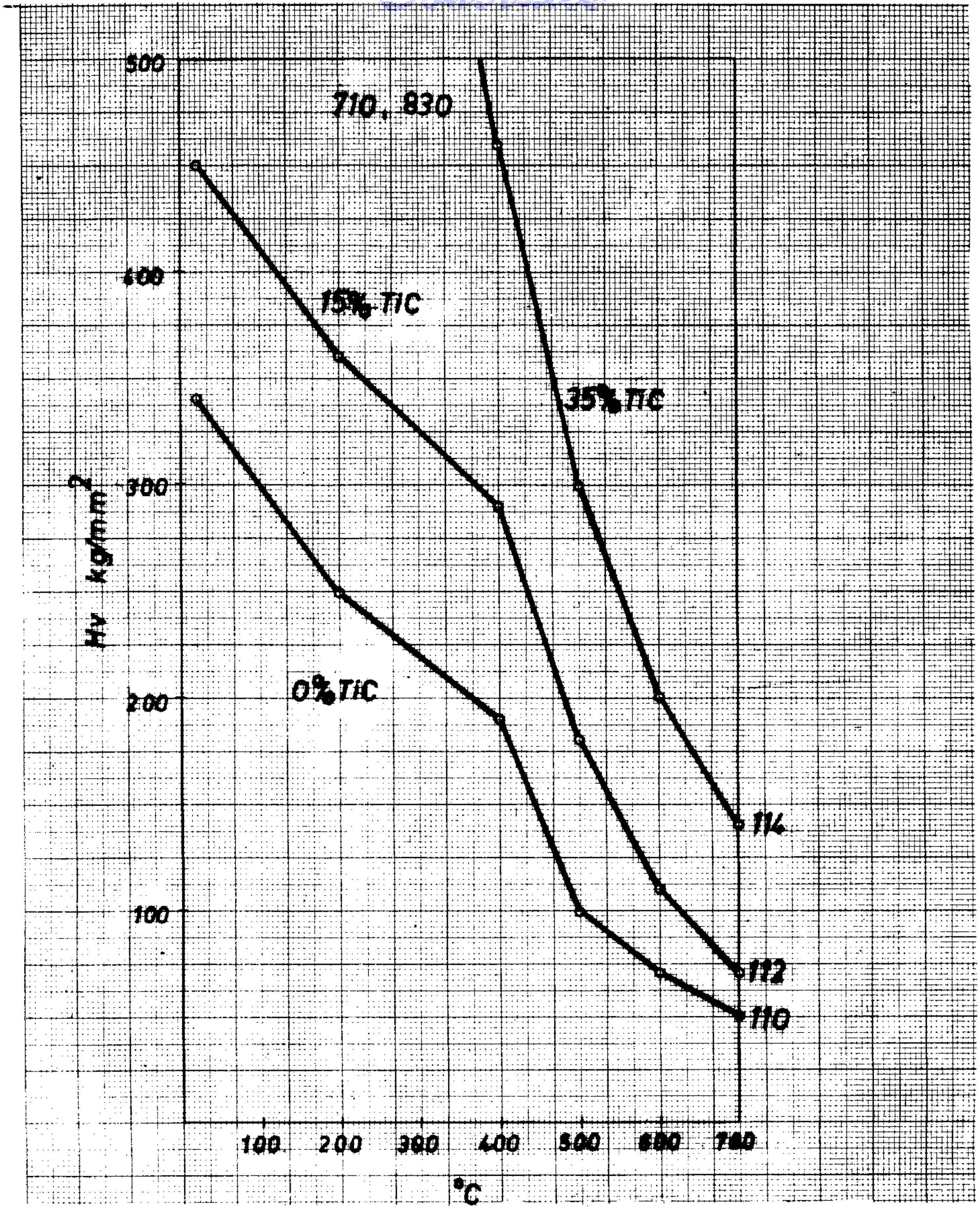

Figure 21. Hot hardness Fe-14Al-TiC/Cr_3C_2 90/10-B (10)

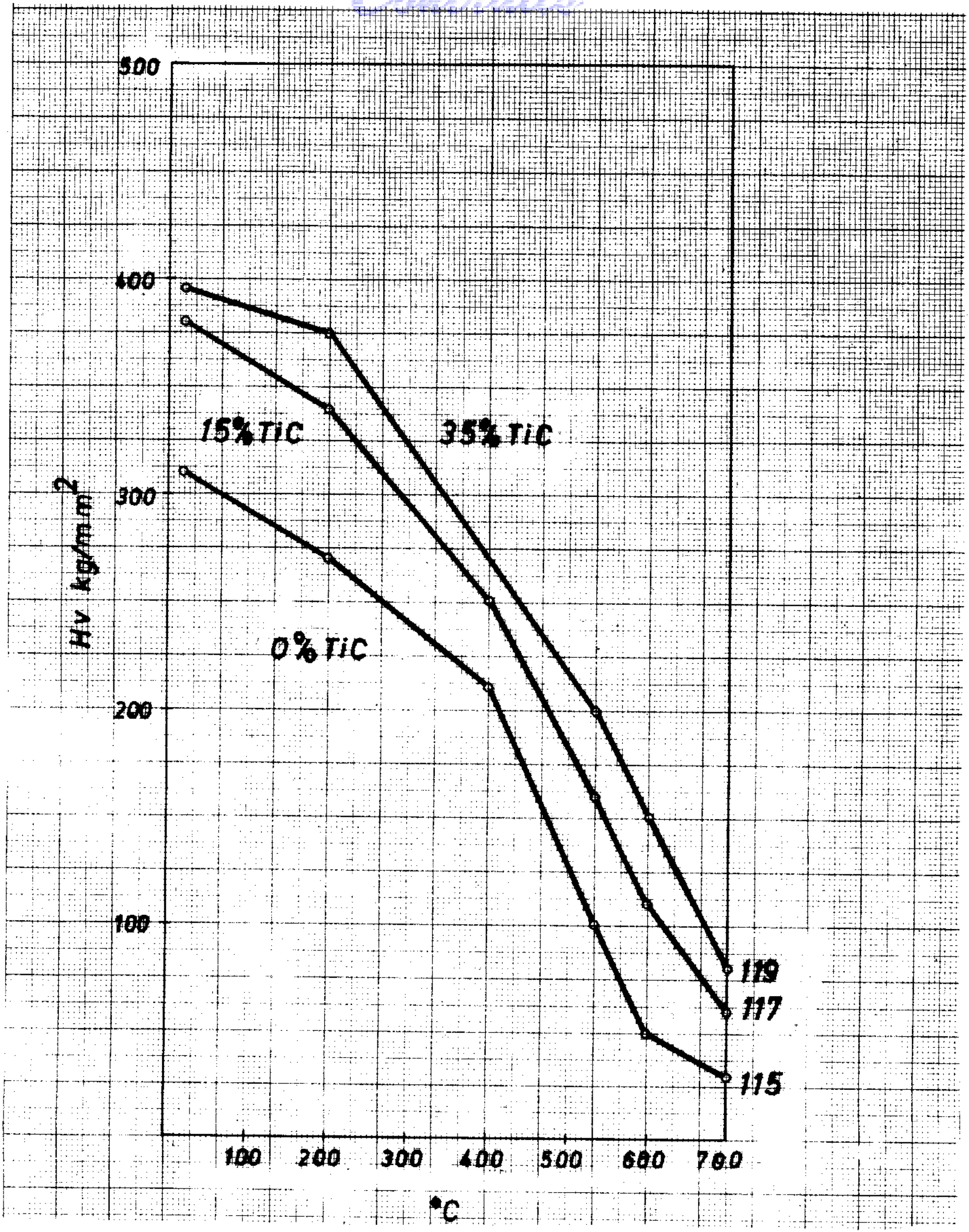

Figure 22. Hot hardness Fe-14Al-TiC/Cr_3C_2 80/20-B (11)

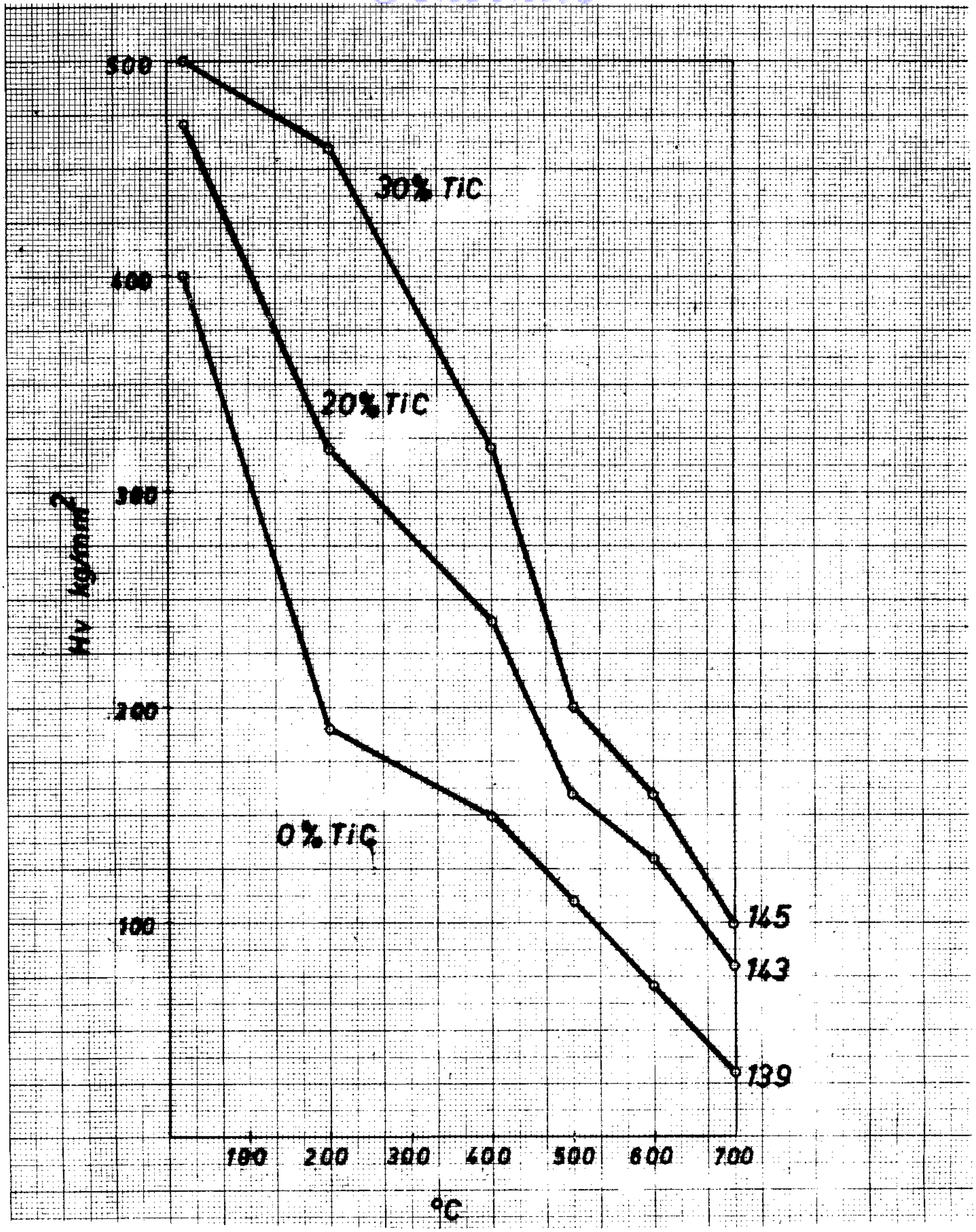

Figure 23. Hot hardness Fe-Al-Mo-TiC/Cr_3C_2 90/10-B wet milled (12)

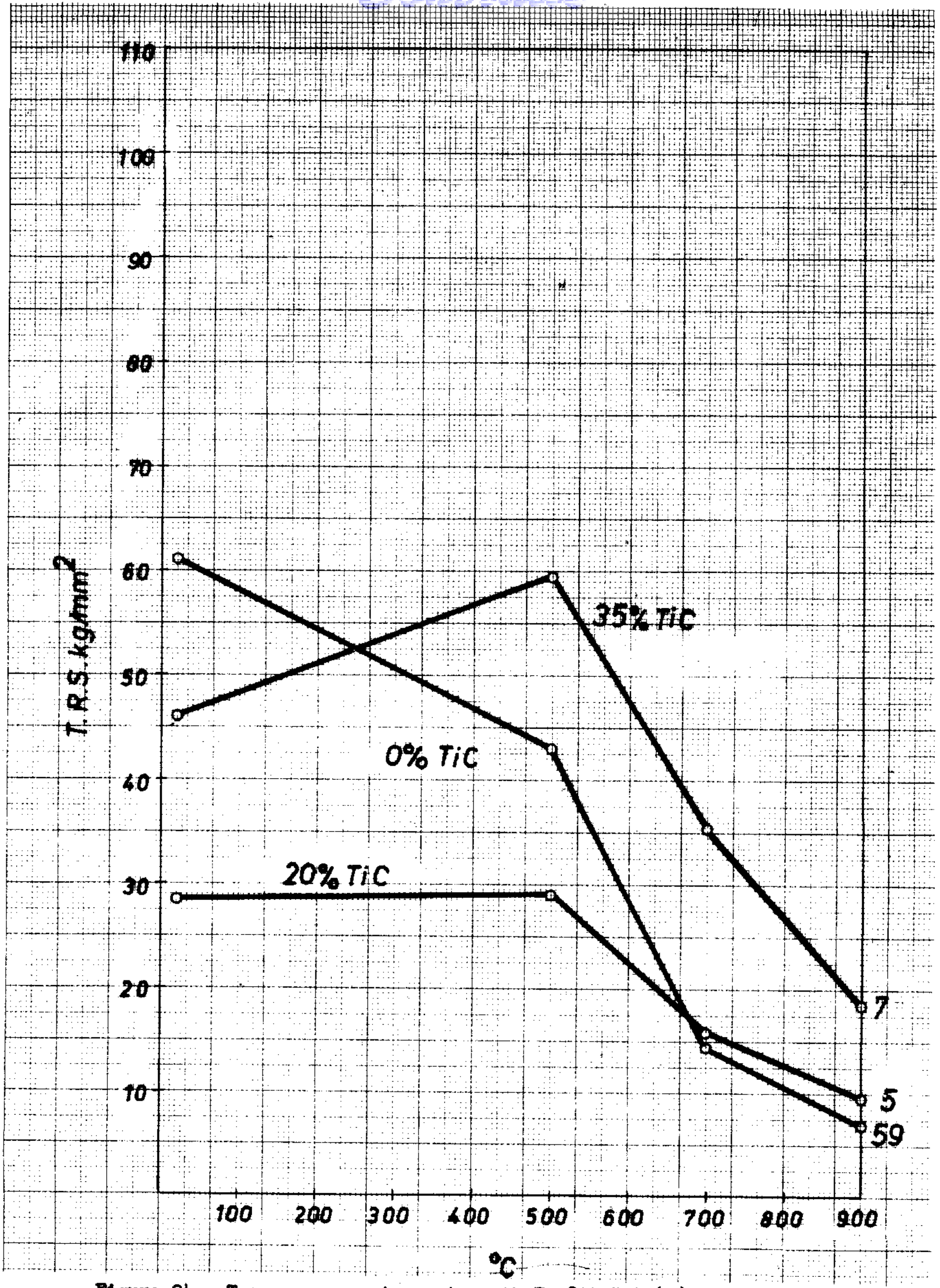

Figure 24. Transverse rupture strength Fe-8Al-TiC (1)

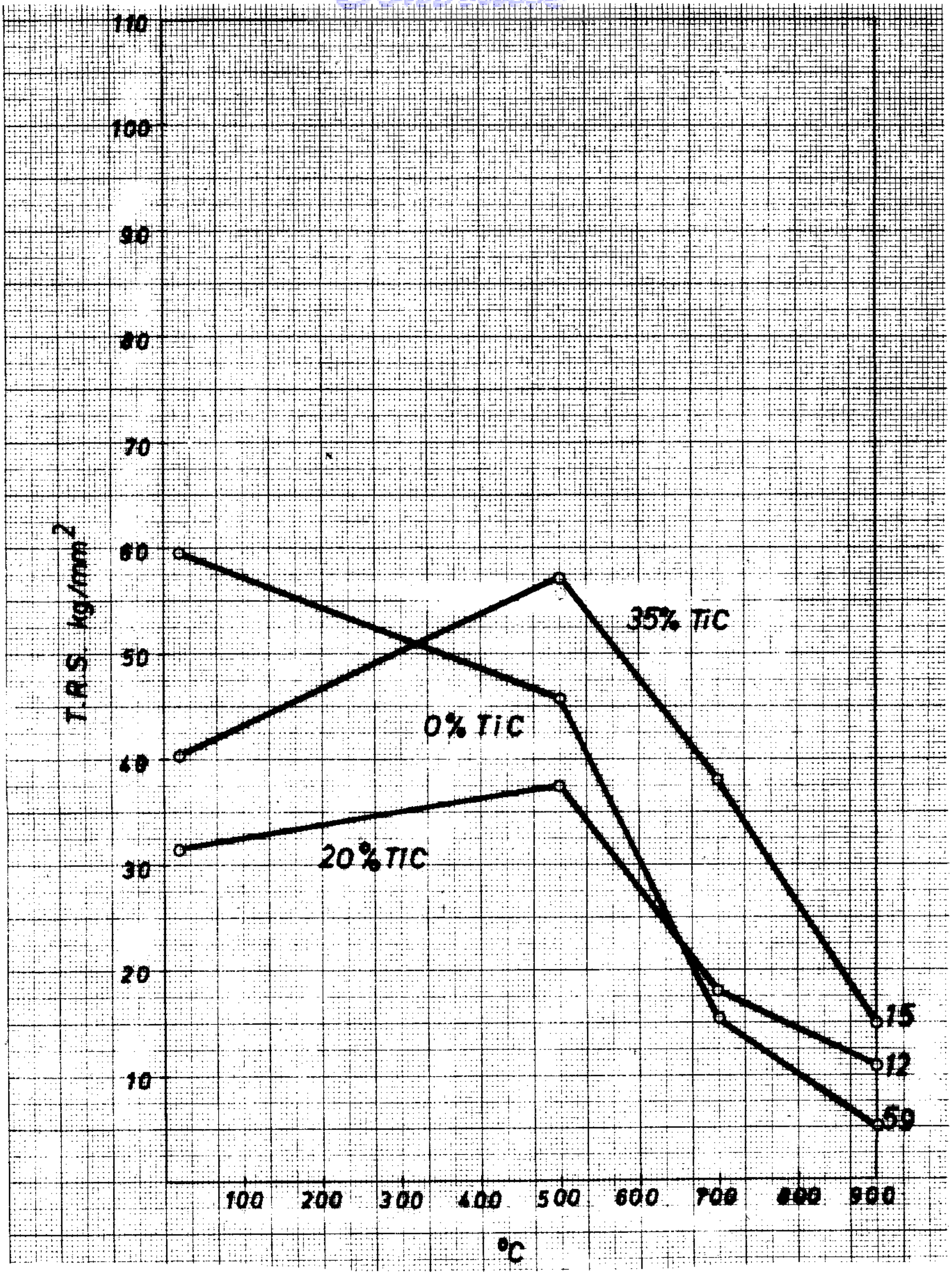

Figure 25. Transverse rupture strength Fe-10Al-TiC (2)

