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(54) **METHOD FOR PRODUCING A WEAR-RESISTANT ALUMINUM ALLOY, AN ALUMINUM ALLOY OBTAINED ACCORDING TO THE METHOD, AND USE THEREOF**

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(57) **ABSTRACT**

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The invention relates to a method for producing a wear-resistant aluminum alloy, to an aluminum alloy produced according to the method, and to the use thereof. The method comprises the steps of: (i) providing an aluminum alloy having the composition Fe: 3-10; X: 3-10; Y: 0-1.5; Z: 0-10; wherein X represents an element or combination of elements (a) V and Si; (b) Cr and Ti; (c) Ce; or (d) Mn; each time with the proviso that the proportion of the individual elements in the combinations of elements (a) and (b) is at least 0.5 wt %; Y represents one or more grain-refining elements selected from the group of B, Ce, Sr, Sc, Mg, Nb, Mn and Zr, unless already present as X; Z represents one or more additives increasing the heat resistance, selected from the group of ceramic fibers, particles and platelets, the figures referring to % by weight in the alloy, and Al and production-related impurities representing the remaining proportion in the alloy to make 100 wt %, with the proviso that the proportion of Al in the alloy is at least 80 wt %; (ii) melting the aluminum alloy, dissolving and homogenizing the alloy elements at temperatures of from 650° C. to 1,000° C.; and (iii) casting the melt into a casting mold at a casting temperature ranging from the melting temperature of the alloy up to a temperature 150° C. above the melting temperature.

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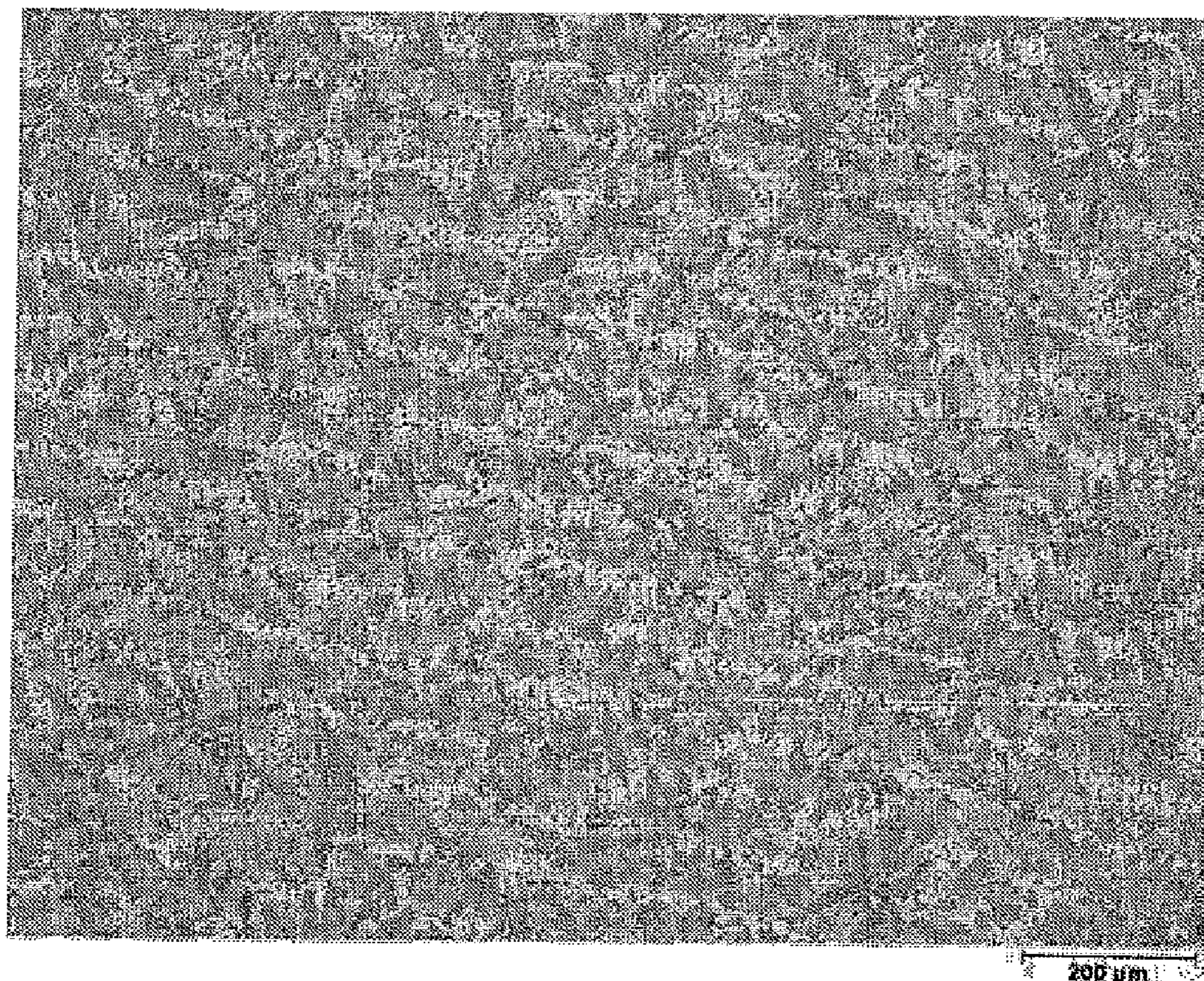
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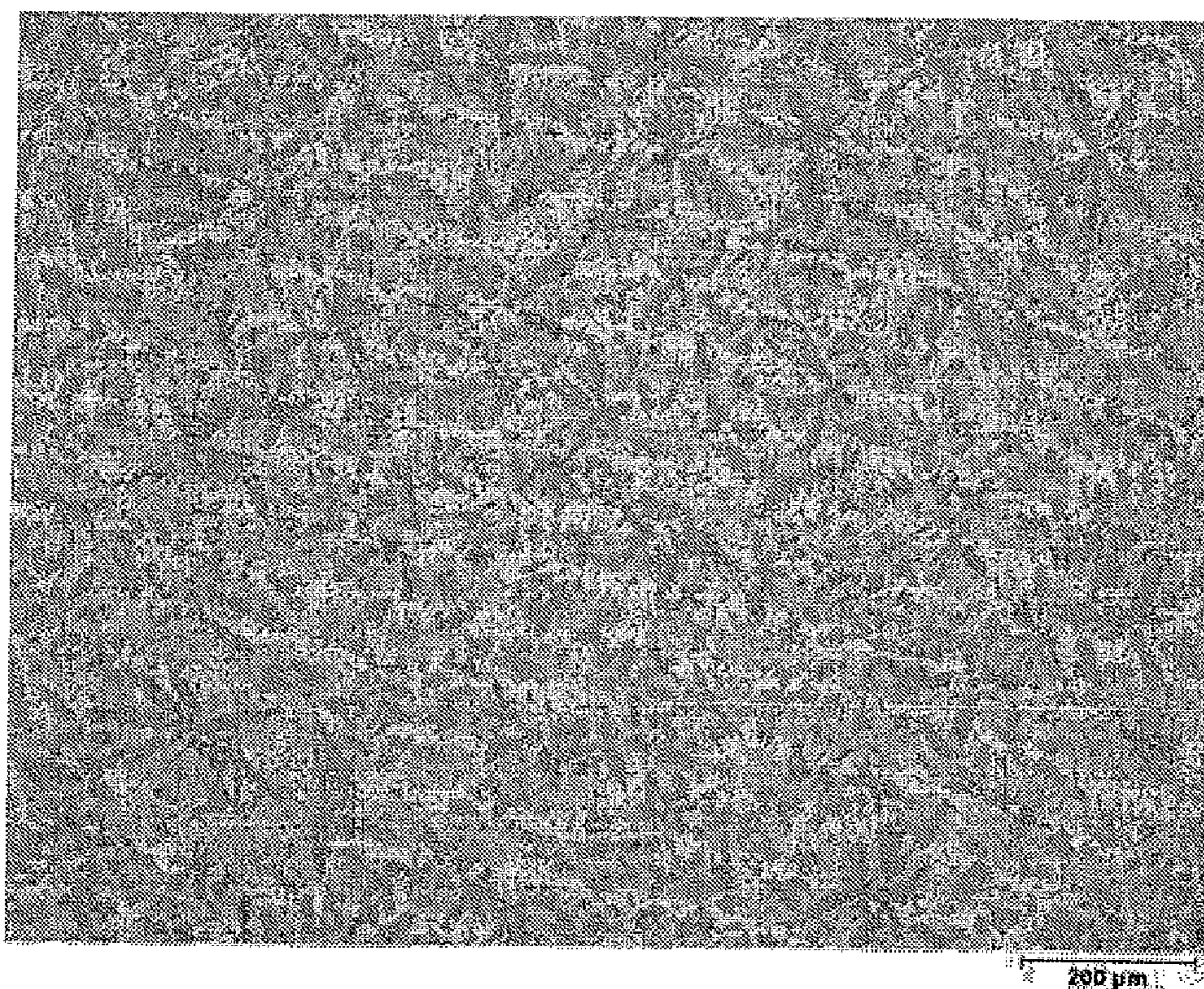