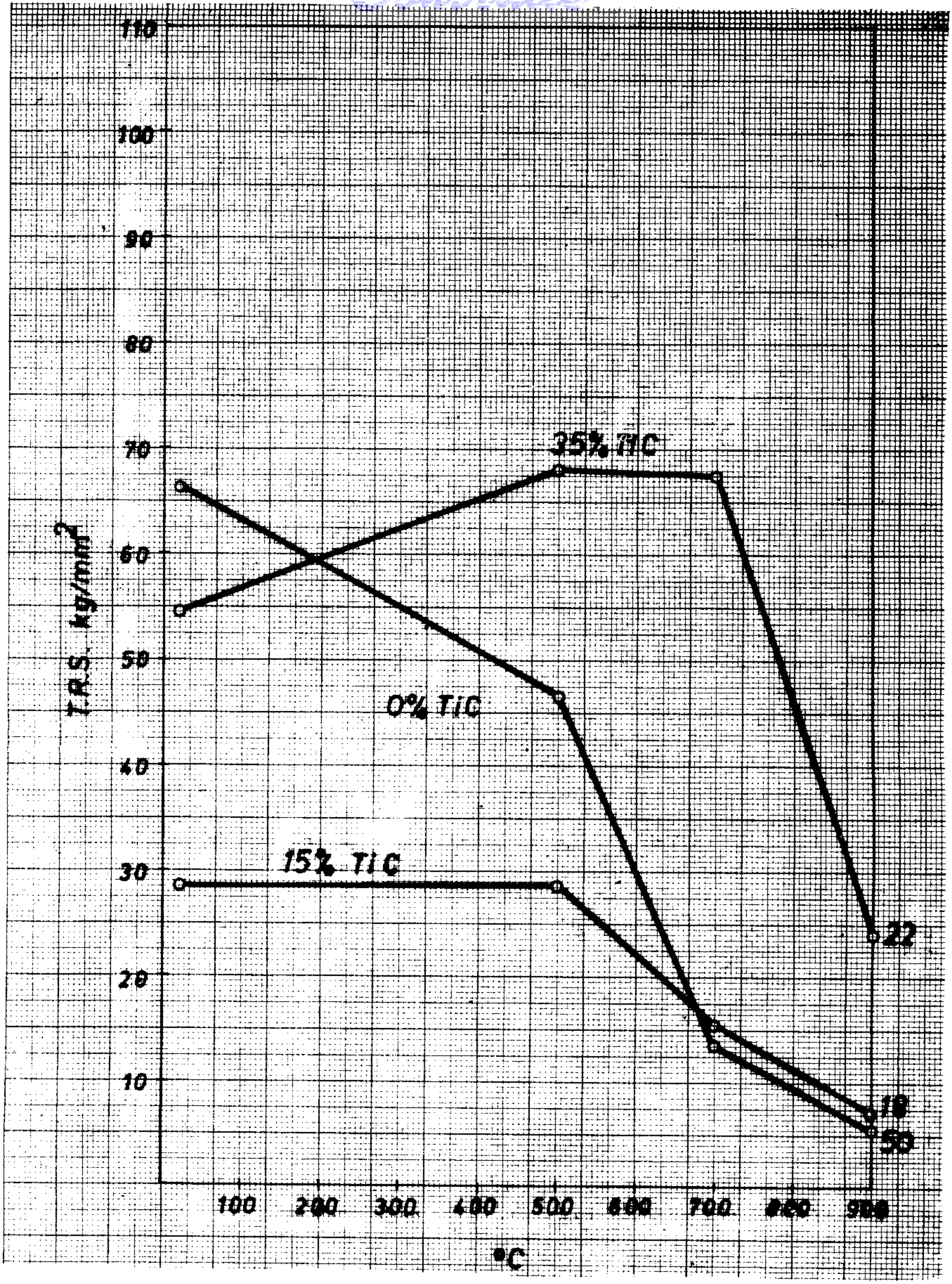

Figure 26. Transverse rupture strength Fe-12Al-TiC (3)

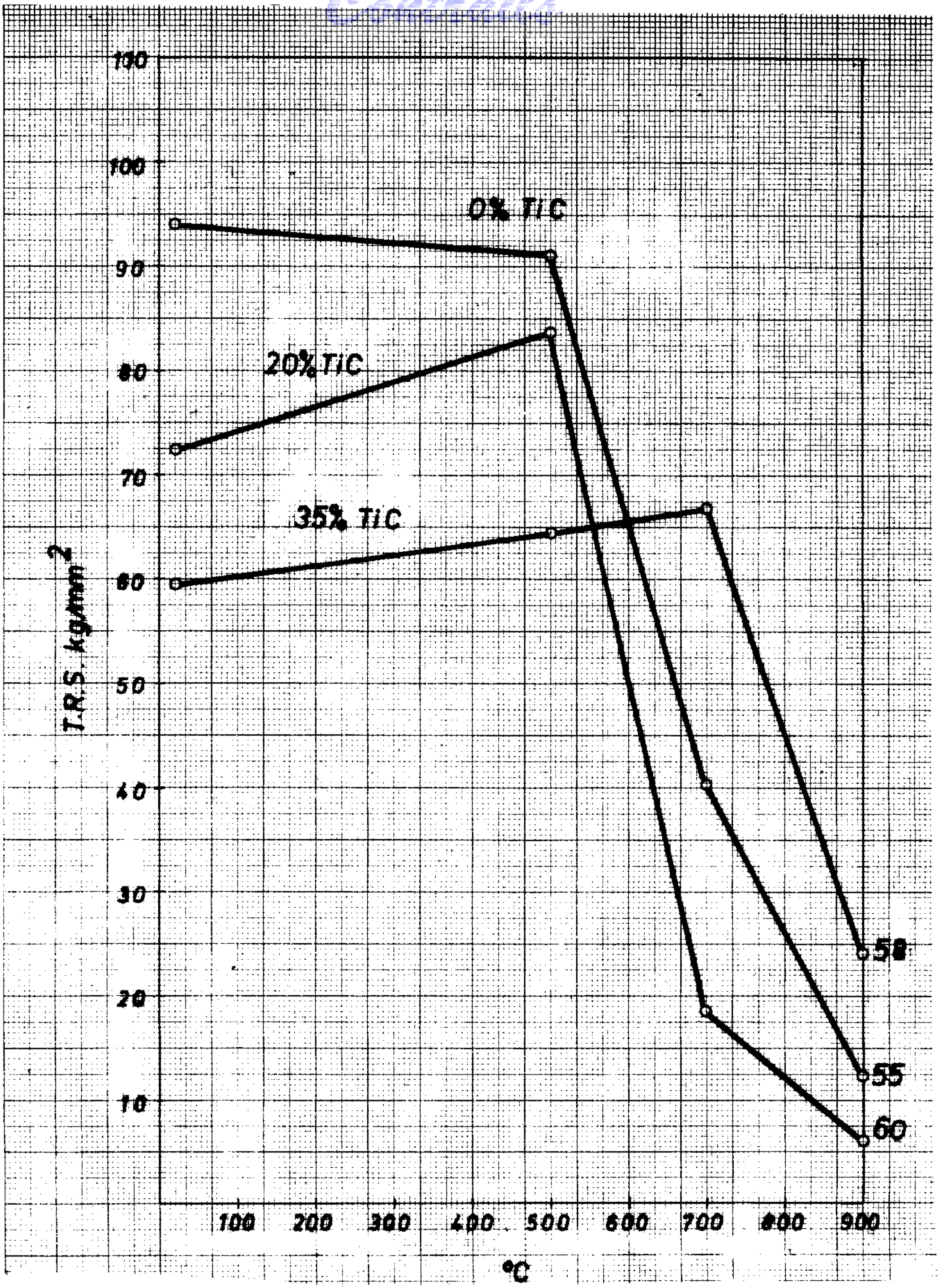

Figure 27. Transverse rupture strength Fe-12Al-TiC-B (4)

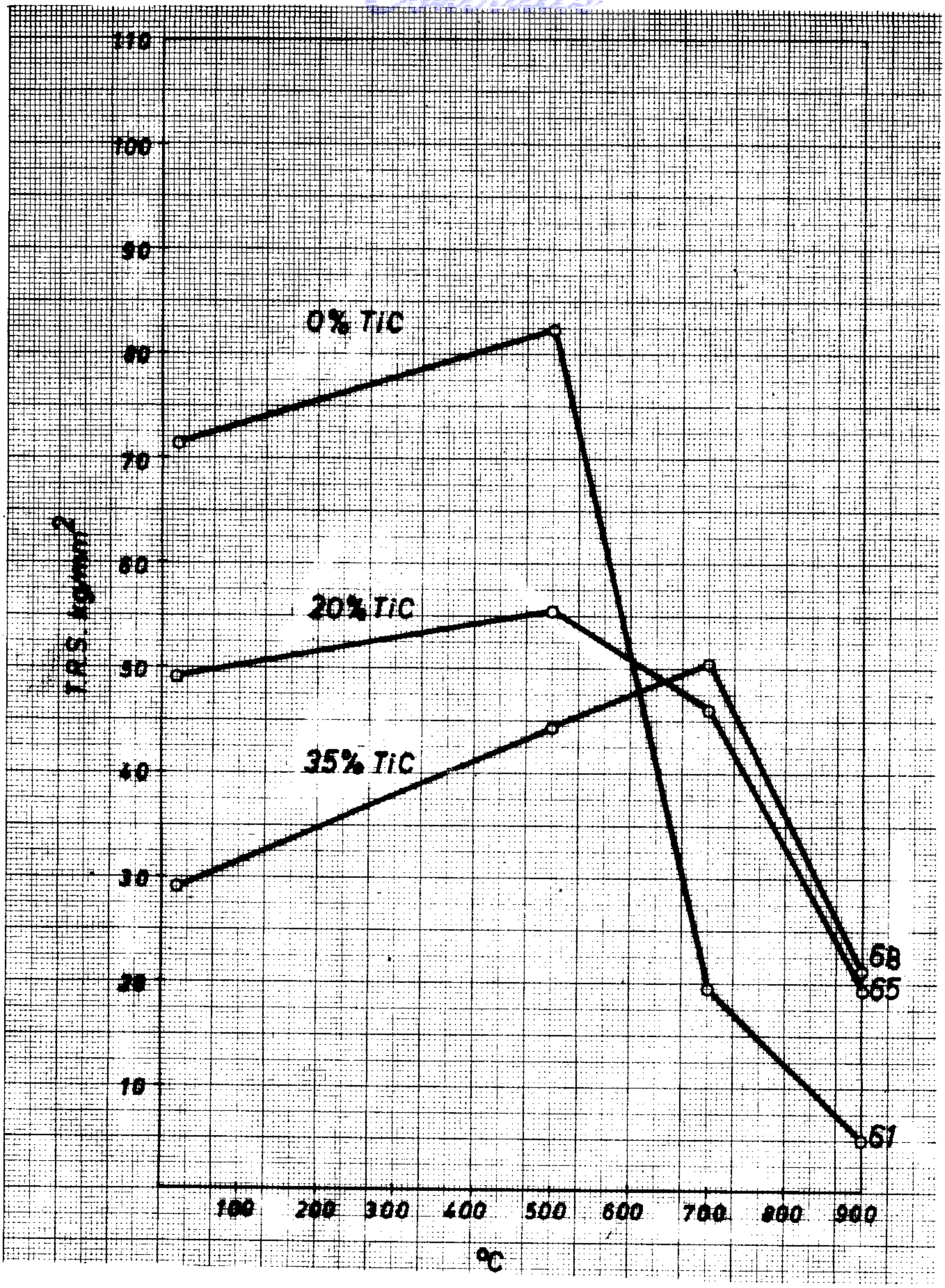

Figure 28. Transverse rupture strength Fe-Al-Cr-TiC-B (5)

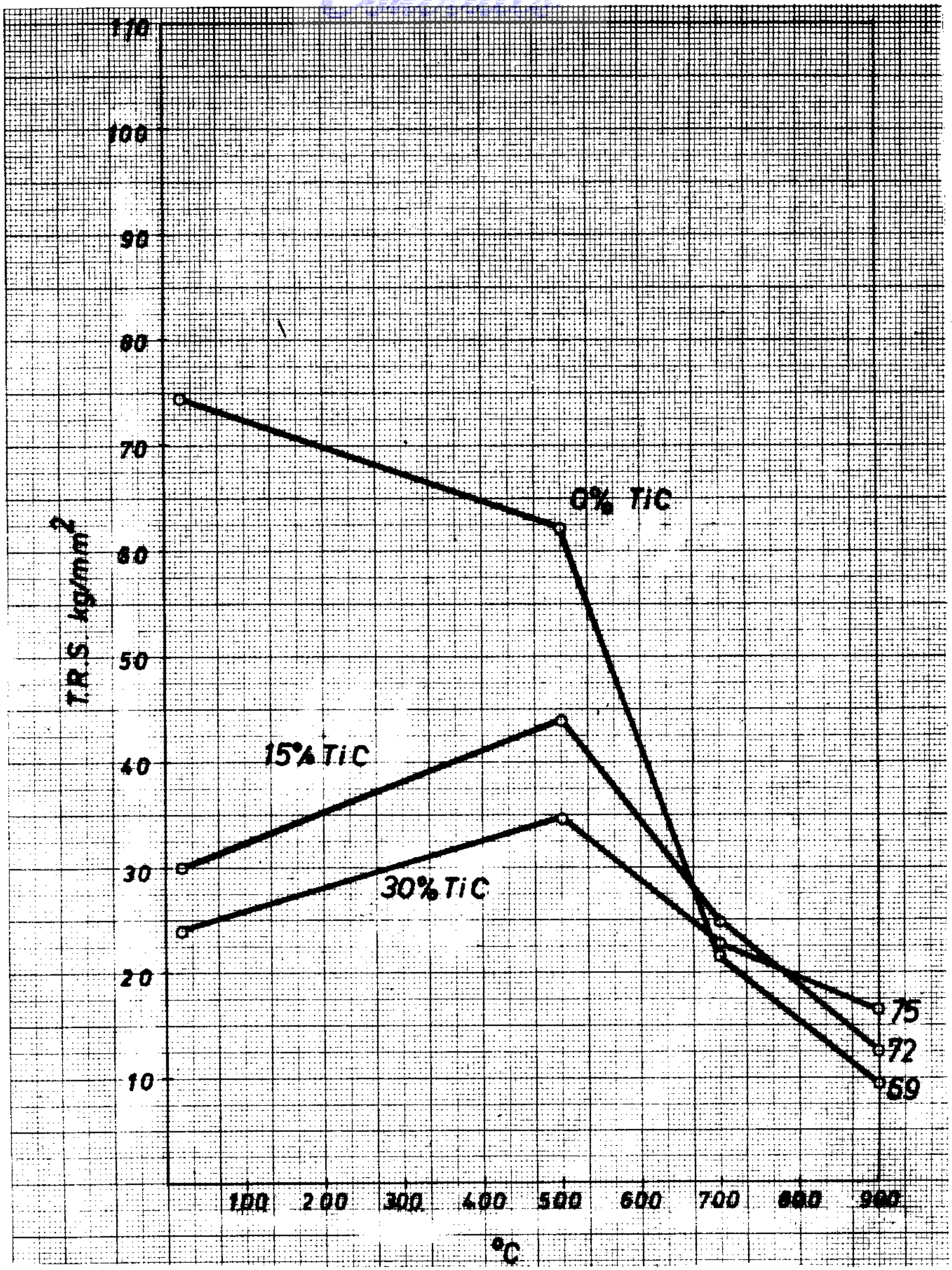

Figure 29. Transverse rupture strength Fe-Cr-Al-TiC-B (6)

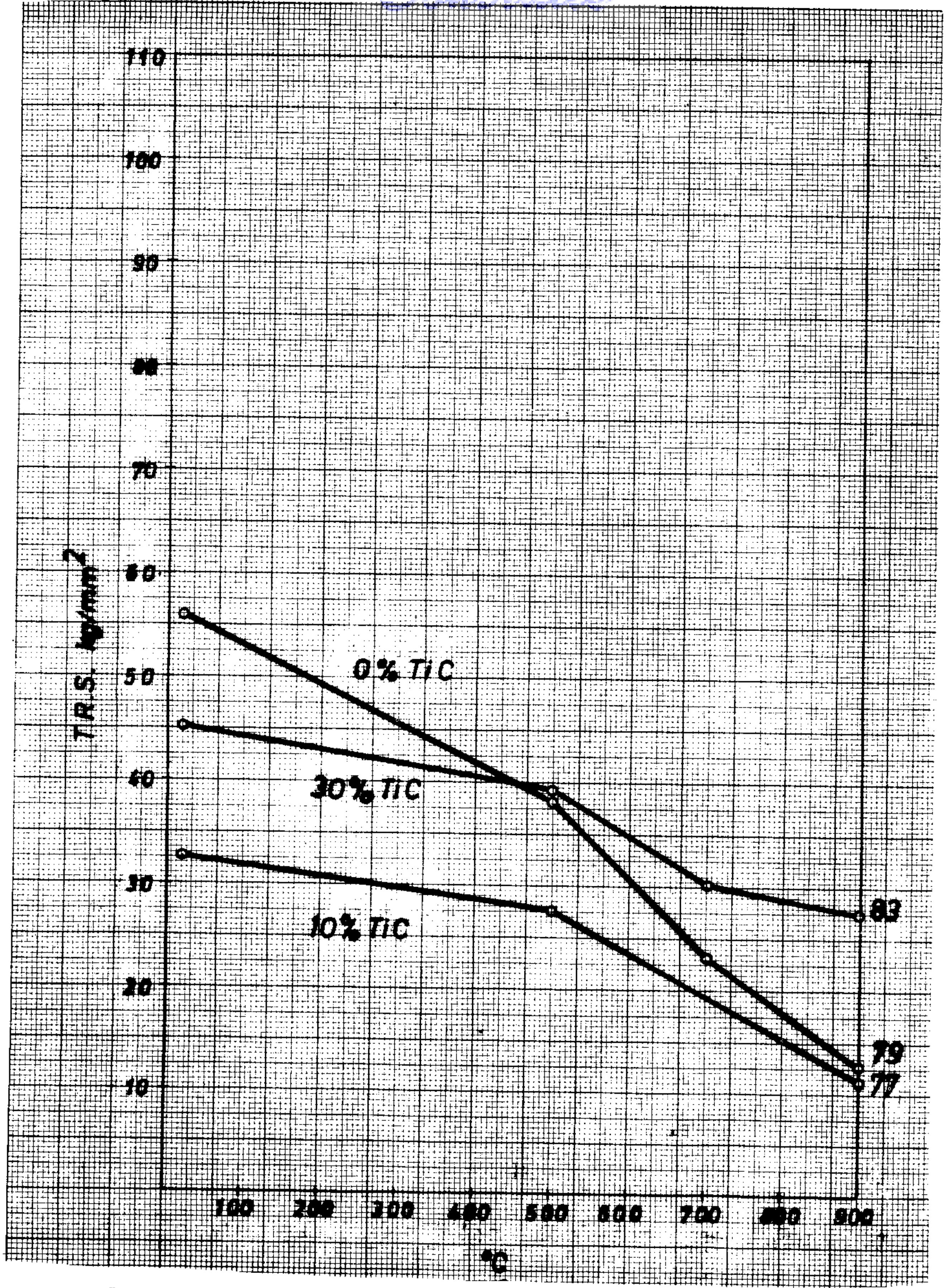

Figure 30. Transverse rupture strength Fe-Ni-Cr-TiC-B (7)