Fig.1

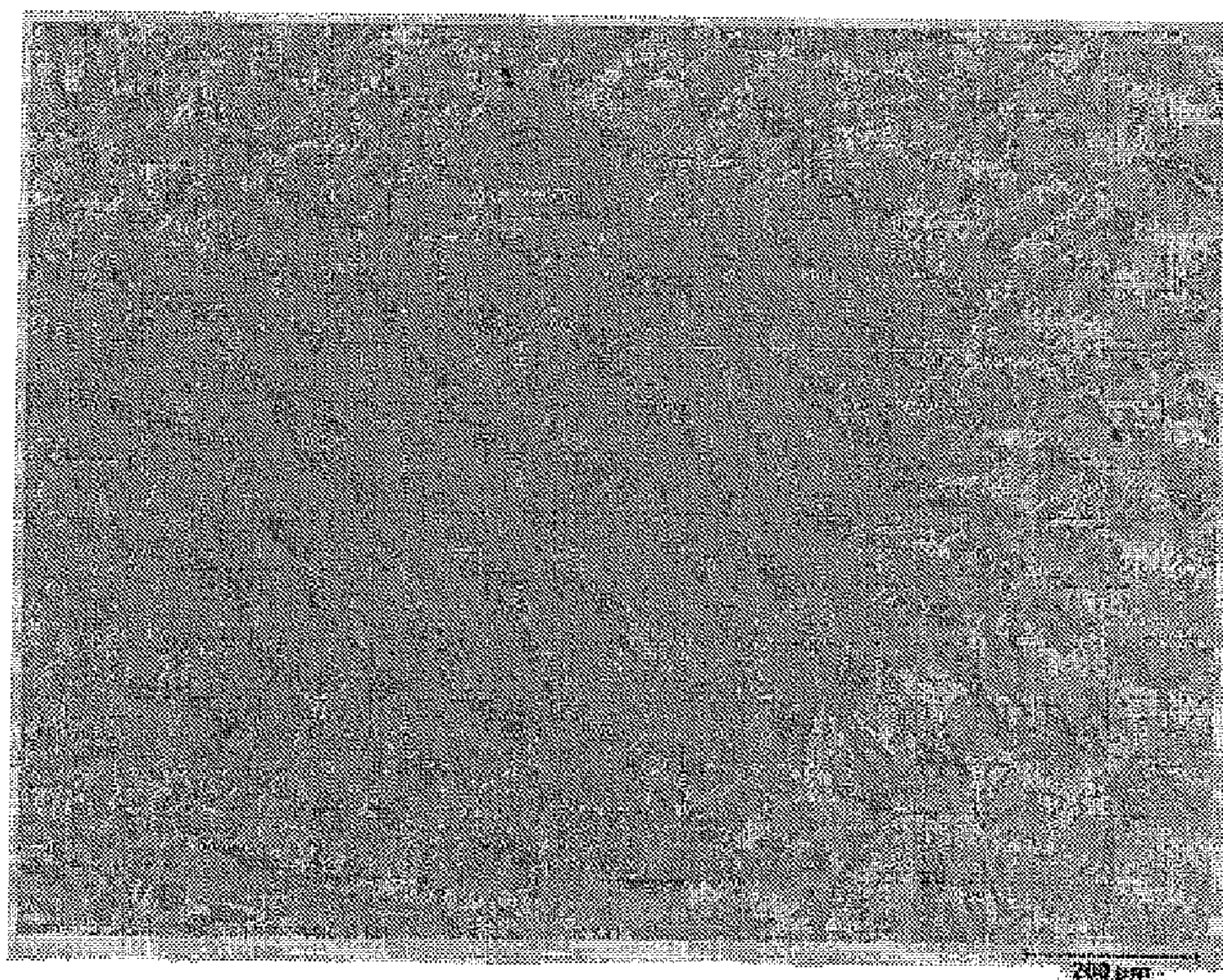


Fig.2

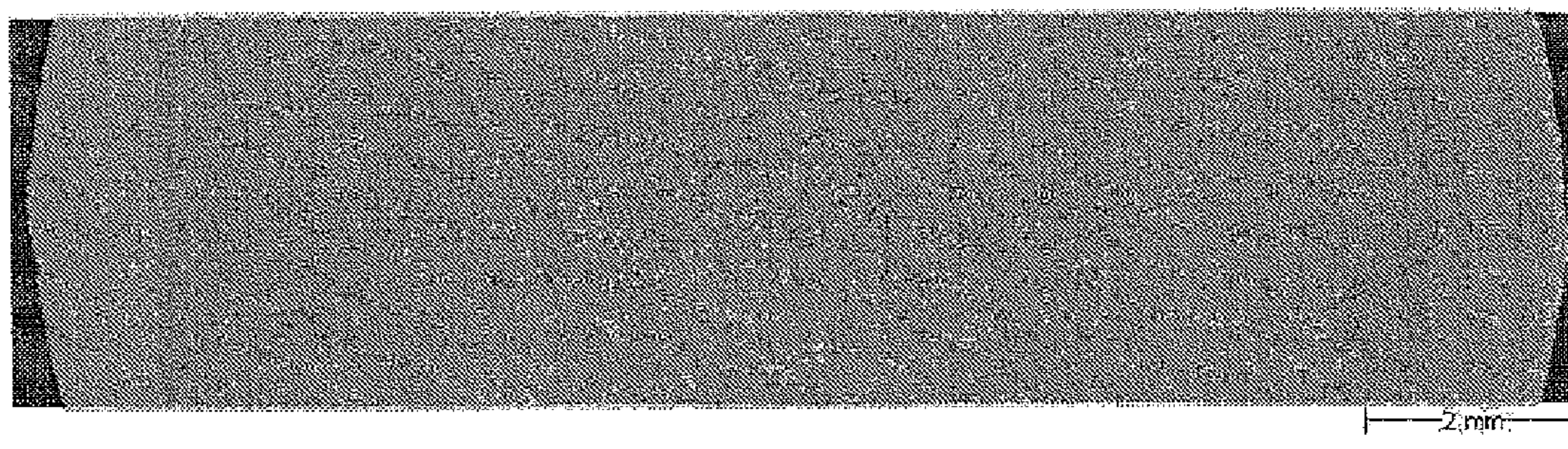


Fig.3

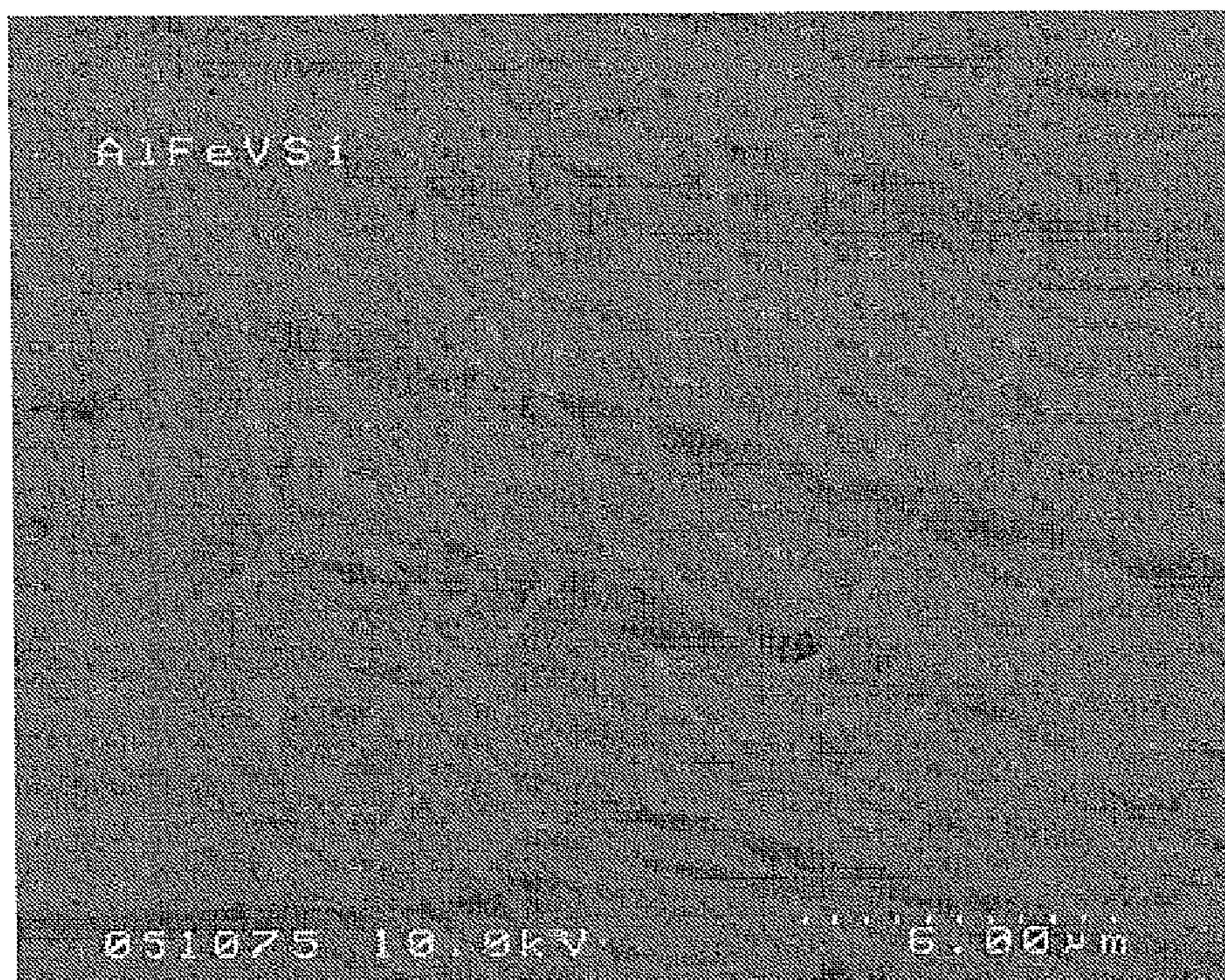


Fig.4

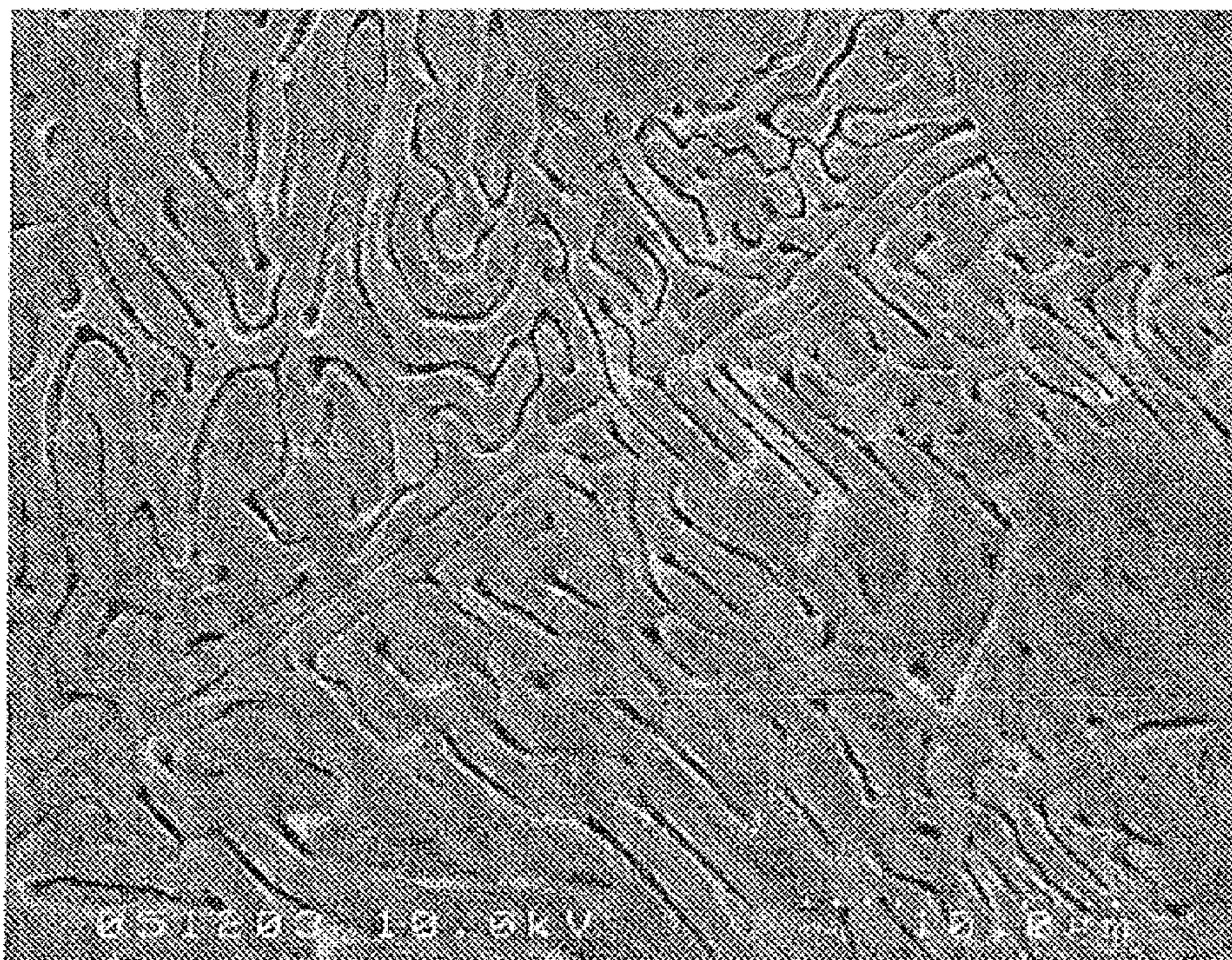