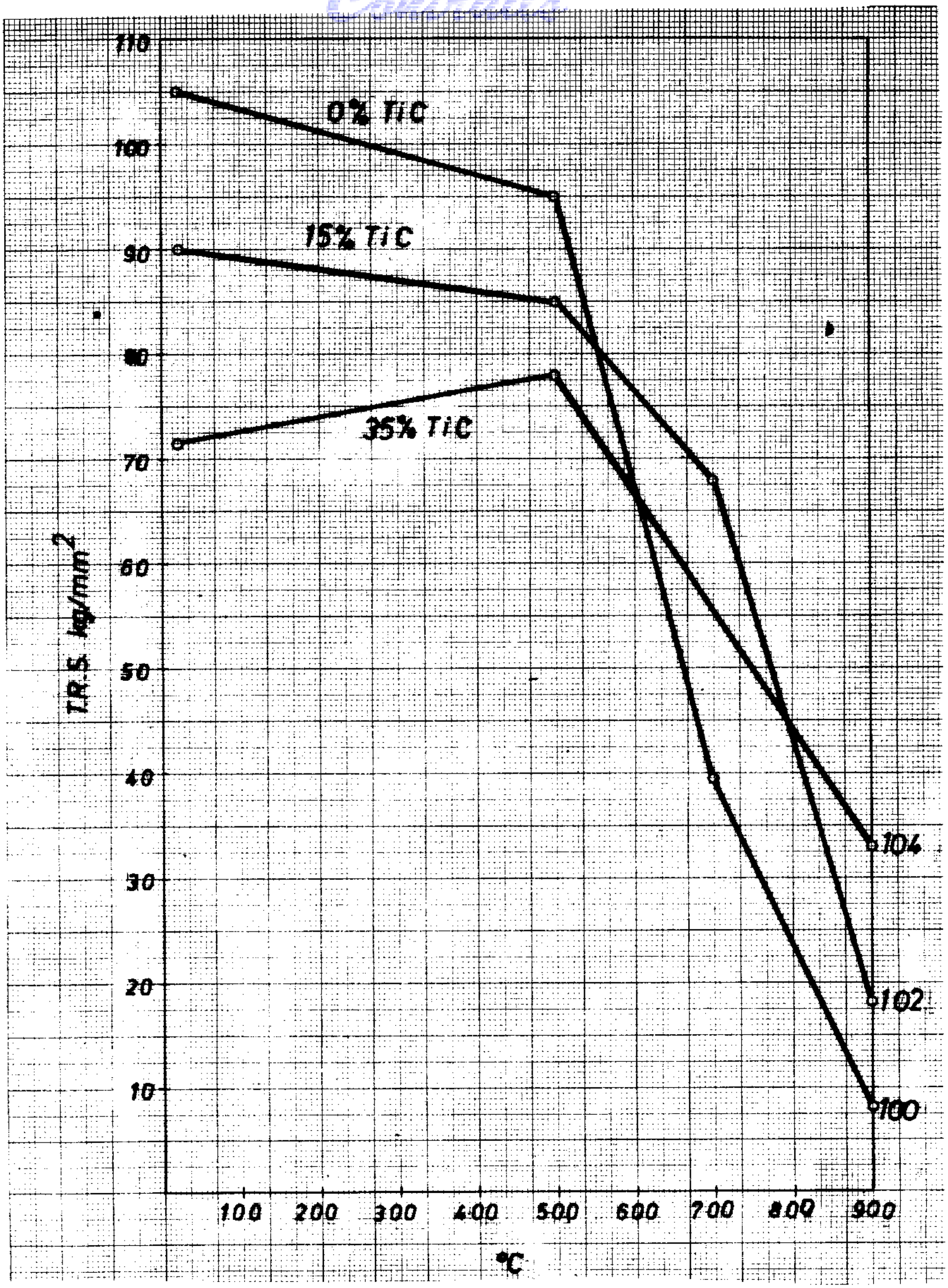

Figure 31. Transverse rupture strength Fe-12Al-TiC-Mo_2C-B (8)

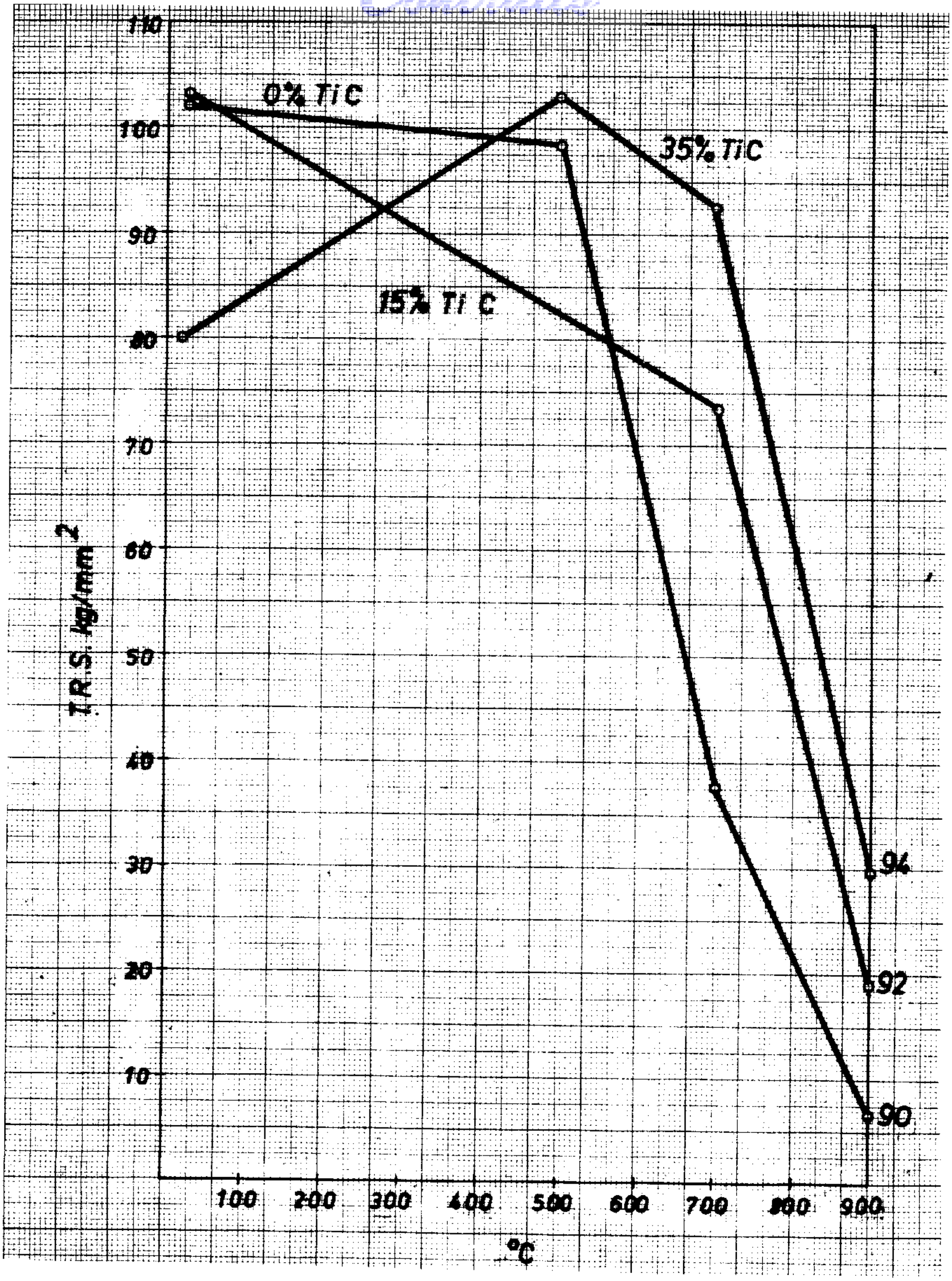

Figure 32. Transverse rupture strength Fe-12Al-TiC/VC-B (9)

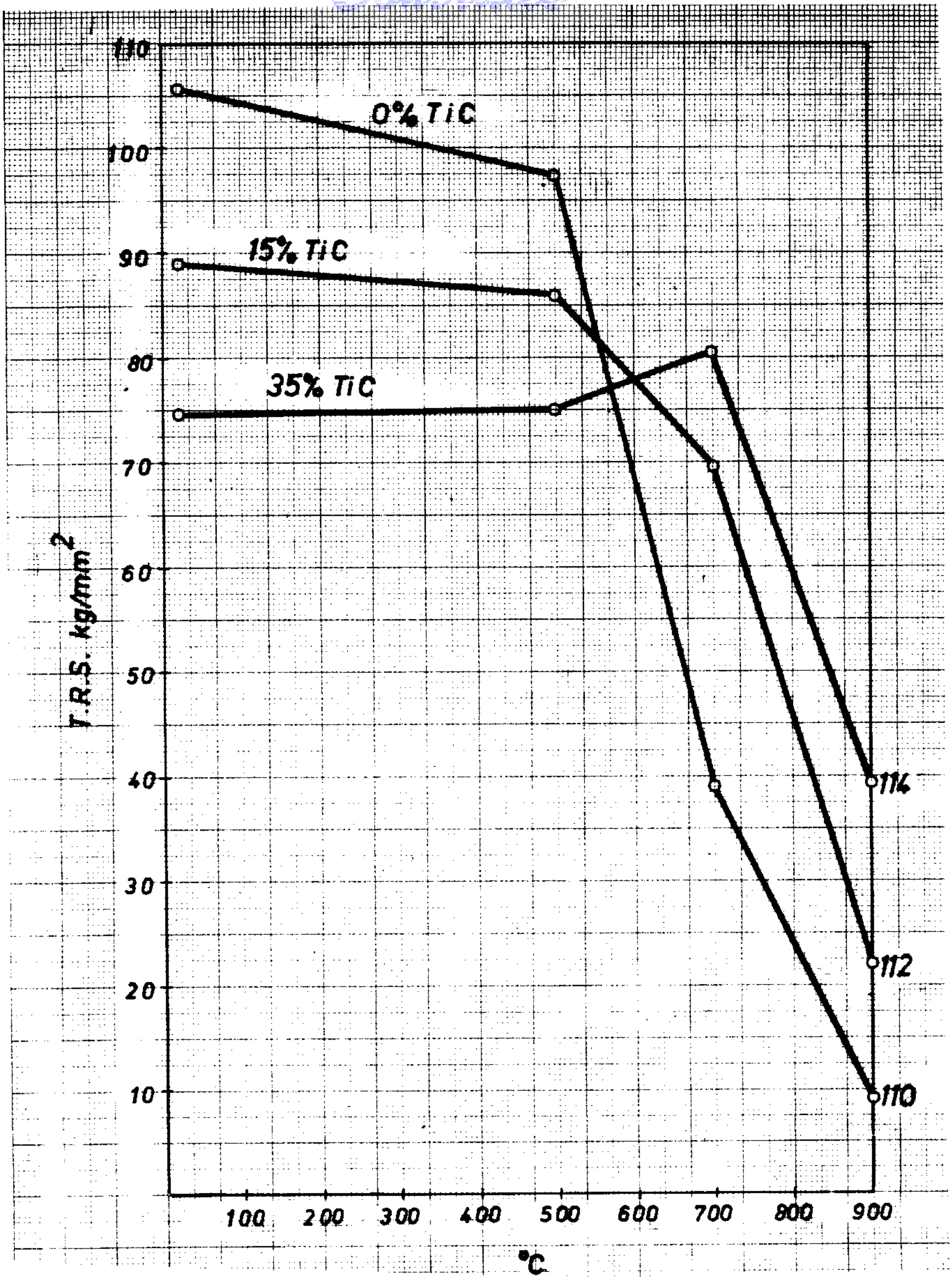

Figure 33. Transverse rupture strength Fe-12Al-TiC/Cr_3C_2 90/10-B (10)

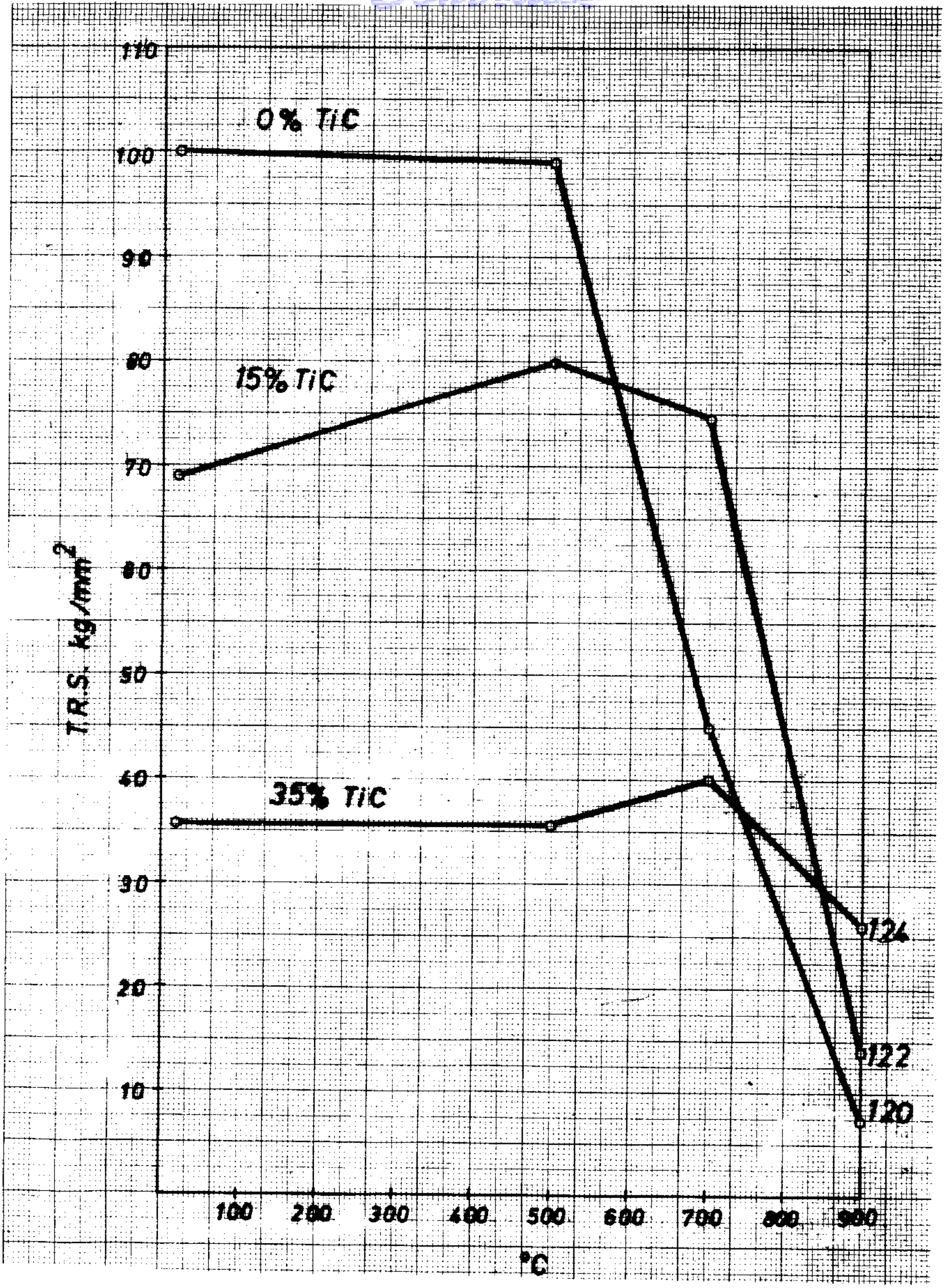

Figure 34. Transverse rupture strength Fe-12Al-TiC/Cr_3C_2 80/20-B (11)

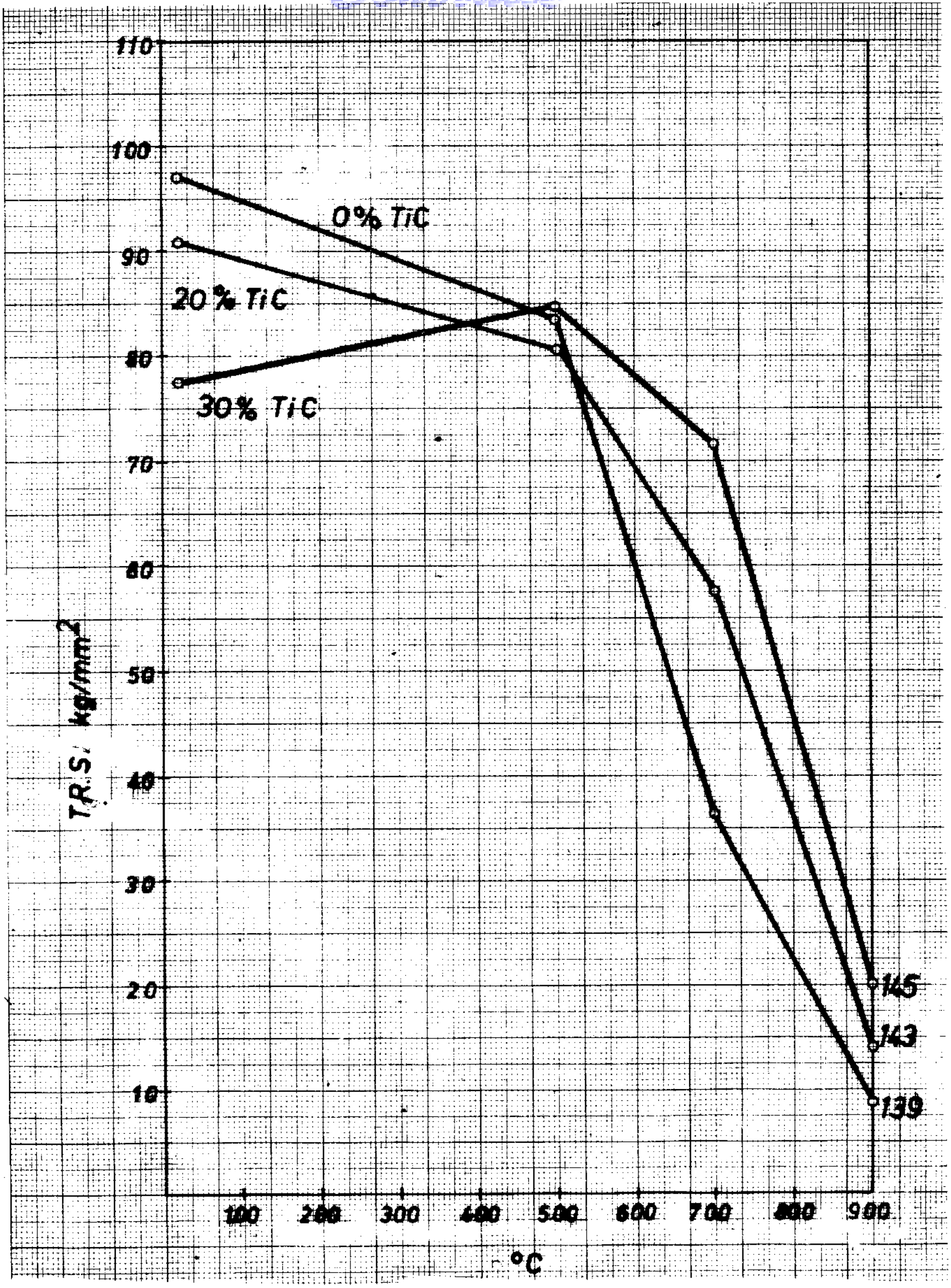

Figure 35. Transverse rupture strength Fe-Al-Mo-TiC/Cr_3C_2 90/10-B (12)