Fig. 5

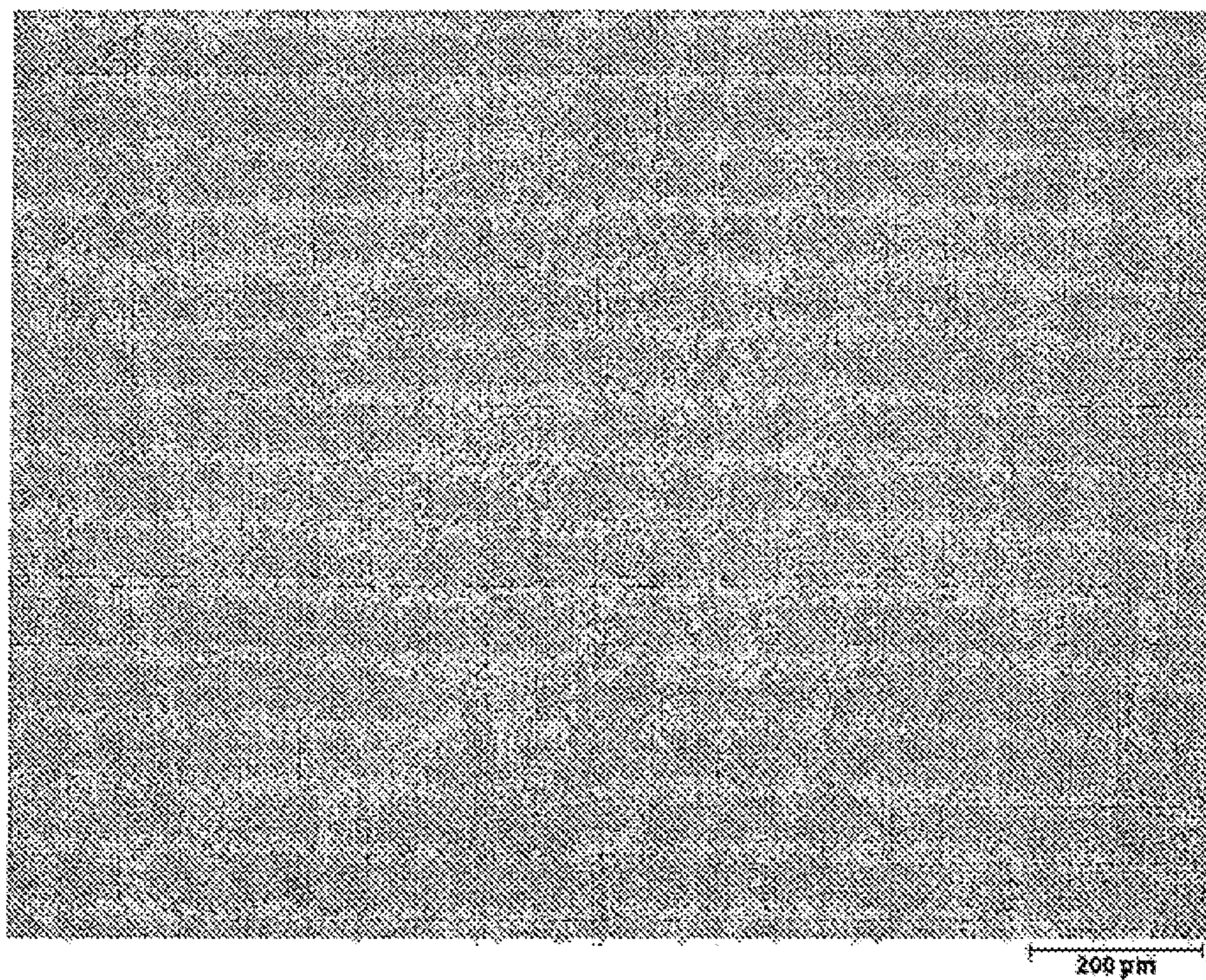


Fig. 6

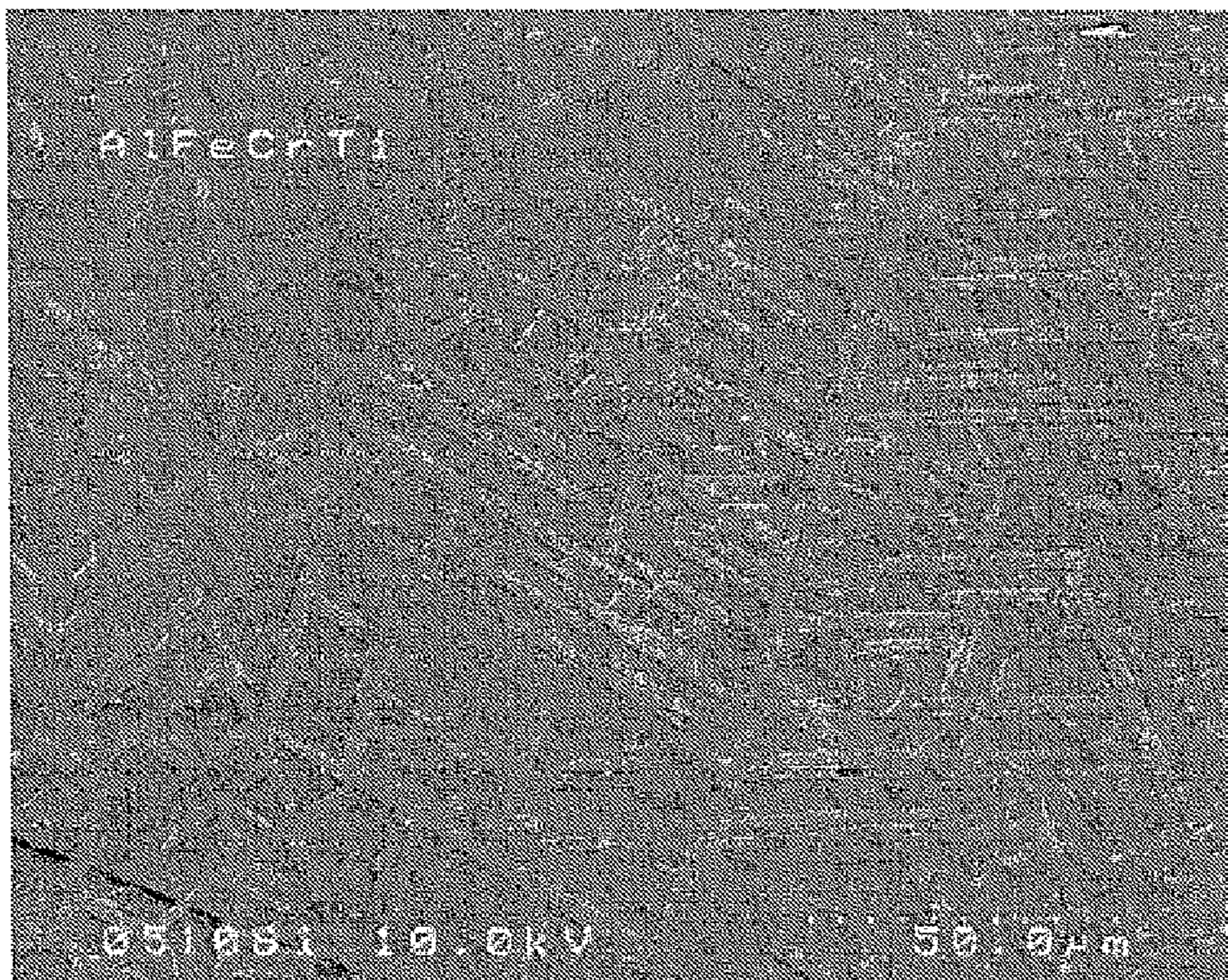


Fig.7

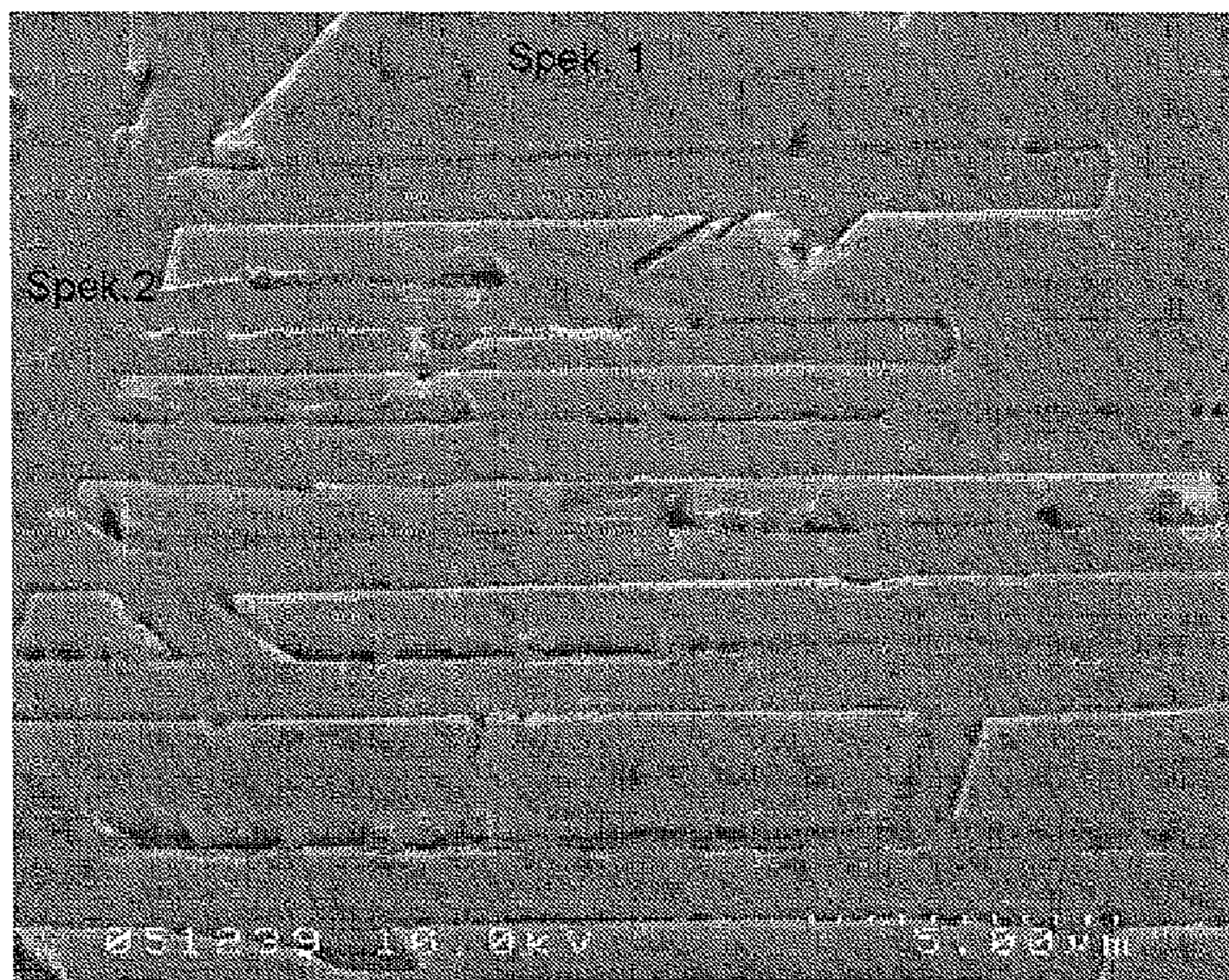


Fig.8