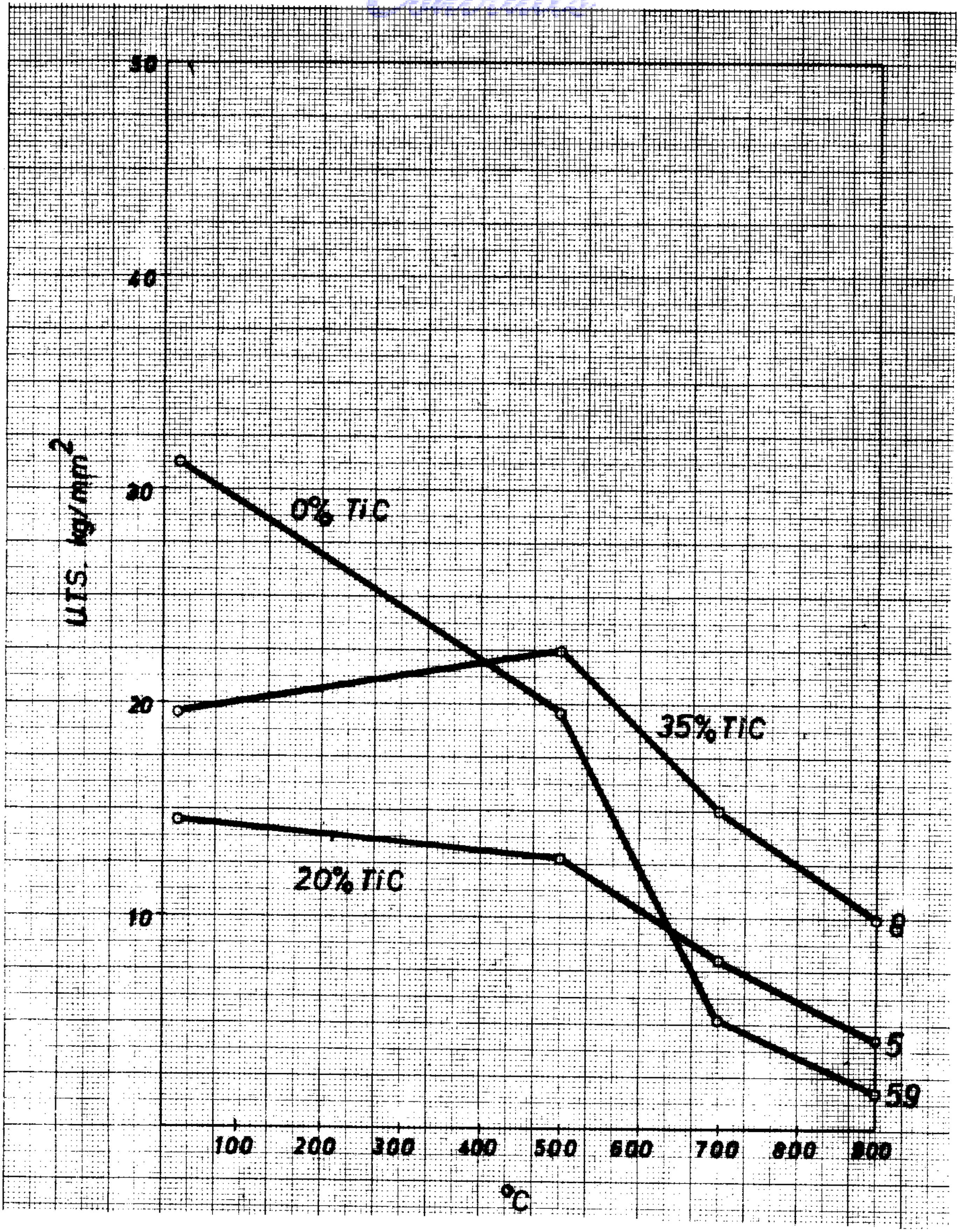

Figure 36. Tensile strength Fe-8Al-TiC (1)

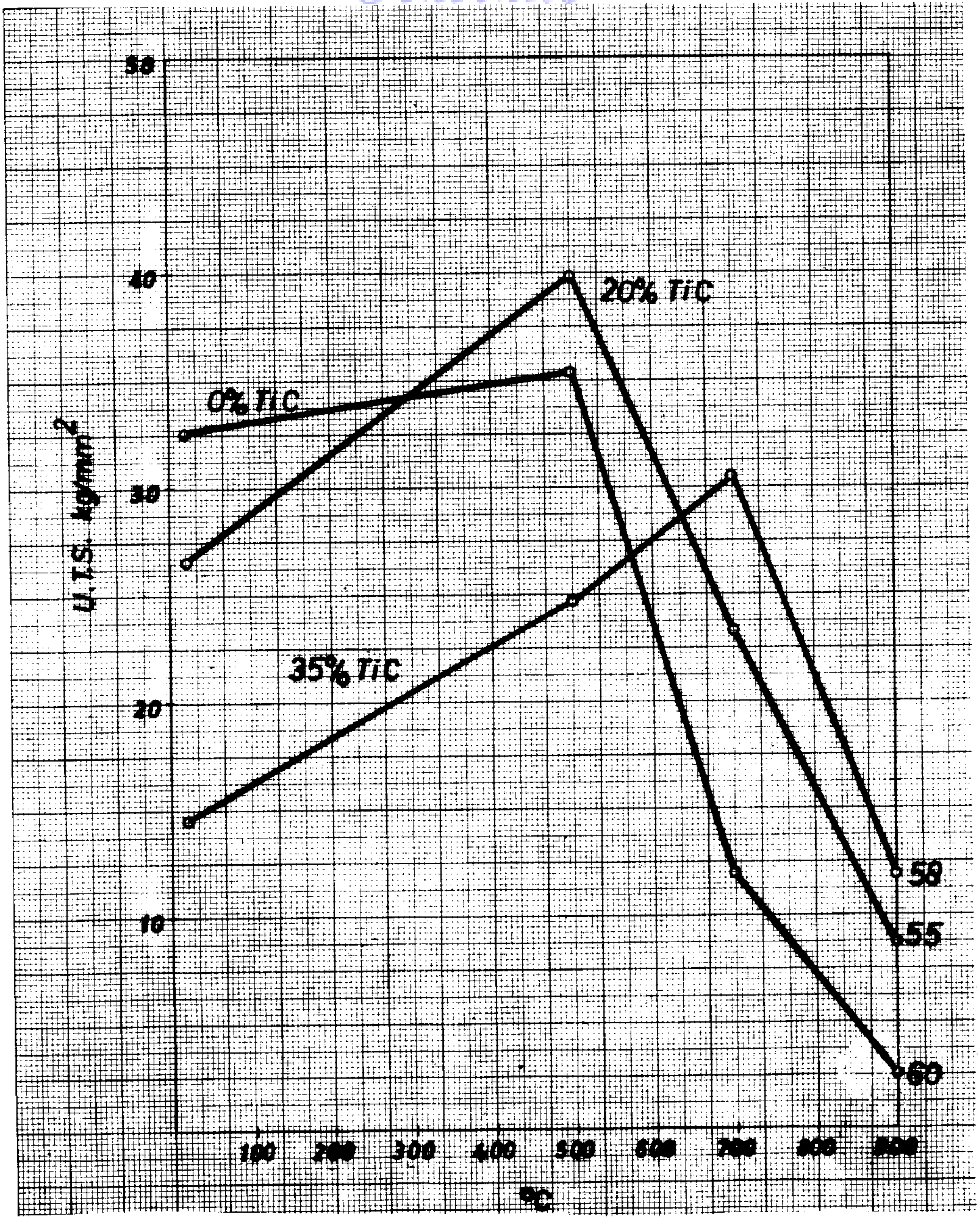

Figure 37. Tensile strength Fe-12Al-TiC-B (4)

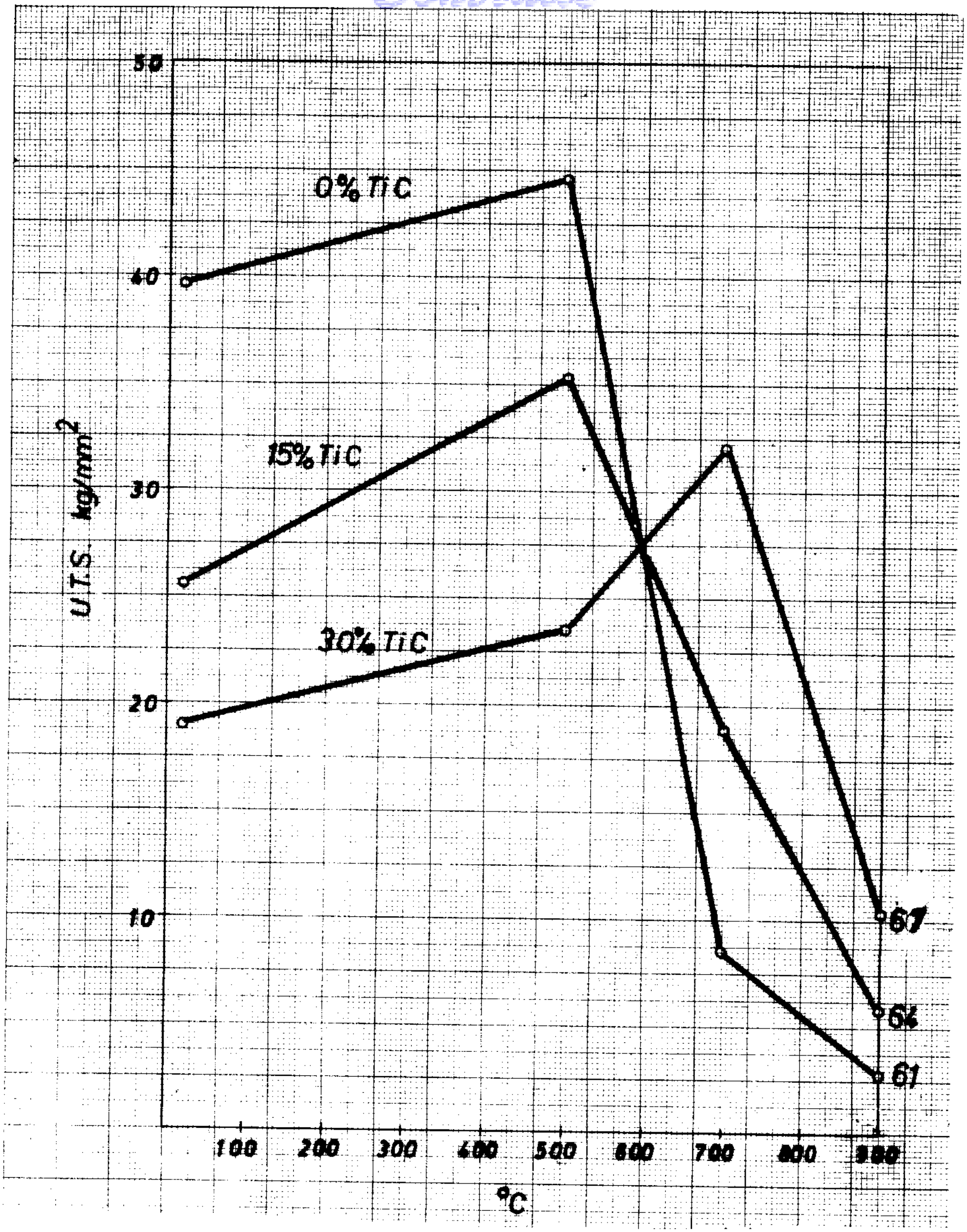

Figure 38. Tensile strength Fe-Al-Cr-TiC-B (5)

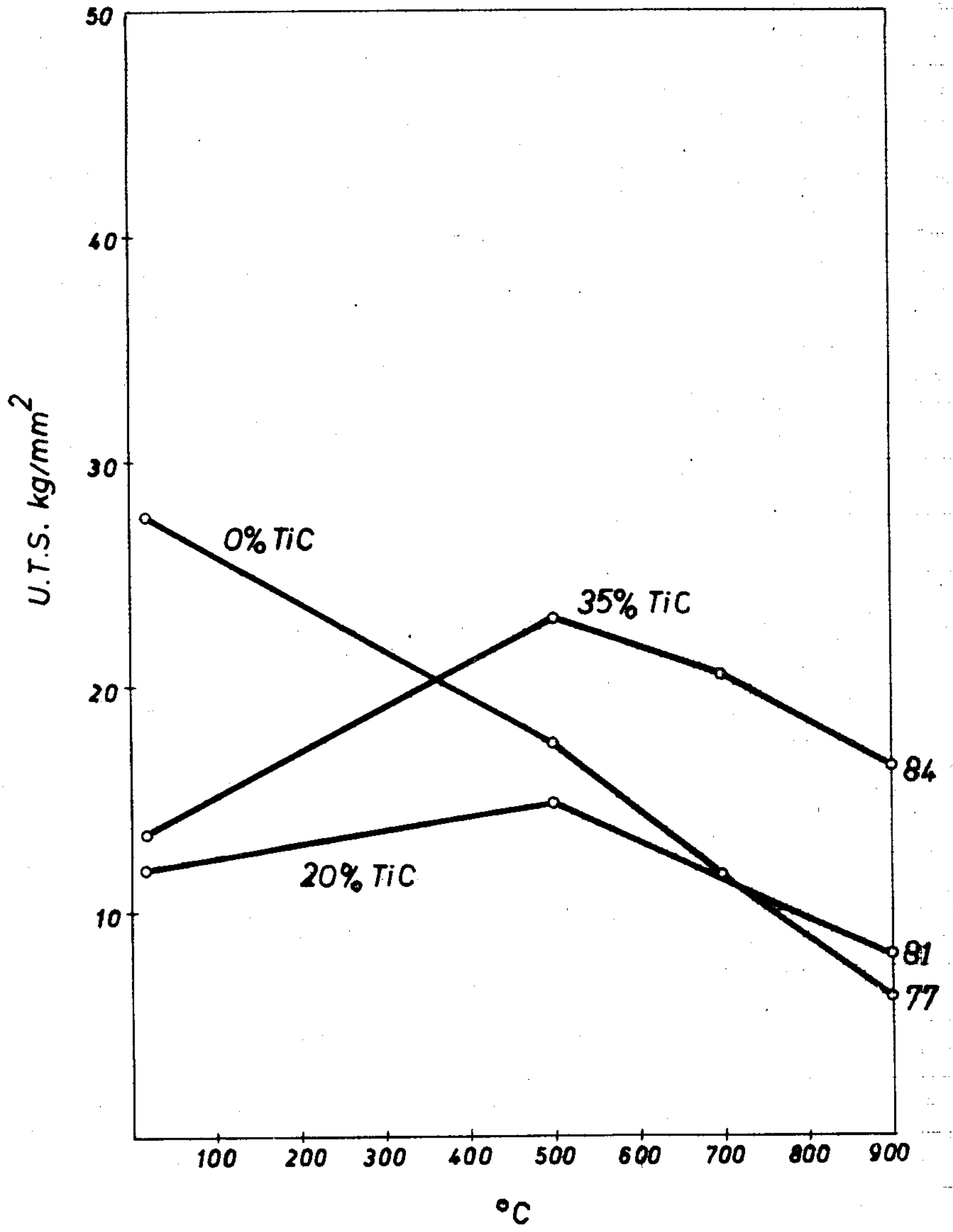

Figure 39. Tensile strength Fe-Ni-Cr-TiC-B (7)

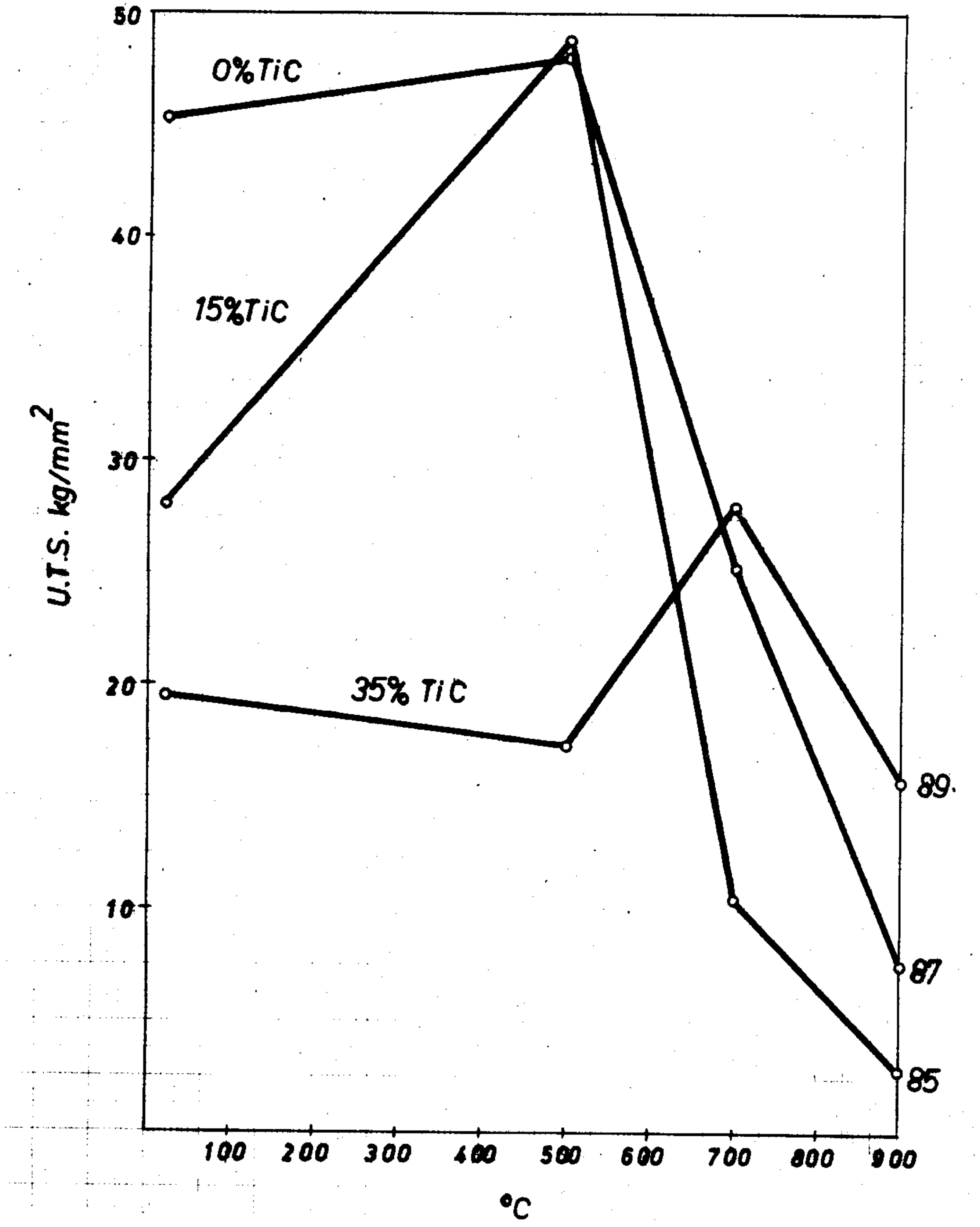

Figure 40. Tensile strength Fe-12Al-TiC/Mo_2C-B (8)