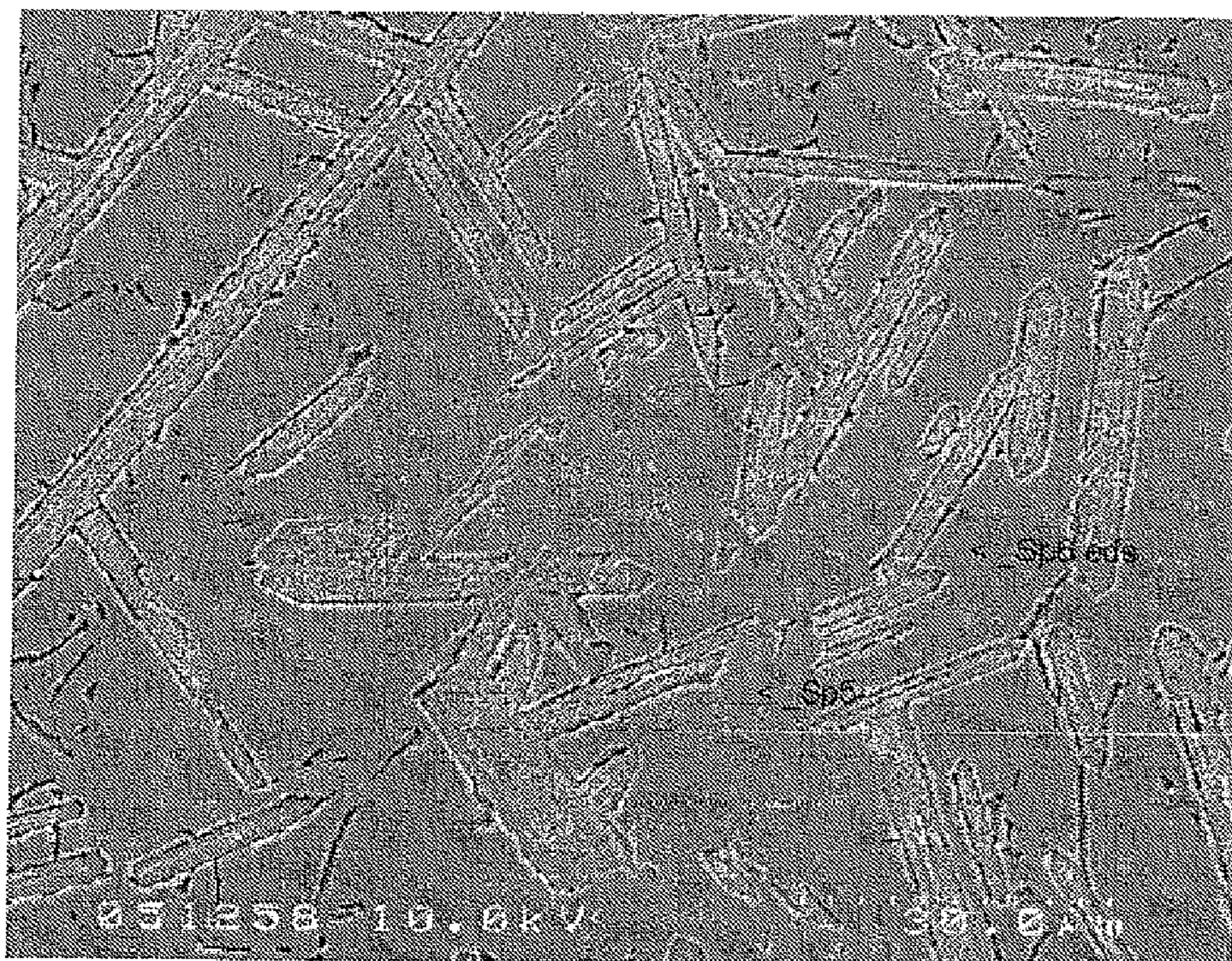


Fig.9

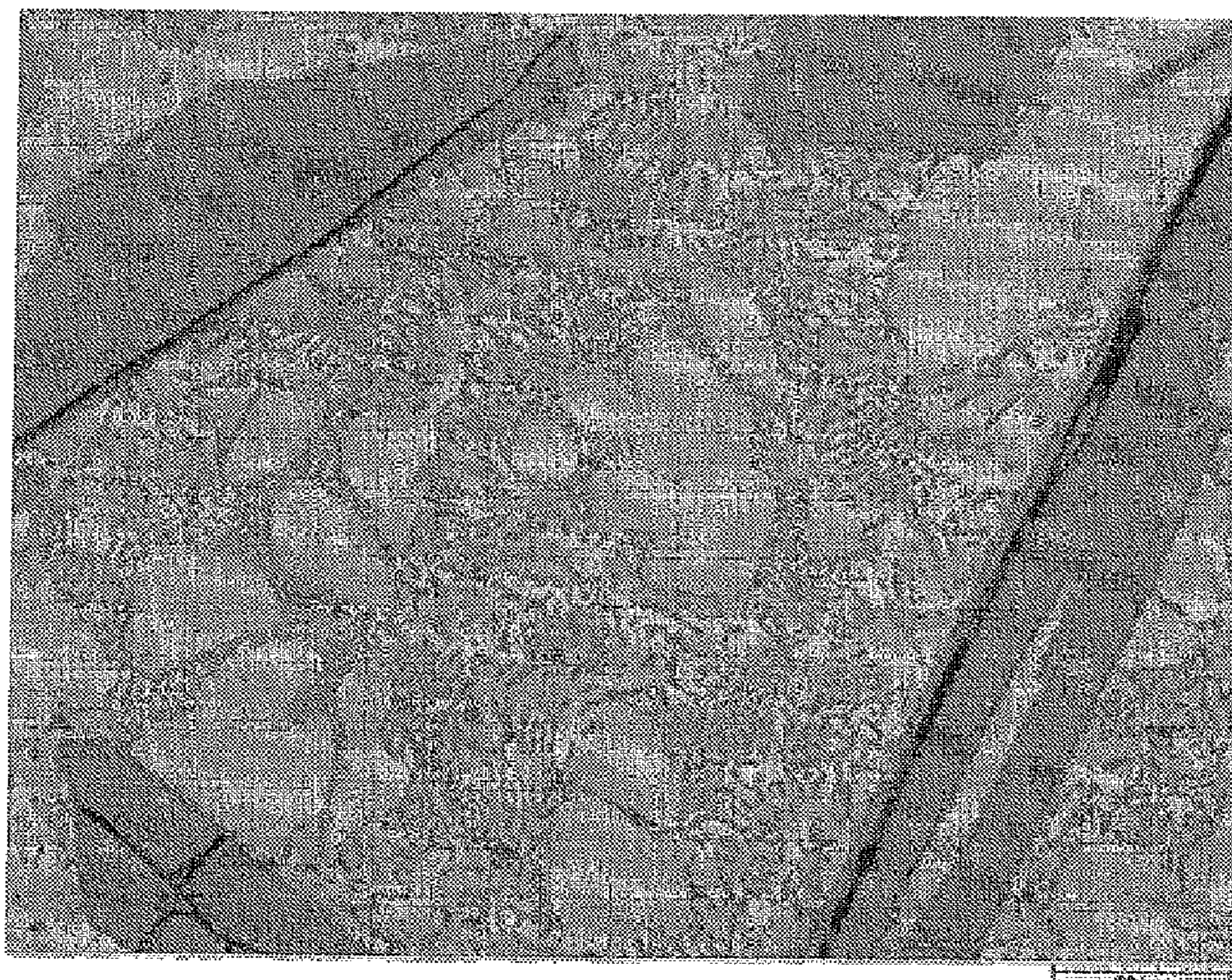


Fig.10

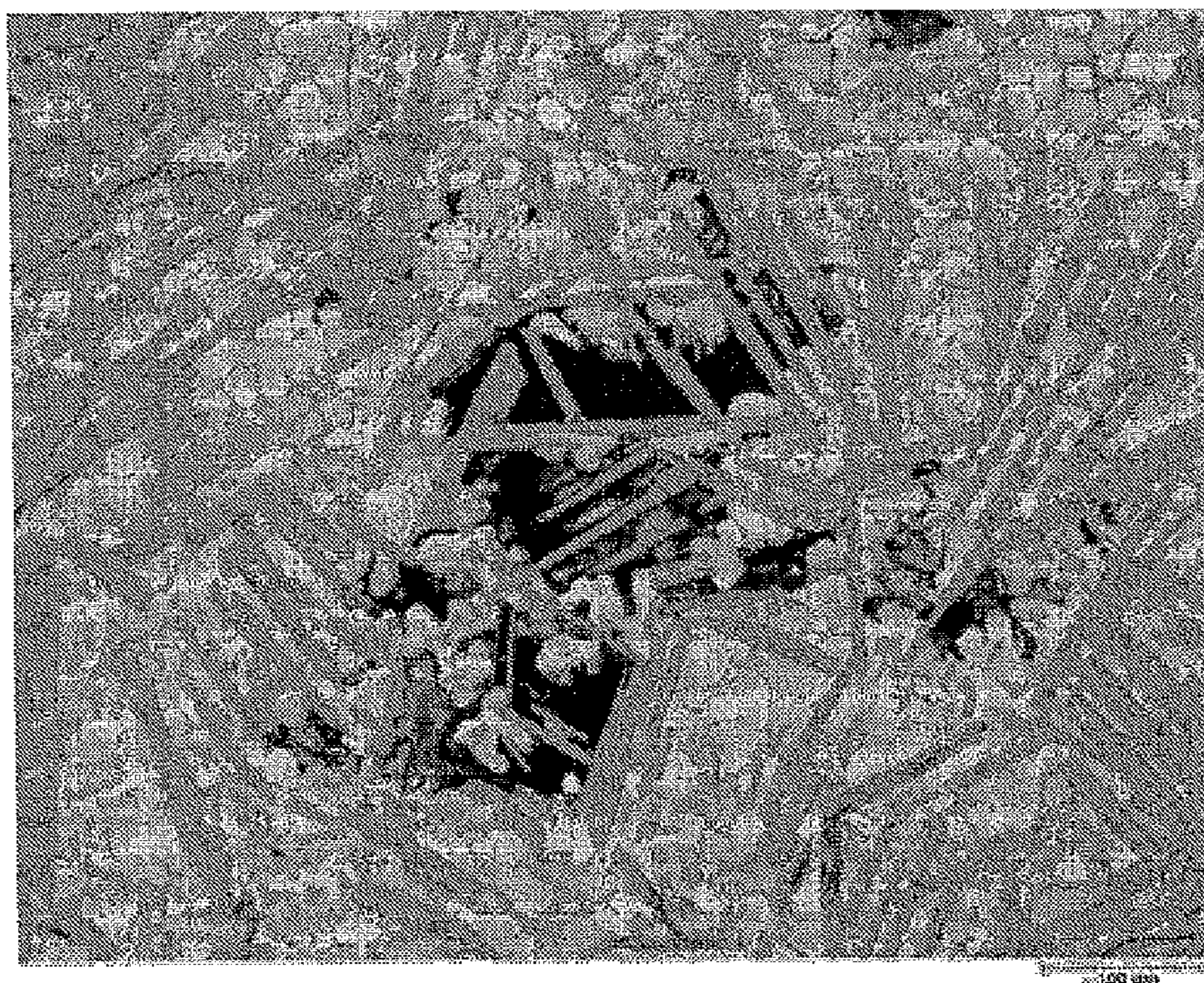


Fig.11

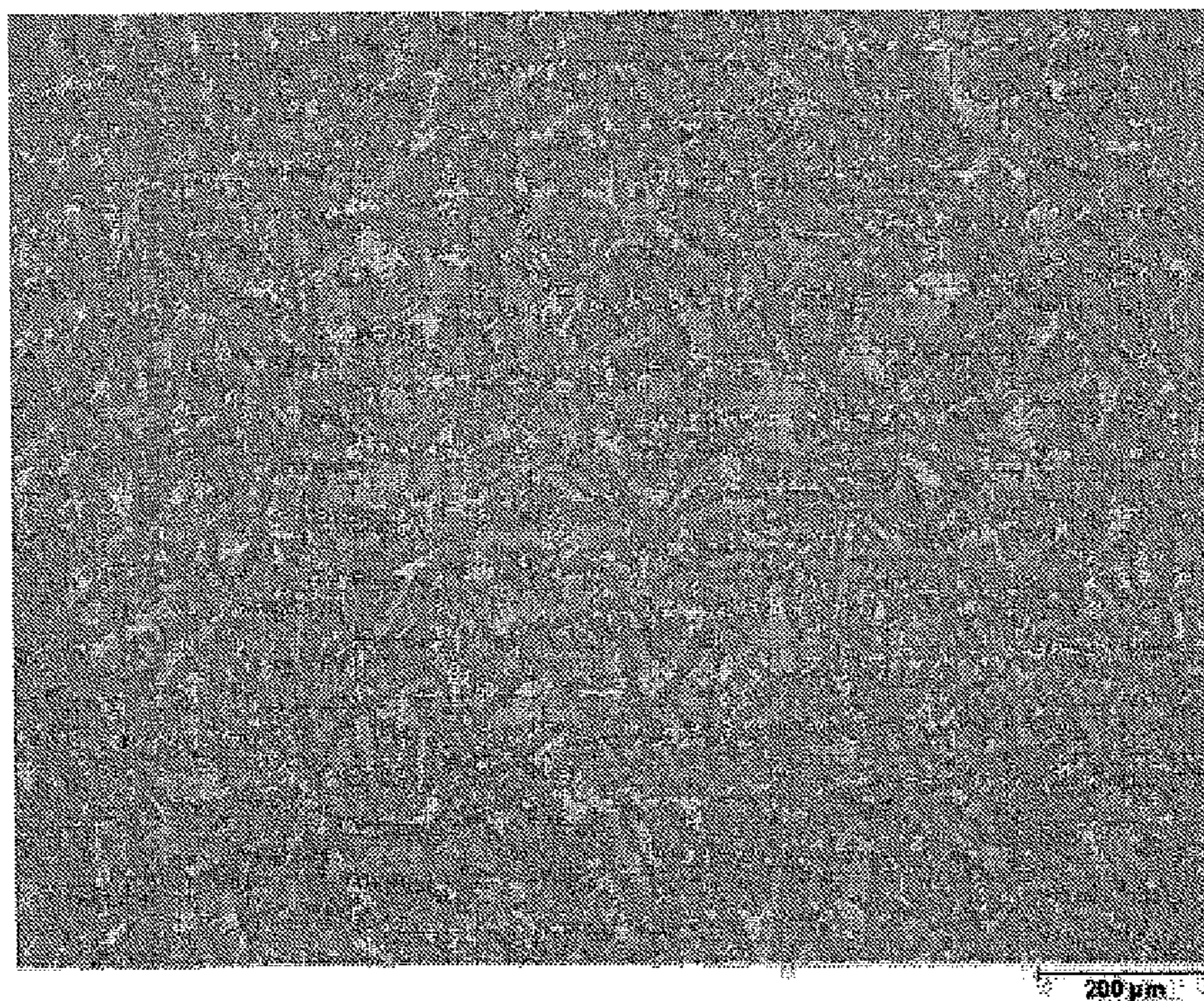


Fig.12