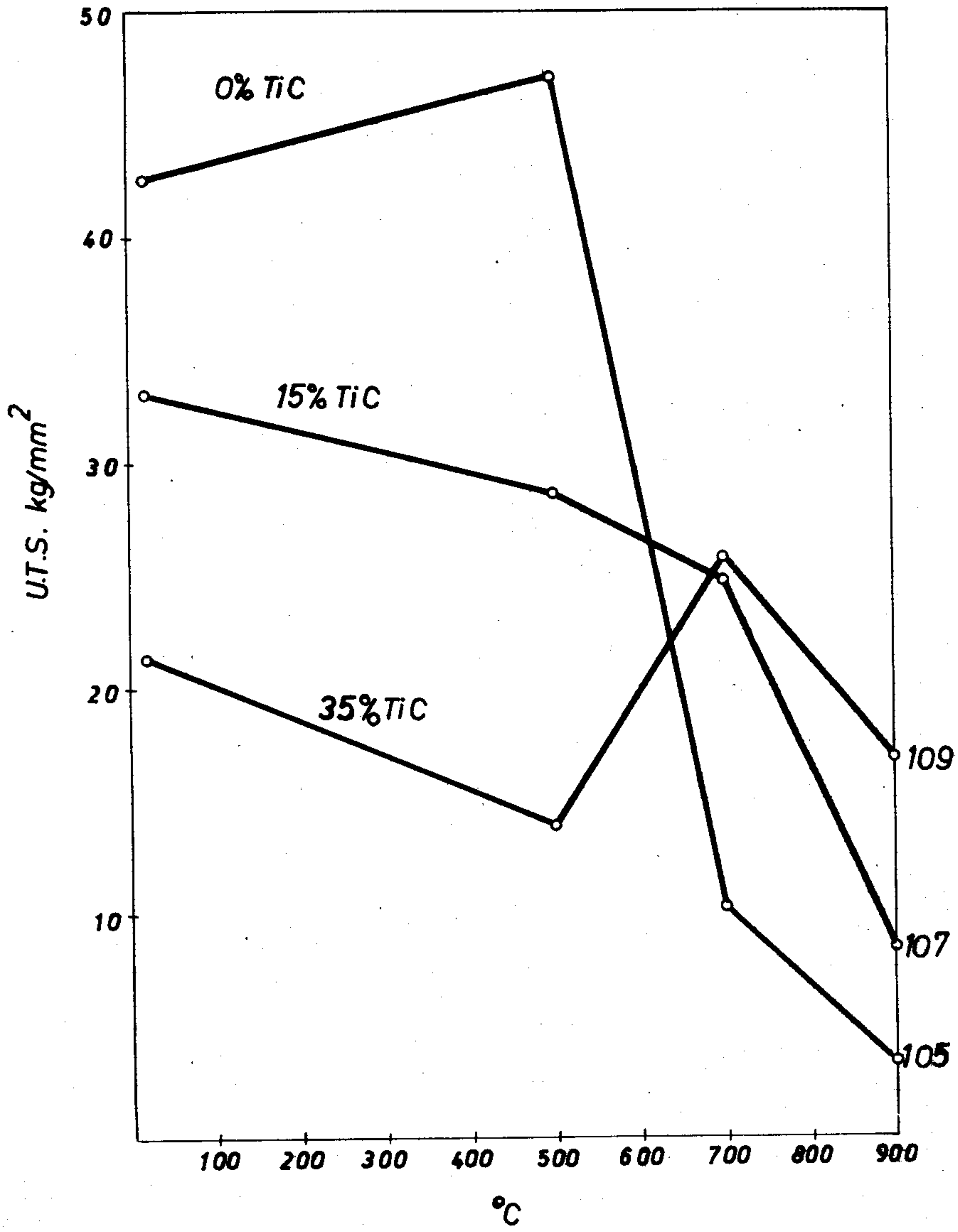

Figure 41. Tensile strength Fe-12Al-TiC/Cr_3C_2 90/10-B (10)

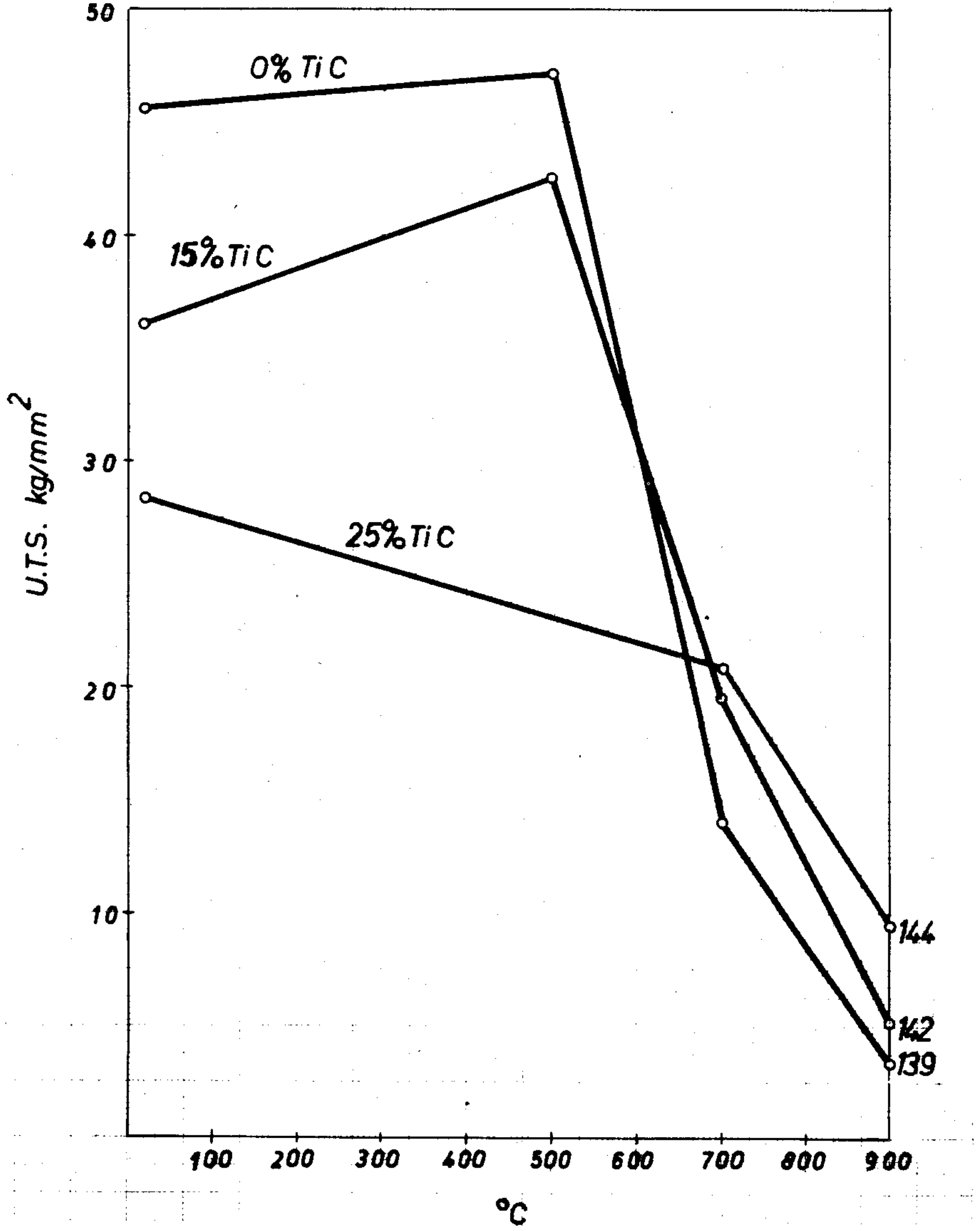

Figure 42. Tensile strength Fe-Al-Mo-TiC/Cr_3C_2 90/10-B, wet milled (12)

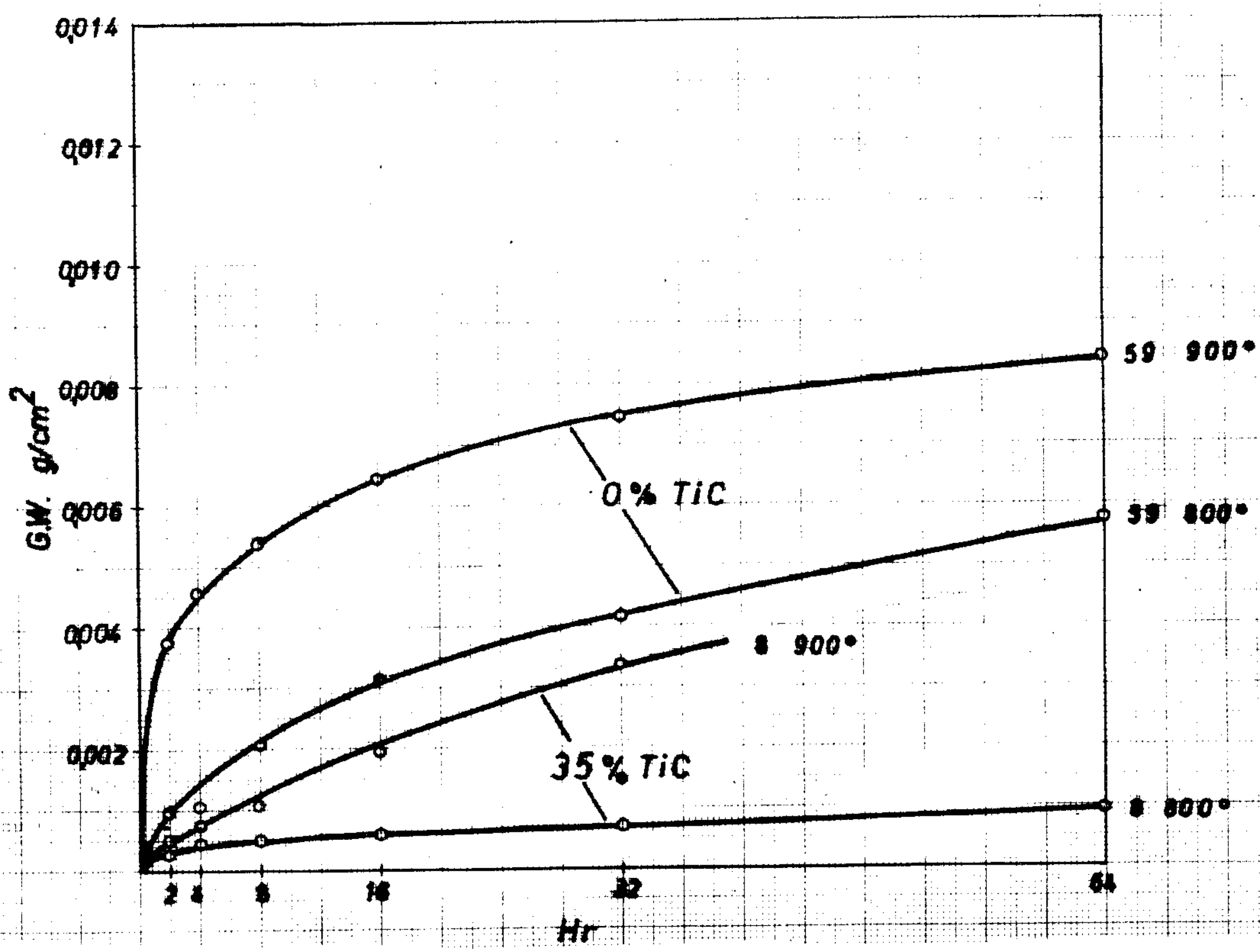

Figure 43. Scaling isotherms Fe-8Al-TiC (1)

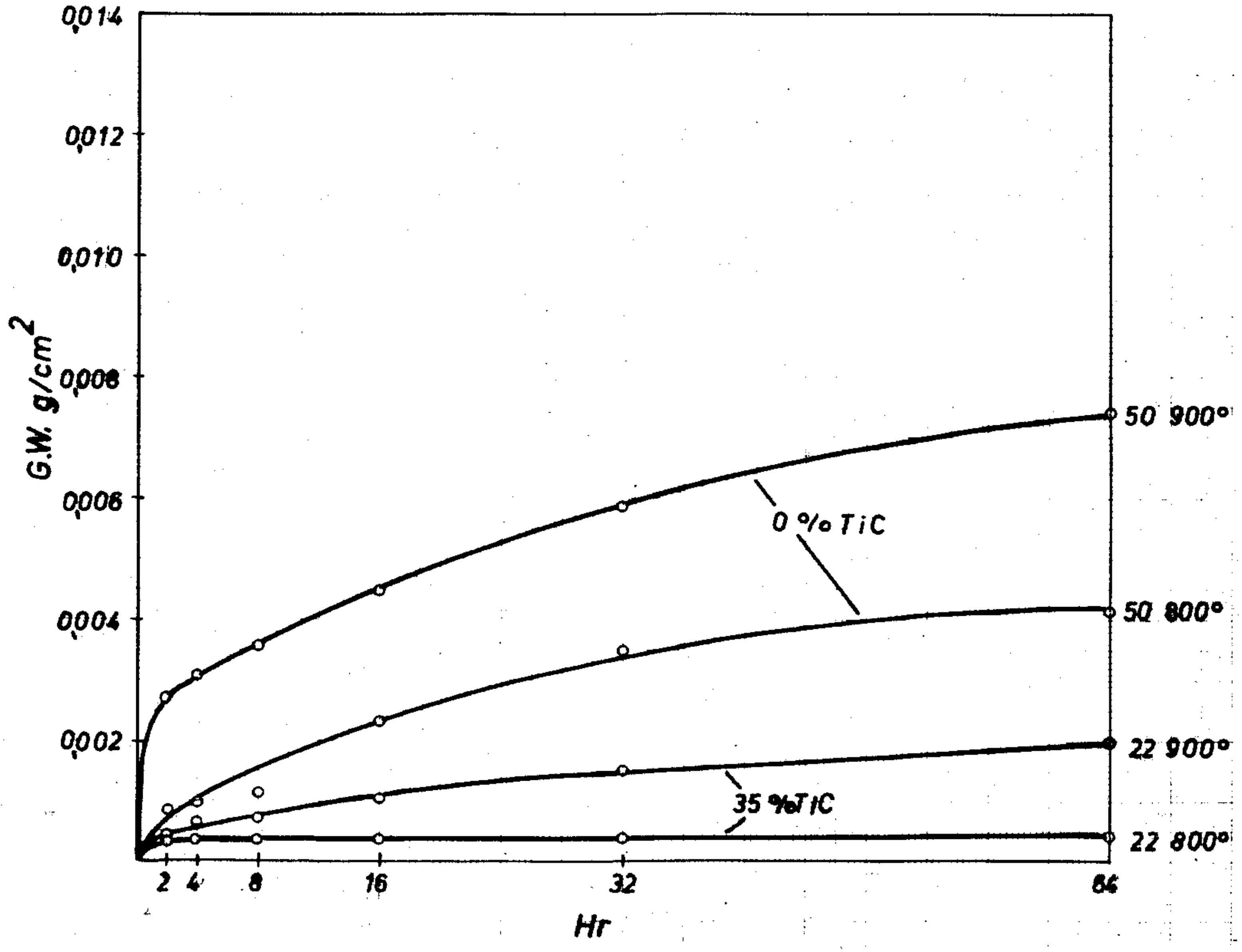

Figure 44. Scaling isotherms Fe-12Al-TiC (3)

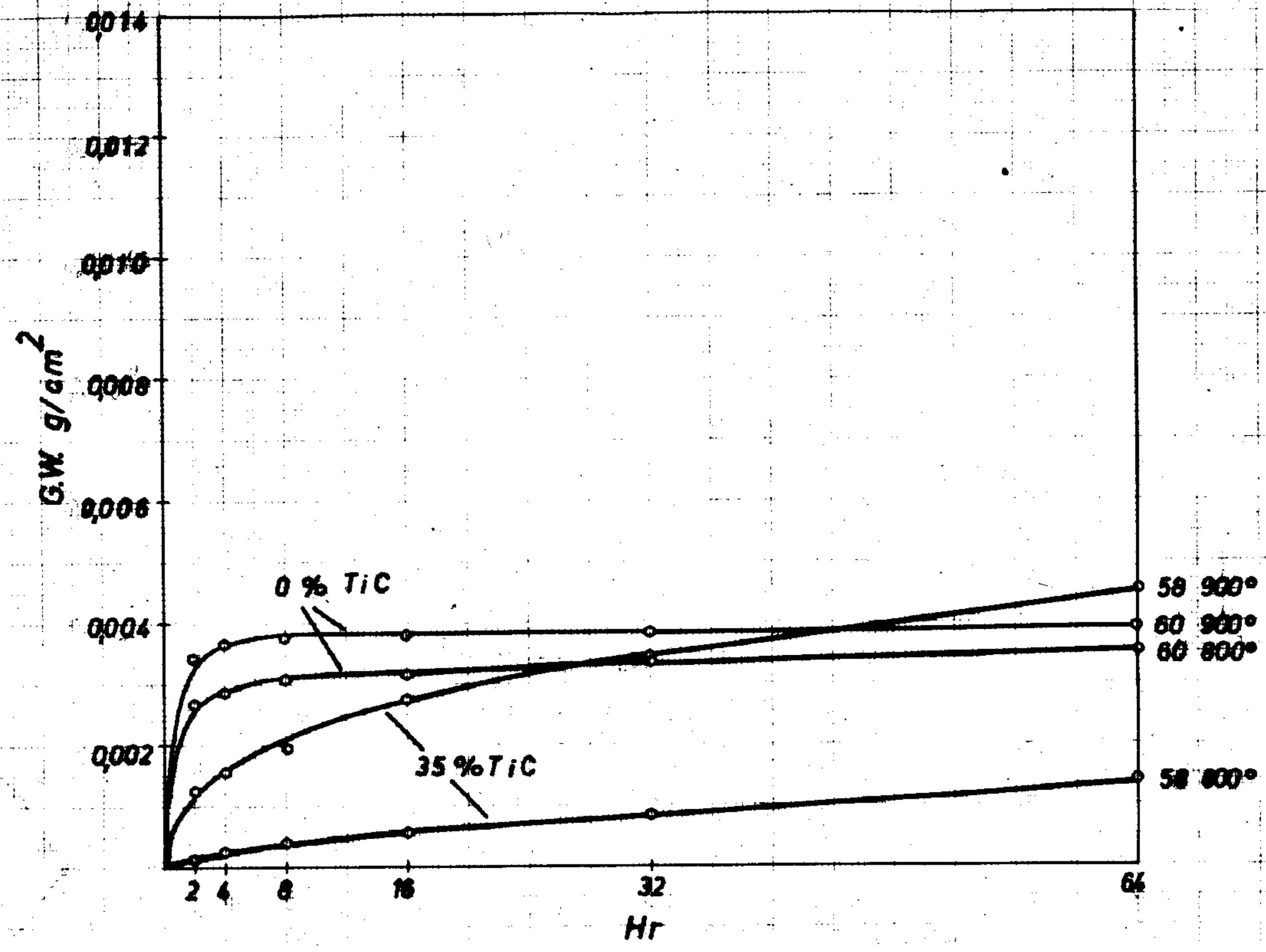

Figure 45. Scaling isotherms Fe-12Al-TiC-B (4)

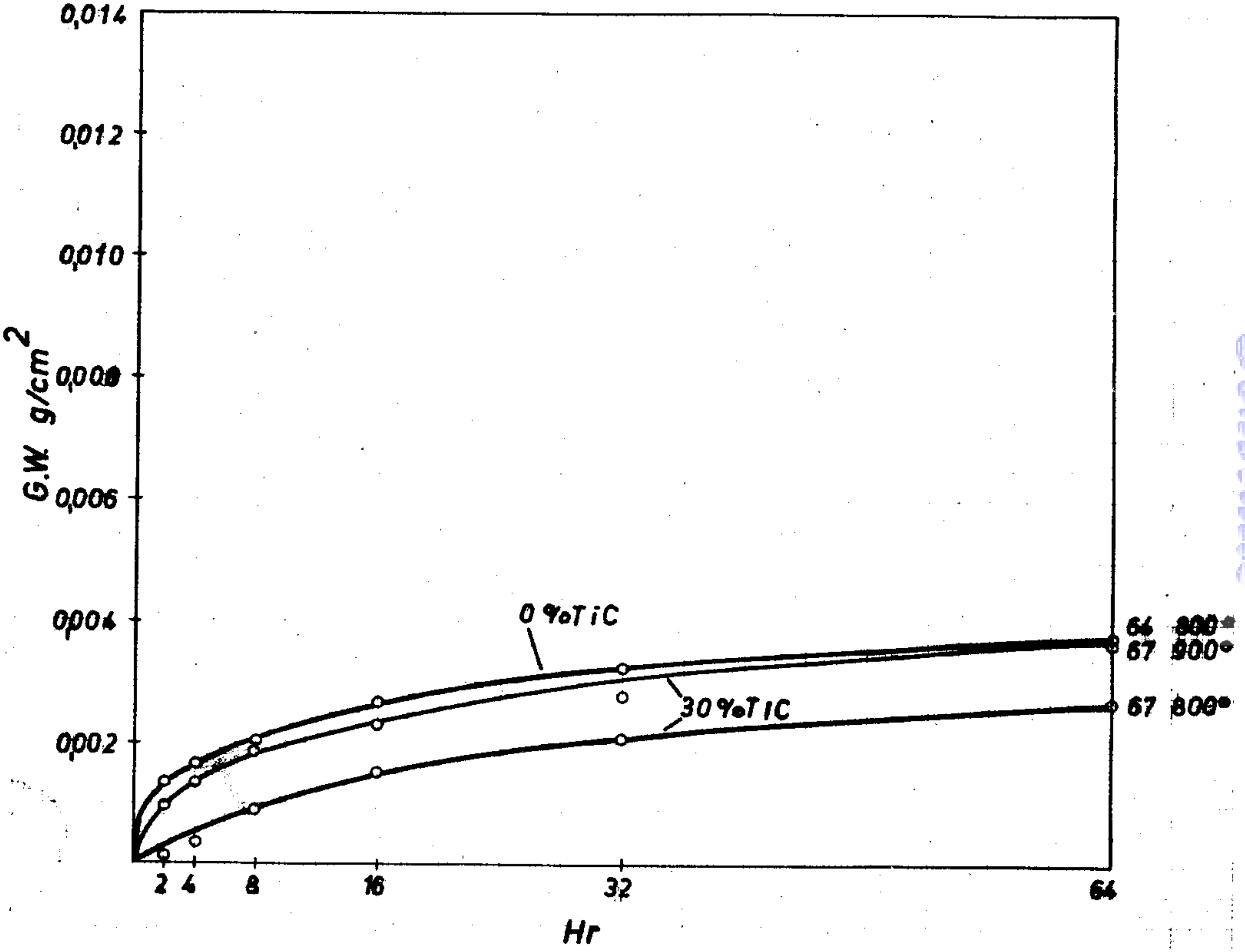

Figure 46. Scaling isotherms Fe-Al-Cr-TiC-B (5)

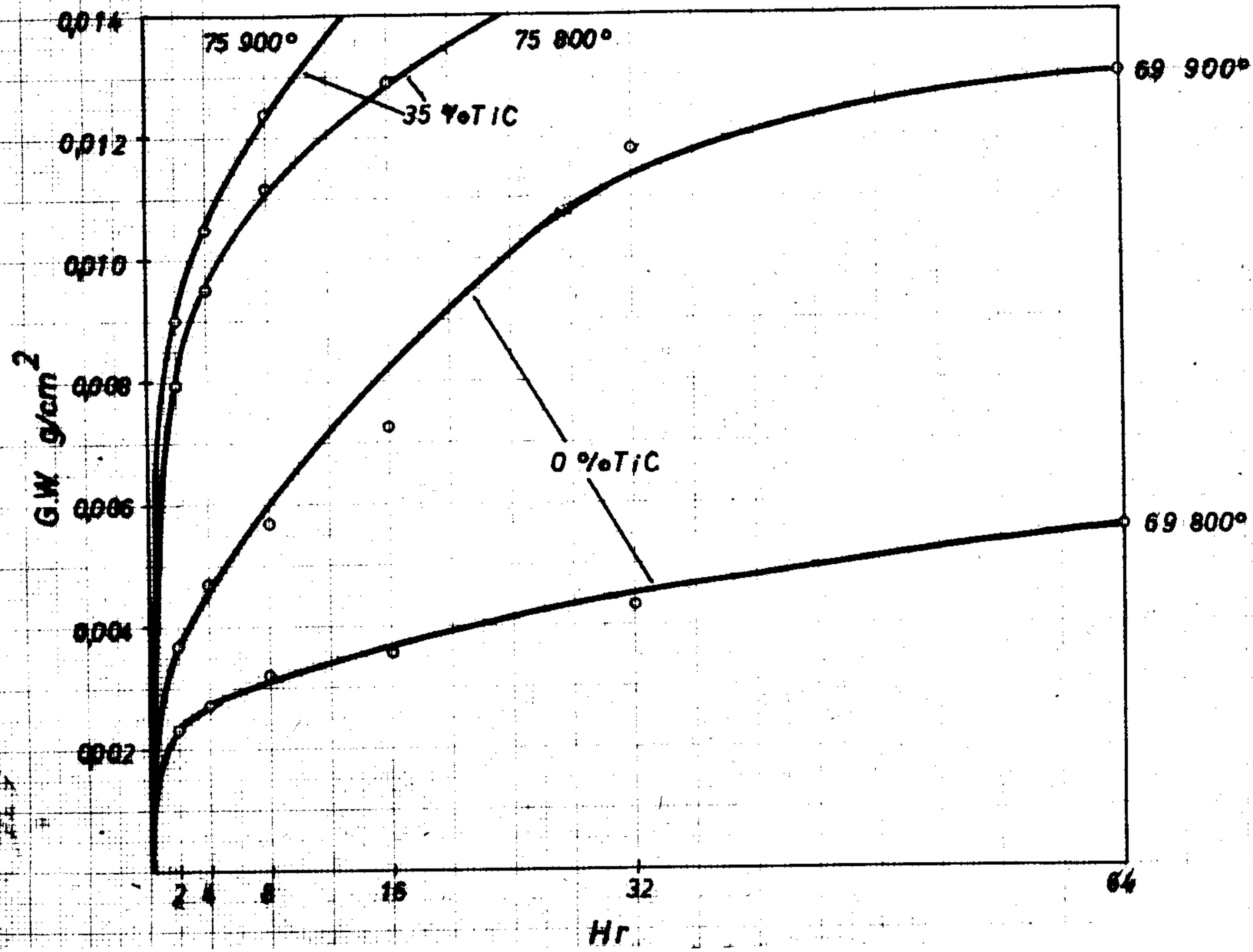

Figure 47. Scaling isotherms Fe-Cr-Al-TiC-B (6)

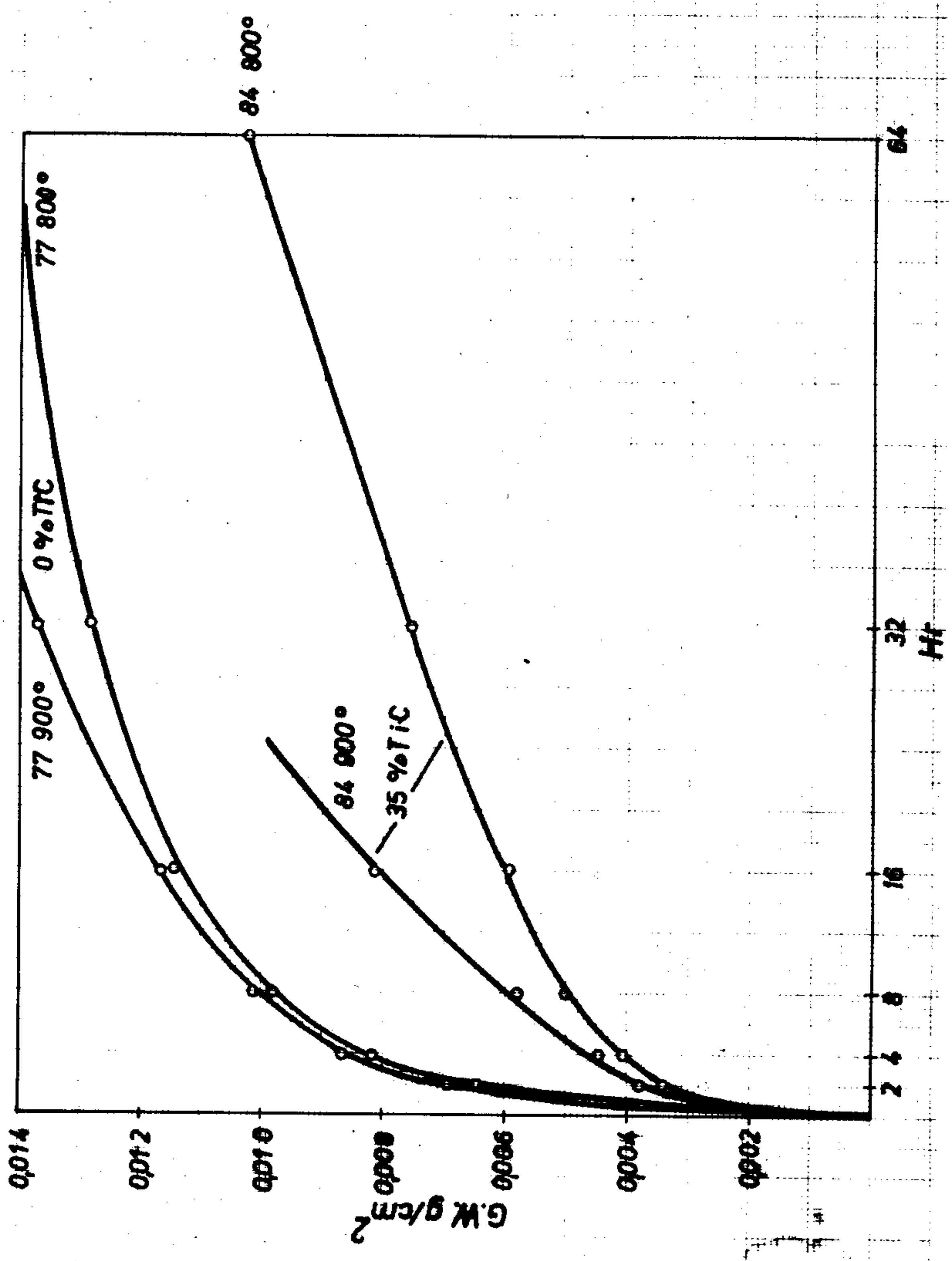

Figure 48. Scaling isotherms Fe-Ni-Cr-TiC-B (7)

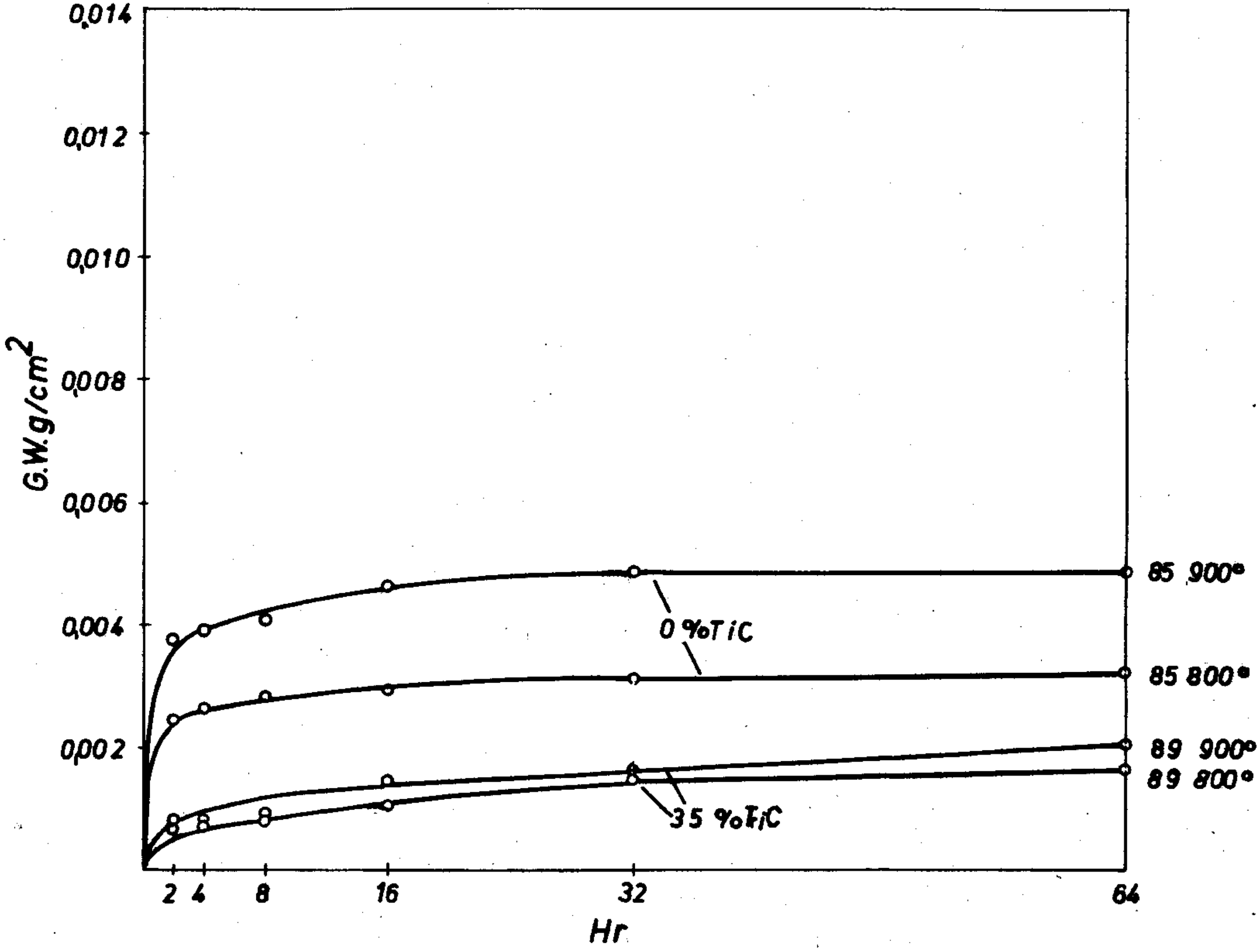

Figure 49. Scaling isotherms Fe-12Al-TiC/Mo_2C-B (8)

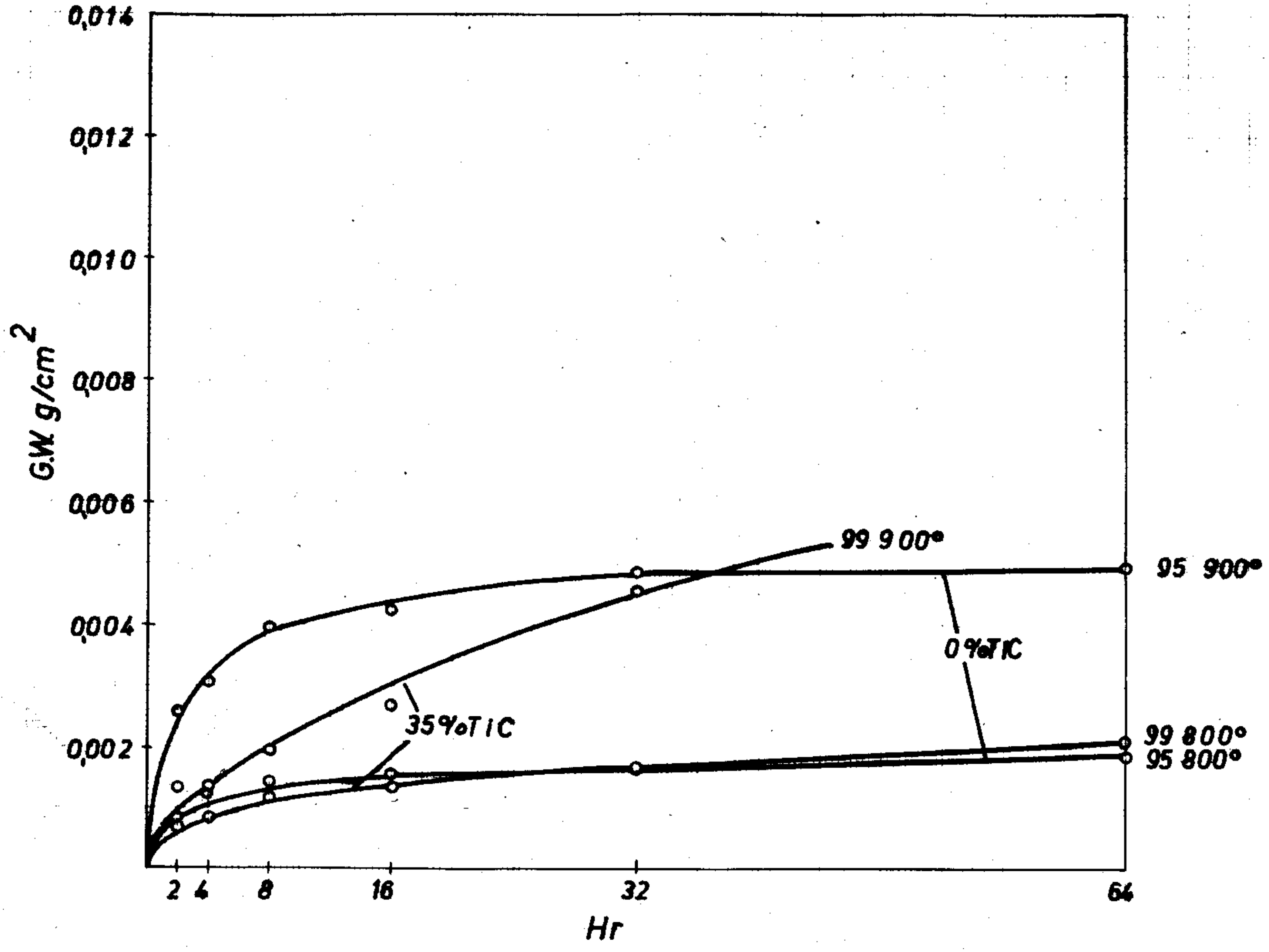

Figure 50. Scaling isotherms Fe-12Al-TiC/VC-B (9)

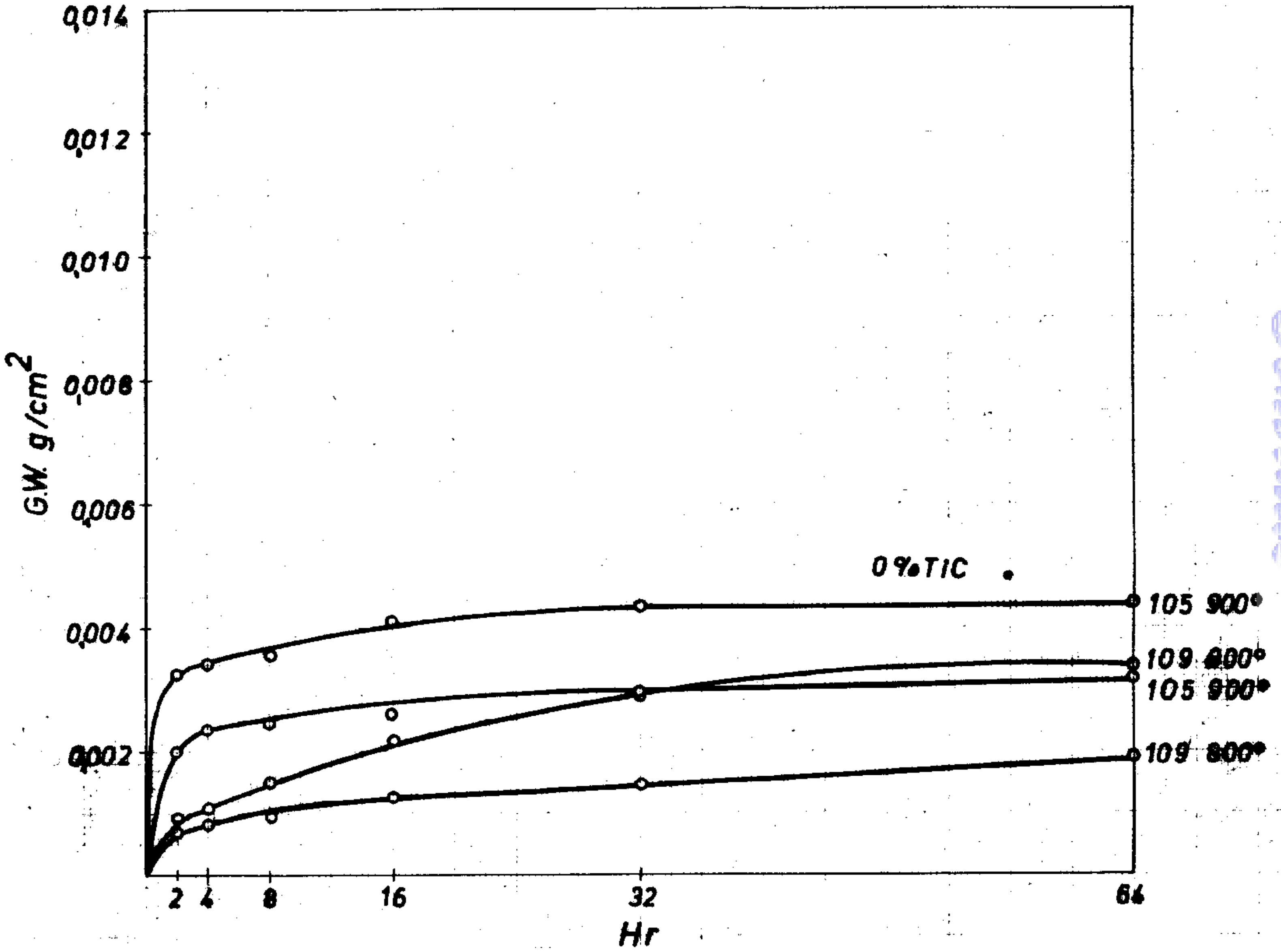

Figure 51. Scaling isotherms Fe-12Al-TiC/Cr_3C_2 90/10-B (10)

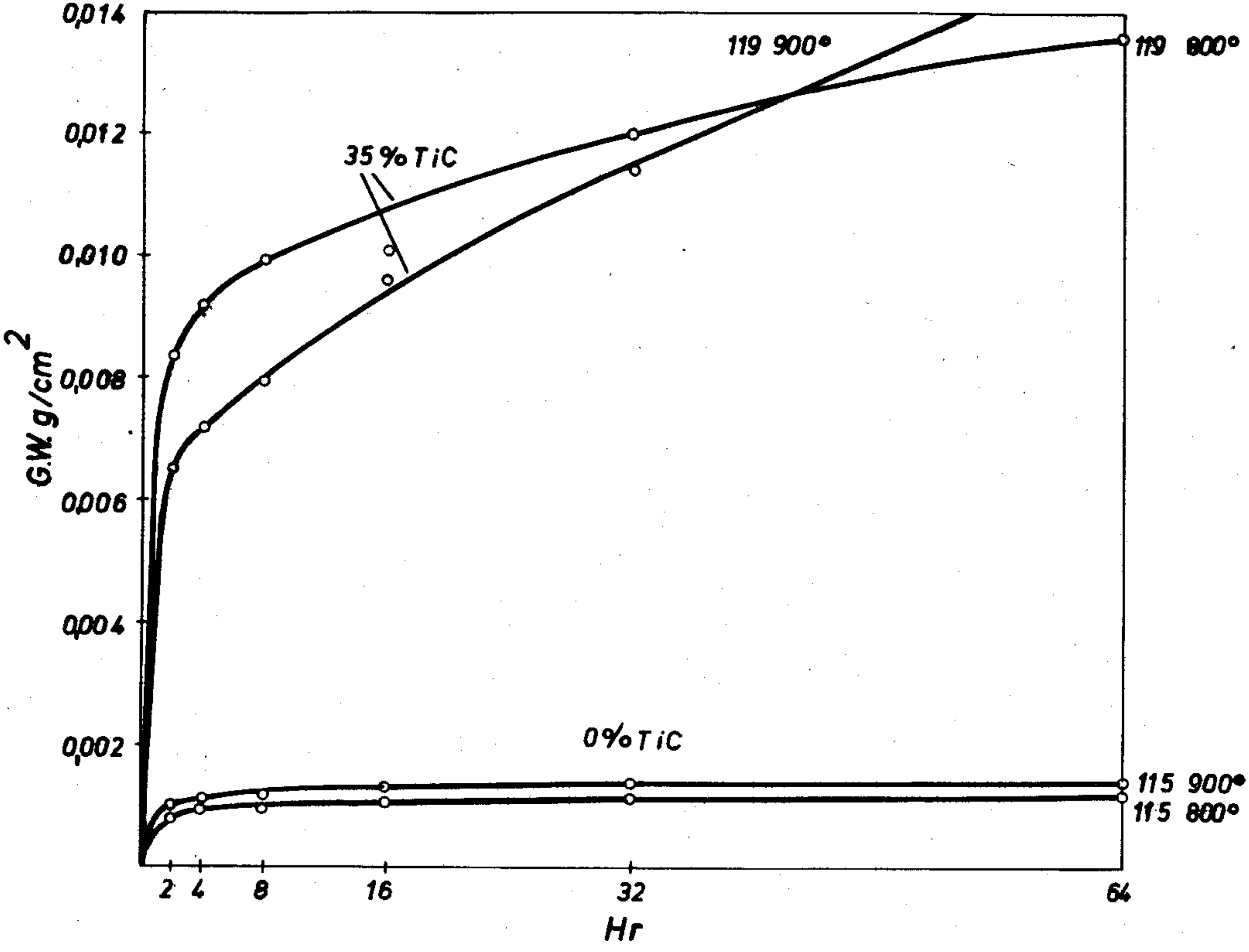

Figure 52. Scaling isotherms Fe-12Al-TiC/Cr_3C_2 80/20-B (11)

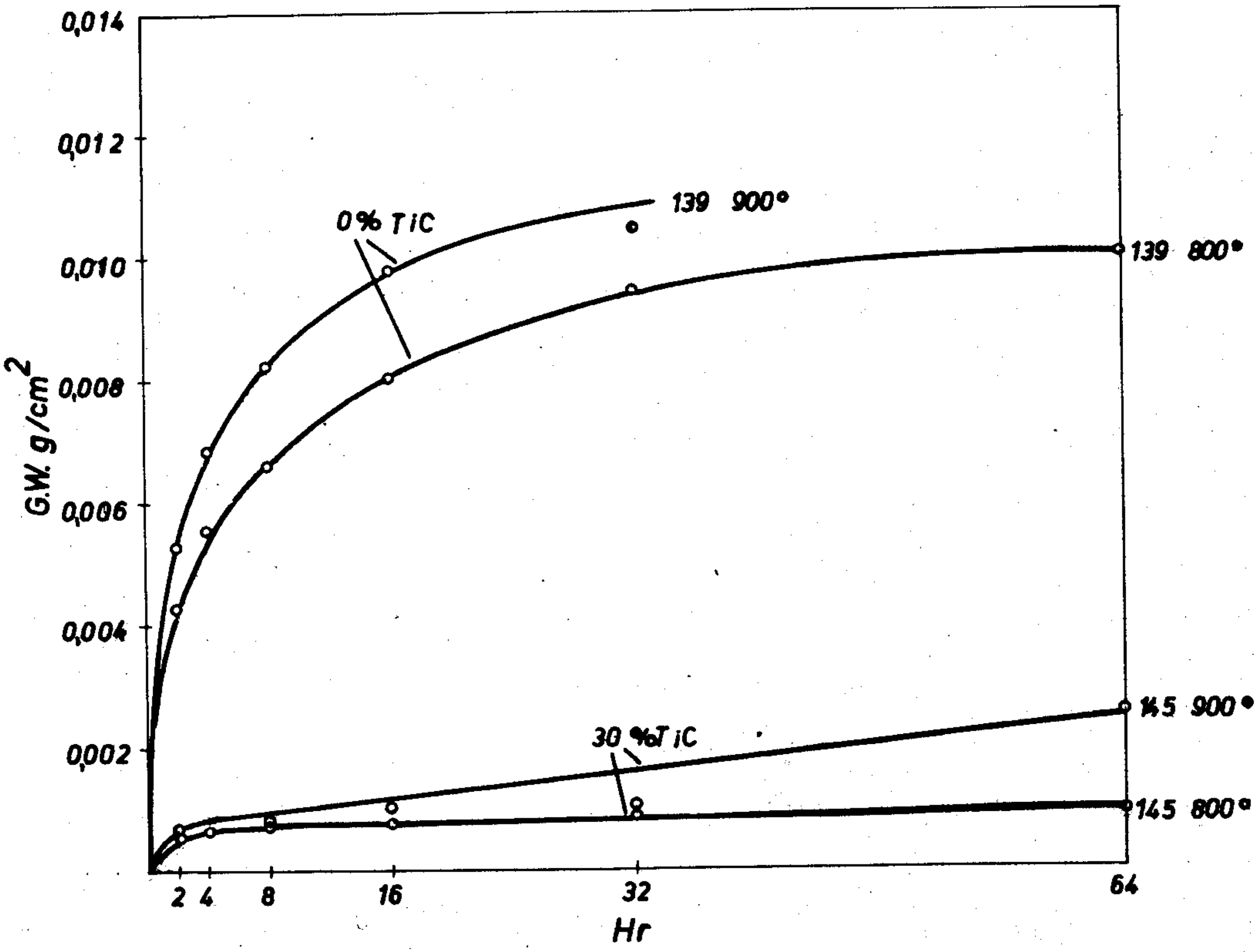

Figure 53. Scaling isotherms Fe-Al-Mo-TiC/Cr_3C_2 90-B (12) wet milled

TABLE I

Composition Fe-Al-TiC

Sample No.	Composition %			Approx. %		
	Carbonyl-iron	Ferro-aluminium	Titanium Carbide	Fe	Al	TiC
59	84	16	-	92	8	-
2	79	16	5	87	8	5
3	74	16	10	82	8	10
4	69	16	15	77	8	15
5	64	16	20	72	8	20
6	59	16	25	67	8	25
7	54	16	30	62	8	30
8	49	16	35	57	8	35
49	80	20	-	90	10	-
9	75	20	5	85	10	5
10	70	20	10	80	10	10
11	65	20	15	75	10	15
12	60	20	20	70	10	20
13	55	20	25	65	10	25
14	50	20	30	60	10	30
15	45	20	35	55	10	35
50	76	24	-	88	12	-
16	71	24	5	83	12	5
17	66	24	10	78	12	10
18	61	24	15	73	12	15
19	56	24	20	68	12	20
20	51	24	25	63	12	25
21	46	24	30	58	12	30
22	41	24	35	53	12	35
51	72	28	-	86	14	~

TABLE II

Composition Fe-Al-TiC (hot pressed)

Sample No.	Composition % Carbonyl-iron	Ferro-aluminium	Titanium Carbide	Approx.% Fe	Al	TiC
45	84	16	-	92	8	-
24	79	16	5	87	8	5
25	74	16	10	82	8	10
26	69	16	15	77	8	15
27	64	16	20	72	8	20
28	59	16	25	67	8	25
29	54	16	30	62	8	30
30	49	16	35	57	8	35
46	80	20	-	90	10	-
31	75	20	5	85	10	5
32	70	20	10	80	10	10
33	65	20	15	75	10	15
34	60	20	20	70	10	20
35	55	20	25	65	10	25
36	50	20	30	60	10	30
37	45	20	35	55	10	35
47	76	24	-	88	12	-
38	71	24	5	83	12	5
39	66	24	10	78	12	10
40	61	24	15	73	12	15
41	56	24	20	68	12	20
42	51	24	25	63	12	25
43	46	24	30	58	12	30
44	41	24	35	53	12	35
48	72	28	-	86	14	-

TABLE III

Composition Fe-Al-TiC-B

Sample No.	Composition %				Approx. %			
	Carbonyl-Iron	Ferro-aluminium	Titanium Carbide	Ferrobor	Fe	Al	TiC	B
60	72	24	-	4	87,5	12	-	0,5
52	67	24	5	4	82,5	12	5	0,5
53	62	24	10	4	77,5	12	10	0,5
54	57	24	15	4	72,5	12	15	0,5
55	52	24	20	4	67,5	12	20	0,5
56	47	24	25	4	62,5	12	25	0,5
57	42	24	30	4	57,5	12	30	0,5
58	37	24	35	4	52,5	12	35	0,5

TABLE IV

Composition Fe-Al-Cr-TiC-B

Sample No.	Composition %					Approx. %				
	Carbonyl-iron	Ferro-aluminium	Chromium	Titanium Carbide	Ferrobor	Fe	Al	Cr	TiC	B
61	69	24	3	-	4	84,5	12	3	-	0,5
62	64	24	3	5	4	79,5	12	3	5	0,5
63	59	24	3	10	4	74,5	12	3	10	0,5
64	54	24	3	15	4	69,5	12	3	15	0,5
65	49	24	3	20	4	64,5	12	3	20	0,5
66	44	24	3	25	4	59,5	12	3	25	0,5
67	39	24	3	30	4	54,5	12	3	30	0,5
68	34	24	3	35	4	49,5	12	3	35	0,5

TABLE V

Composition Fe-Cr-Al-TiC-B

Sample No.	Composition %					Approx. %				
	Carbonyl-iron	Chromium	Ferro-aluminium	Titanium Carbide	Ferrobor	Fe	Cr	Al	TiC	B
69	56	30	10	-	4	64,5	30	5	-	0,5
70	51	30	10	5	4	59,5	30	5	5	0,5
71	46	30	10	10	4	54,5	30	5	10	0,5
72	41	30	10	15	4	49,5	30	5	15	0,5
73	36	30	10	20	4	44,5	30	5	20	0,5
74	31	30	10	25	4	39,5	30	5	25	0,5
75	26	30	10	30	4	34,5	30	5	30	0,5
76	21	30	10	35	4	29,5	30	5	35	0,5

TABLE VI

Composition Fe-Ni-Cr-TiC-B

Sample No.	Composition %					Approx. %				
	Carbonyl-iron	Carbonyl-nickel	Chromium	Titanium Carbide	Ferrobor	Fe	Ni	Cr	TiC	B
77	51	20	25	-	4	54,5	20	25	-	0,5
78	46	20	25	5	4	49,5	20	25	5	0,5
79	41	20	25	10	4	44,5	20	25	10	0,5
80	36	20	25	15	4	39,5	20	25	15	0,5
81	31	20	25	20	4	34,5	20	25	20	0,5
82	26	20	25	25	4	29,5	20	25	25	0,5
83	21	20	25	30	4	24,5	20	25	30	0,5
84	16	20	25	35	4	19,5	20	25	35	0,5

TABLE VII

Composition Fe-Al-TiC/Mo_2C-B

Sample No.	Composition %				Approx. %			
	Carbonyl iron	Ferro-aluminium	TiC/ Mo_2C	Ferro-boron	Fe	Al	TiC/ Mo_2C	B
85	72	24	-	4	87,5	12	-	0,5
86	67	24	5	4	82,5	12	5	0,5
87	57	24	15	4	72,5	12	15	0,5
88	47	24	25	4	62,5	12	25	0,5
89	37	24	35	4	52,5	12	35	0,5
90	68	28	-	4	85,5	14	-	0,5
91	63	28	5	4	80,5	14	5	0,5
92	53	28	15	4	70,5	14	15	0,5
93	43	28	25	4	60,5	14	25	0,5
94	33	28	35	4	50,5	14	35	0,5

TABLE VIII

Composition Fe-Al-TiC/VC-B

Sample No.	Composition %				Approx. %			
	Carbonyl-iron	Ferro-aluminium	TiC/VC	Ferro-boron	Fe	Al	TiC/VC	B
95	72	24	-	4	87,5	12	-	0,5
96	67	24	5	4	82,5	12	5	0,5
97	57	24	15	4	72,5	12	15	0,5
98	47	24	25	4	62,5	12	25	0,5
99	37	24	35	4	52,5	12	35	0,5
100	68	28	-	4	85,5	14	-	0,5
101	63	28	5	4	80,5	14	5	0,5
102	53	28	15	4	70,5	14	15	0,5
103	43	28	25	4	60,5	14	25	0,5
104	33	28	35	4	50,5	14	35	0,5

TABLE IX

Composition Fe-Al-TiC/Cr_3C_2,90/10,-B

Sample No.	Composition %				Approx %			
	Carbonyl-iron	Ferro-aluminiu	TiC/Cr_3C_2	Ferro-boron	Fe	Al	TiC/Cr_3C_2	B
105	72	24	-	4	87,5	12	-	0,5
106	67	24	5	4	82,5	12	5	0,5
107	57	24	15	4	72,5	12	15	0,5
108	47	24	25	4	62,5	12	25	0,5
109	37	24	35	4	52,5	12	35	0,5
110	68	28	-	4	85,5	14	-	0,5
111	63	28	5	4	80,5	14	5	0,5
112	53	28	15	4	70,5	14	15	0,5
113	43	28	25	4	60,5	14	25	0,5
114	33	28	35	4	50,5	14	35	0,5

TABLE X

Composition Fe-Al-TiC/Cr_3C_2,80/20,-B

Sample No.	Composition %				Approx. %			
	Carbonyl iron	Ferro-aluminium	TiC/Cr_3C_2	Ferro-boron	Fe	Al	TiC/Cr_3C_2	B
115	72	24	-	4	87,5	12	-	0,5
116	67	24	5	4	82,5	12	5	0,5
117	57	24	15	4	72,5	12	15	0,5
118	47	24	25	4	62,5	12	25	0,5
119	37	24	35	4	52,5	12	35	0,5
120	68	28	-	4	85,5	14	-	0,5
121	63	28	5	4	80,5	14	5	0,5
122	53	28	15	4	70,5	14	15	0,5
123	43	28	25	4	60,5	14	25	0,5
124	33	28	35	4	50,5	14	35	0,5

TABLE XI

Composition NiAl-TiC/Cr_3C_2,90/10,-B

Sample No.	Composition %			Approx. %				
	NiAl	TiC/Cr_3C_2	Ferro-boron	Ni	Al	Fe	TiC/Cr_3C_2	B
125	96	-	4	65,3	30,7	3,5	-	0,5
126	91	5	4	61,9	29,1	3,5	5	0,5
127	86	10	4	58,5	27,5	3,5	10	0,5
128	81	15	4	55,1	25,9	3,5	15	0,5
129	76	20	4	51,7	24,3	3,5	20	0,5
130	71	25	4	48,3	22,7	3,5	25	0,5
131	66	30	4	44,9	21,1	3,5	30	0,5

TABLE XII

Composition Fe-Al-Mo-TiC/Cr_3C_2,90/10,-B

Sample No.	Composition %					Approx. %					
	Carbonyl-iron	Ferro-aluminium	Molybdenum	TiC/Cr_3C_2	Ferro-boron	Fe	Al	Mo	TiC/ Cr_3C_2	B
132	63	28	5	-	4	80,5	14	5	-	0,5
133	60	26,2	4,8	5	4	76,6	13,1	4,8	5	0,5
134	56,5	25	4,5	10	4	72,5	12,5	4,5	10	0,5
135	53,2	23,6	4,2	15	4	68,5	11,8	4,2	15	0,5
136	50,0	22,1	3,9	20	4	64,6	11	3,9	20	0,5
137	46,8	20,5	3,6	25	4	60,6	10,3	3,6	25	0,5
138	43,4	19,3	3,3	30	4	56,5	9,7	3,3	30	0,5

TABLE XIII

Composition Fe-Al-Mo-TiC/Cr_3C_2,90/10,-B (wet milled)

Sample No.	Composition %					Approx. %				
	Carbonyl-iron	Ferro-aluminium	Molybdenum	TiC/Cr_3C_2	Ferro-boron	Fe	Al	Mo	TiC/Cr_3C_2	B
139	63	28	5	-	4	80,5	14	5	-	0,5
140	60	26,2	4,8	5	4	76,6	13,1	4,8	5	0,5
141	56,5	25	4,5	10	4	72,5	12,5	4,5	10	0,5
142	53,2	23,6	4,2	15	4	68,5	11,8	4,2	15	0,5
143	50,0	22,1	3,9	20	4	64,6	11	3,9	20	0,5
144	46,8	20,6	3,6	25	4	60,6	10,3	3,6	25	0,5
145	43,4	19,3	3,3	30	4	56,5	9,7	3,3	30	0,5

TABLE XIV

Physical Properties Fe-Al-TiC (Sintering temperature 1300°C)

Sample No.	Density g/cm^3		Shrinkage %	Hardness H_V kg/mm^2	Tensile strength kg/mm^2	Elongation %	Impact strength mkg/cm^2
	pressed	sintered					
59	5,62	6,16	3,1	128 - 136	31,8	2	0,7
2	5,59	5,64	0,5	107 - 117	23,4	-	0,4
3	5,38	5,42	0,6	117 - 128	17,3	-	0,25
4	5,22	5,30	1,0	136 - 145	15,9	-	o,15
5	5,06	5,28	1,7	170 - 190	14,5	-	0,14
6	5,02	5,33	3,4	240 - 270	16,o	-	0,13
7	4,98	5,40	5,2	350 - 370	17,8	-	0,13
8	4,81	5,41	6,1	430 - 450	19,4	-	0,12

TABLE XV

Physical Properties Fe-Al-TiC (Sintering temperature 1300°C)

Sample No.	Density g/cm^3		Shrinkage %	Hardness H_V kg/mm^2	Tensile strength kg/mm^2	Elongation %	Tensile strength mkg/cm^2
	pressed	sinterd					
49	5,43	5,82	2,2	128 - 140	30,0	-	0,4
9	5,38	5,40	0,5	110 - 120	20,6	-	0,28
10	5,16	5,21	1,2	132 - 145	18,8	-	0,14
11	5,06	5,19	1,4	165 - 177	15,0	-	0,15
12	4,91	5,11	1,7	184 - 198	14,6	-	0,12
13	4,70	5,09	2,6	230 - 250	11,5	-	0,10
14	4,61	5,04	3,7	270 - 280	11,7	-	0,10
15	4,52	5,03	4,5	300 - 320	9,8	-	0,10

TABLE XVI

Physical Properties Fe-Al-TiC (Sintering temperature 1300°C)

Sample No.	Density g/cm^3		Shrinkage	Hardness H_V kg/mm^2	Tensile strength kg/mm^2	Elongation	Tensile strength mkg/cm^2
	pressed	sintered	%			%	
50	5,19	5,63	2,5	150 - 165	26,8	-	0,35
16	5,15	5,18	0	124 - 136	14,8	-	0,20
17	5,01	5,07	0,1	140 - 150	14,1	-	0,16
18	4,88	4,93	0,3	145 - 155	8,9	-	0,13
19	4,72	4,80	0,5	155 - 165	8,6	-	0,10
20	4,55	4,63	0,7	160 - 181	8,0	-	0,10
21	4,44	5,13	5,2	320 - 350	19,2	-	0,14
22	4,33	5,33	7,2	440 - 450	16,6	-	0,19
51	5,12	5,43	1,7	132 - 145	21,1	-	0,35

TABLE XVII

Physical Properties Fe-Al-TiC (Sintering temperature 1350°C)

Sample No.	Density g/cm^3		Shrinkage %	Hardness H_V kg/mm^2	Tensile strength kg/mm^2	Elongation %	Impact strength mkg/cm^2
	pressed	sintered					
59	5,62	6,23	3,5	124 - 132	35,1	2	1,2
2	5,59	5,74	1,2	117 - 120	26,6	-	0,34
3	5,38	5,62	1,6	128 - 136	25,5	-	0,22
4	5,22	5,89	4,1	223 - 232	32,6	-	0,20
5	5,06	6,06	6,3	330 - 350	33,4	-	0,17
6	5,02	5,95	6,6	400 - 430	29,3	-	0,20
7	4,98	5,94	7,5	450 - 480	16,7	-	0,15
8	4,81	5,77	7,6	540 - 560	18,4	-	0,14

TABLE XVIII

Physical Properties Fe-Al-TiC (Sintering temperature 1350°C)

Sample No.	Density g/cm^3		Shrinkage %	Hardness H_V kg/mm^2	Tensile strength kg/mm^2	Elongation %	Impact strength mkg/cm^2
	pressed	sintered					
49	5,43	5,97	3,2	145 - 155	32,7	-	0,39
9	5,38	5,56	1,5	136 - 45	23,9	-	0,24
10	5,16	5,37	2,2	140 - 155	19,2	-	0,17
11	5,06	5,37	2,1	165 - 177	18,7	-	0,15
12	4,91	5.21	2,0	223 - 232	13,0	-	0,13
13	4,70	5,18	2,8	233 - 242	11,0	-	0,12
14	4,61	5,56	7,1	430 - 450	12,7	-	0,16
15	4,52	5,66	6,5	600 - 620	13,5	-	0,17

TABLE XIX

Physical Properties Fe-Al-TiC (Sintering temperature 1350°C)

Sample No.	Density g/cm^3		Shrinkage %	Hardness H_v kg/mm^2	Tensile strength kg/mm^2	Elongation %	Impact strength mkg/cm^2
	pressed	sintered					
50	5,19	5,86	3,6	165 - 171	22,0	-	0,54
16	5,15	5,43	1,6	136 - 145	22,2	-	0,25
17	5,01	5,40	2,3	177 - 191	18,3	-	0,21
18	4,88	5,51	4,2	242 - 275	27,6	-	0,22
19	4,72	5,75	6,9	329 - 348	23,4	-	0,28
20	4,55	5,76	7,3	406 - 430	26,6	-	0,25
21	4,44	5,78	8,6	530 - 540	23,8	-	0,20
22	4,33	5,47	7,6	580 - 620	31.2	-	0,18
51	5,12	5,73	3,2	165 - 184	26,4	-	0,45

TABLE XX

Physical Properties Fe-Al-TiC-B (Sintering temperature 1250°C)

Sample No.	Density g/cm^3		Shrinkage %	Hardness H_V kg/mm^2	Tensile strength kg/mm^2	Elongation %	Impact strength mkg/cm^2
	pressed	sintered					
60	5,23	6,41	4,8	288	32,4	-	0,34
52	5,15	6,03	4,3	275-288	29,7	-	0,31
53	5,06	5,93	4,8	324-331	27,2	-	0,25
54	4,89	5,79	5,2	324-358	22,8	-	0,23
55	4,73	5,76	5,8	385-407	26,5	-	0,22
56	4,75	5,71	6,7	397-430	23,3	-	0,21
57	4,45	5,61	7,1	481-496	20,0	-	0,20
58	4,32	5,55	7,5	527-544	14,5	-	0,18

TABLE XXI

Physical Properties Fe-Al-Cr-TiC-B (Sintering temperature 1200°C)

Sample No.	Density g/cm³ pressed	Density g/cm³ sintered	Shrinkage %	Hardness H_V kg/mm²	Tensile strength kg/mm²	Elongation %	Impact strength mkg/cm²
61	5,16	5,79	5,6	275-288	39,6	-	0,36
62	5,00	5,61	3,7	231-241	28,3	-	0,22
63	4,97	5,54	3,1	254-262	27,7	-	0,27
64	4,84	5,47	4,2	274-288	25,5	-	0,26
65	4,69	5,44	4,9	367-377	25,0	-	0,23
66	4,52	5,35	5,5	331-354	22,0	-	0,21
67	4,37	5,18	5,5	454-481	18,8	-	0,19
68	4,23	4,84	4,9	394-417	16,9	-	0,14

TABLE XXII

Physical Properties Fe-Cr-Al-TiC-B (Sintering temperature 1200°C)

Sample No.	Density g/cm^3		Shrinkage %	Hardness H_V kg/mm^2	Tensile strength kg/mm^2	Elongation %	Impact strength mkg/cm^2
	pressed	sintered					
69	5,42	6,19	4,6	136-142	23,7	-	0,44
70	5,32	5,36	0,5	113-116	11,8	-	0,15
71	5,20	5,20	0,3	128-136	9,4	-	0,12
72	5,04	5,07	0,4	145-149	8,4	-	0,11
73	4,92	4,95	0,5	149-171	6,2	-	0,09
74	4,76	4,80	0,7	136-155	4,4	-	0,07
75	4,58	4,69	1,1	184-205	4,3	-	0,06
76	4,47	4,52	1,0	232-238	3,1	-	0,05

TABLE XXIII

Physical Properties Fe-Cr-Al-TiC-B (Sintering temperature 1300°C)

Sample No.	Density g/cm^3		Shrinkage %	Hardness H_V kg/mm^2	Tensile strength kg/mm^2	Elongation %	Impact strength mkg/cm^2
	pressed	sintered					
69	5,47	6,50	5,8	180 - 190	32,8	3	0,62
70	5,36	5,87	1,9	160 - 170	21,4	-	0,13
71	5,24	5,41	1,1	180 - 190	17,6	-	0,16
72	5,07	5,08	0,3	200 - 215	11,5	-	0,11
73	4,92	5,00	0,2	220 - 225	9,4	-	0,10
74	4,77	4,89	1,2	210 - 230	8,6	-	0,07
75	4,60	4,85	2,9	250 - 260	6,2	-	0,16
76	4,47	4,76	3,1	-	3,5	-	0,08

TABLE XXIV

Physical Properties Fe-Ni-Cr-TiC-B (Sintering temperature 1200°C)

Sample No.	Density g/cm^3		Shrinkage %	Hardness H_V kg/mm^2	Tensile strength kg/mm^2	Elongation %	Impact strength mkg/cm^2
	pressed	sintered					
77	6,04	6,81	4,1	145 - 158	27,4	4	2,78
78	5,85	6,33	2,9	126 - 138	19,2	-	0,72
79	5,68	5,88	1,6	147 - 156	11,4	-	0,33
30	5,46	5,77	1,0	149 - 162	9,8	-	0,18
81	5,20	5,76	2,4	236 - 245	11,6	-	0,13
82	5,05	5,78	3,9	240 - 250	18,3	-	0,19
83	4,84	5,70	4,3	245 - 270	18,2	-	0,18
84	4,68	5,68	5,4	360 - 410	13,5	-	0,11

TABLE XXV

Physical Properties Fe-Al-TiC/Mo_2C-B (Sintering temperature 1250°C)

Sample No.	Density g/cm^3 pressed	Density g/cm^3 sintered	Shrinkage %	Hardness Hv kg/mm^2	Tensile strength kg/mm^2	Elongation %	Impact strength mkg/cm^2
85	5,14	6,38	5,2	291 - 312	45,3	-	0,29
86	5,04	6,36	7,4	350 - 365	42,0	-	0,41
87	4,79	5,96	7,0	360 - 372	28,1	-	0,35
88	4,54	5,80	7,6	412 - 425	28,9	-	0,30
89	4,29	5,70	9,2	590 - 605	19,6	-	0,26
90	5,00	6,44	7,5	330 - 345	36,7	-	0,41
91	4,87	6,32	7,6	355 - 370	42,3	-	0,68
92	4,67	6,00	7,8	410 - 420	34,7	-	0,45
93	4,47	5,81	8,5	490 - 510	25,0	-	0,35
94	4,22	5,58	8,8	660 - 680	14,6	-	0,27

TABLE XXVI

Physical Properties Fe-Al-TiC/VC-B (Sintering temperature 1250°C)

Sample No.	Density g/cm^3		Shrinkage %	Hardness H_V kg/mm^2	Tensile strength kg/mm^2	Elongation %	Impact strength mkg/cm^2
	pressed	sintered					
95	5,12	6,53	6,7	280 - 300	43,5	-	0,33
96	5,00	6,33	7,1	310 - 340	37,0	-	0,33
97	4,71	6,00	6,8	400 - 430	22,9	-	0,19
98	4,40	5,75	7,9	440 - 460	23,0	-	0,20
99	4,11	5,60	9,3	570 - 610	16,8	-	0,17
100	5,03	6,42	7,0	320 - 350	37,4	-	0,40
101	4,86	6,28	7,4	350 - 370	36,8	-	0,57
102	4,57	5,86	7,6	380 - 410	29,8	-	0,29
103	4,31	5,73	8,6	480 - 510	30,0	-	0,28
104	4,07	5,53	9,0	610 - 630	18,3	-	0,20

TABLE XXVII

Physical Properties Fe-Al-TiC/Cr_3C_2, 90/10-B (Sintering temperature 1250°C)

Sample No.	Density g/cm^3		Shrinkage %	Hardness H_V kg/mm^2	Tensile strength kg/mm^2	Elongation %	Impact strength mkg/cm^2
	pressed	sintered					
105	5,12	6,56	6,9	335 - 348	42,5	--	0,36
106	5,03	6,43	7,5	350 - 364	36,4	--	0,40
107	4,77	6,08	7,9	475 - 493	33,0	--	0,33
108	4,52	5,94	8,6	540 - 550	18,6	--	0,22
109	4,29	5,74	9,1	750 - 770	21,2	--	0,19
110	4,96	6,43	6,9	336 - 345	34,5	--	0,45
111	4,87	6,32	7,3	380 - 393	40,0	--	0,65
112	4,61	6,05	7,7	445 - 460	33,2	--	0,45
113	4,36	5,83	8,5	555 - 570	25,2	--	0,28
114	4,13	5,59	8,6	820 - 840	17,3	--	0,18

TABLE XXVIII

Physical Properties Fe-Al-TiC/Cr_3C_2, 80/20-B (Sintering temperature 1250°C)

Sample No.	Density g/cm^3		Shrinkage %	Hardness H_V kg/mm^2	Tensile strength kg/mm^2	Elongation %	Impact strength mkg/cm^2
	pressed	sintered					
115	5,15	6,49	6,4	290 - 330	43,5	-	0,43
116	5,02	6,11	5,9	335 - 345	33,6	-	0,37
117	4,75	5,61	5,2	370 - 390	25,8	-	0,21
118	4,50	5,34	5,5	380 - 400	21,5	-	0,18
119	4,30	5,09	5,9	380 - 410	13,1	-	0,09
120	5,00	6,39	6,9	330 - 340	37,3	-	0,52
121	4,94	6,05	6,4	320 - 340	38,3	-	0,60
122	4,89	5,58	5,8	310 - 320	29,1	-	0,44
123	4,43	5,20	5,5	320 - 340	19,5	-	0,17
124	4,17	4,96	5,9	245 - 270	10,1	-	0,09

TABLE XXIX

Physical Properties **Fe-Al-Mo-TiC/Cr_3C_2**,90/10-B

Sample No.	Density g/cm^3		Shrinkage %	Hardness H_V kg/mm^2	Tensile strength kg/mm^2	Elongation %	Impact strength mkg/cm^2
	pressed	sintered					
132	5,00	6,45	7,9	330-360	40,6	-	0,57
133	4,94	6,40	7,6	390-410	37,4	-	0,71
134	4,84	6,32	7,5	410-430	32,9	-	0,36
135	4,72	6,21	7,5	440-460	31,5	-	0,22
136	4,64	6,10	7,6	460-480	31,3	-	0,21
137	4,55	6,01	7,8	510-540	18,9	-	0,15
138	4,47	5,92	8,1	550-580	21,8	-	0,15

TABLE XXX

Physical Properties Fe-Al-Mo-TiC/Cr_3C_2,90/10-B (wet milled)

Sample No.	Density g/cm^3		Shrinkage %	Hardness H_V kg/mm^2	Tensile strength kg/mm^2	Elongation %	Impact strength mkg/cm^2
	pressed	sintered					
139	4,29	6,29	14	390-410	45,7	-	0,40
140	4,21	6,30	14,2	390-420	41,7	-	0,36
141	4,12	6,15	14	420-440	29,3	-	0,29
142	4,10	6,10	12,4	450-460	36,1	-	0,26
143	4,03	5,94	12,1	460-480	26,8	-	0,18
144	3,94	5,85	12,0	480-490	28,4	-	0,14
145	3,92	5,76	11,9	490-520	24,7	-	0,16