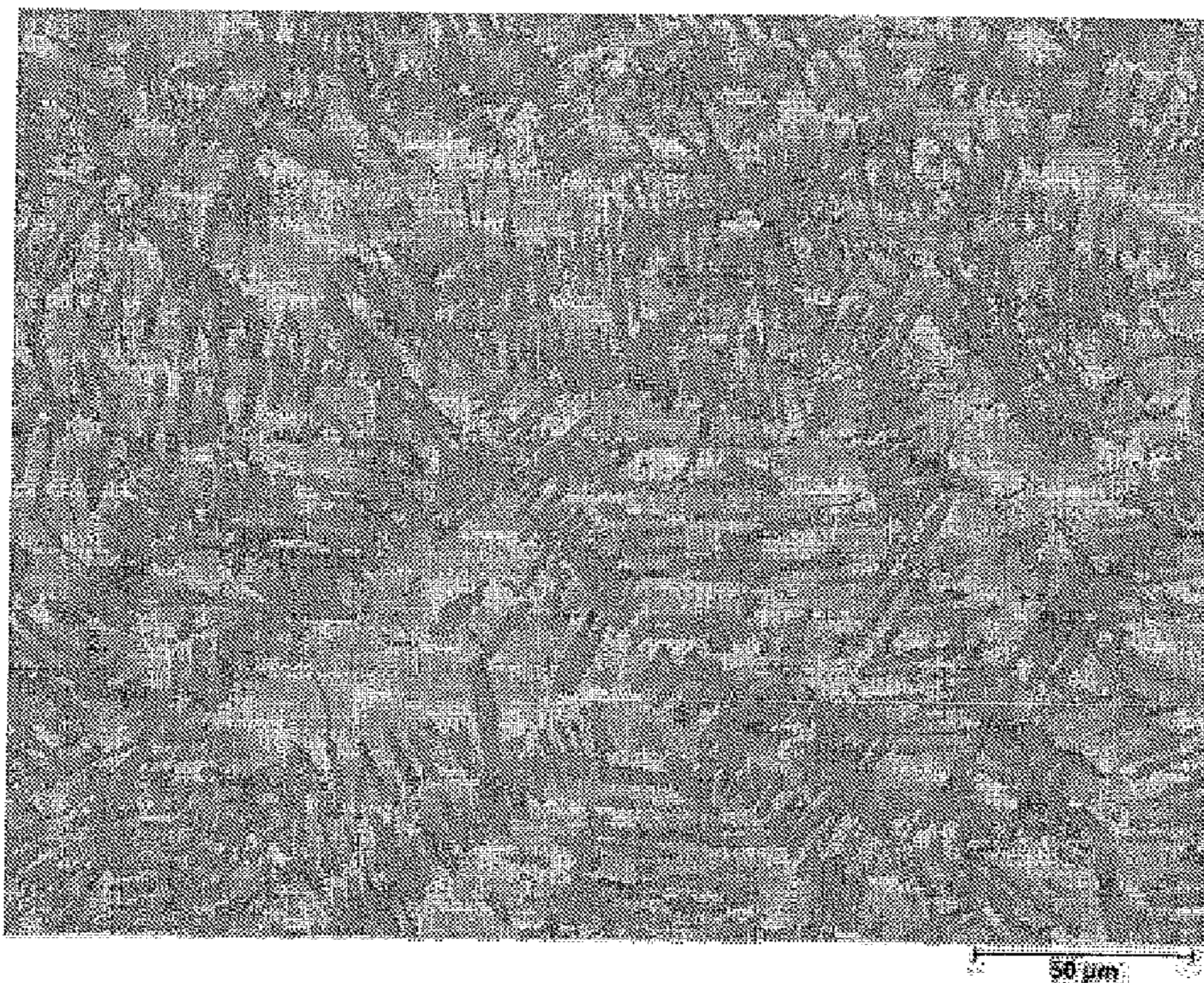


Fig.13

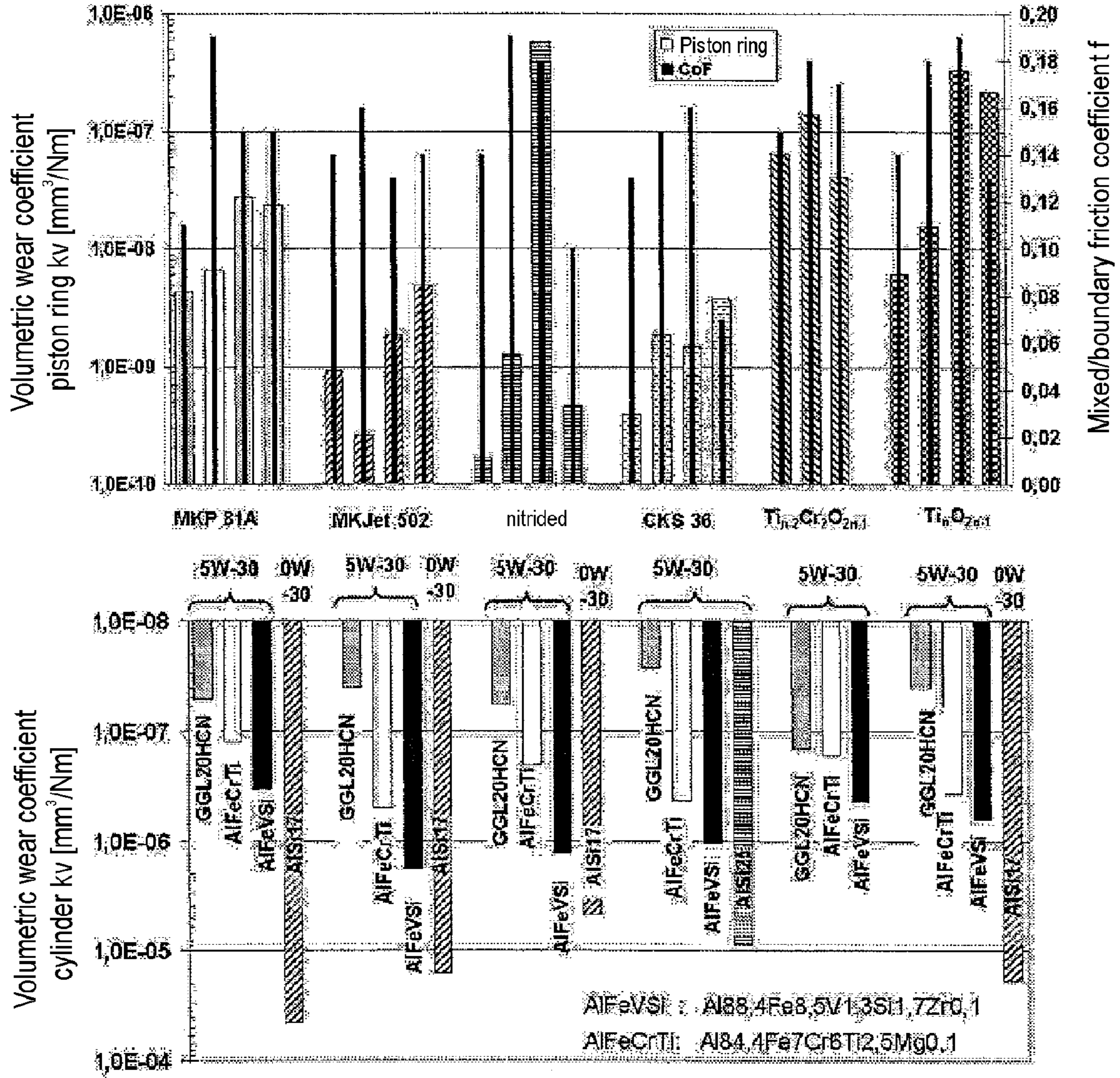


Fig.14

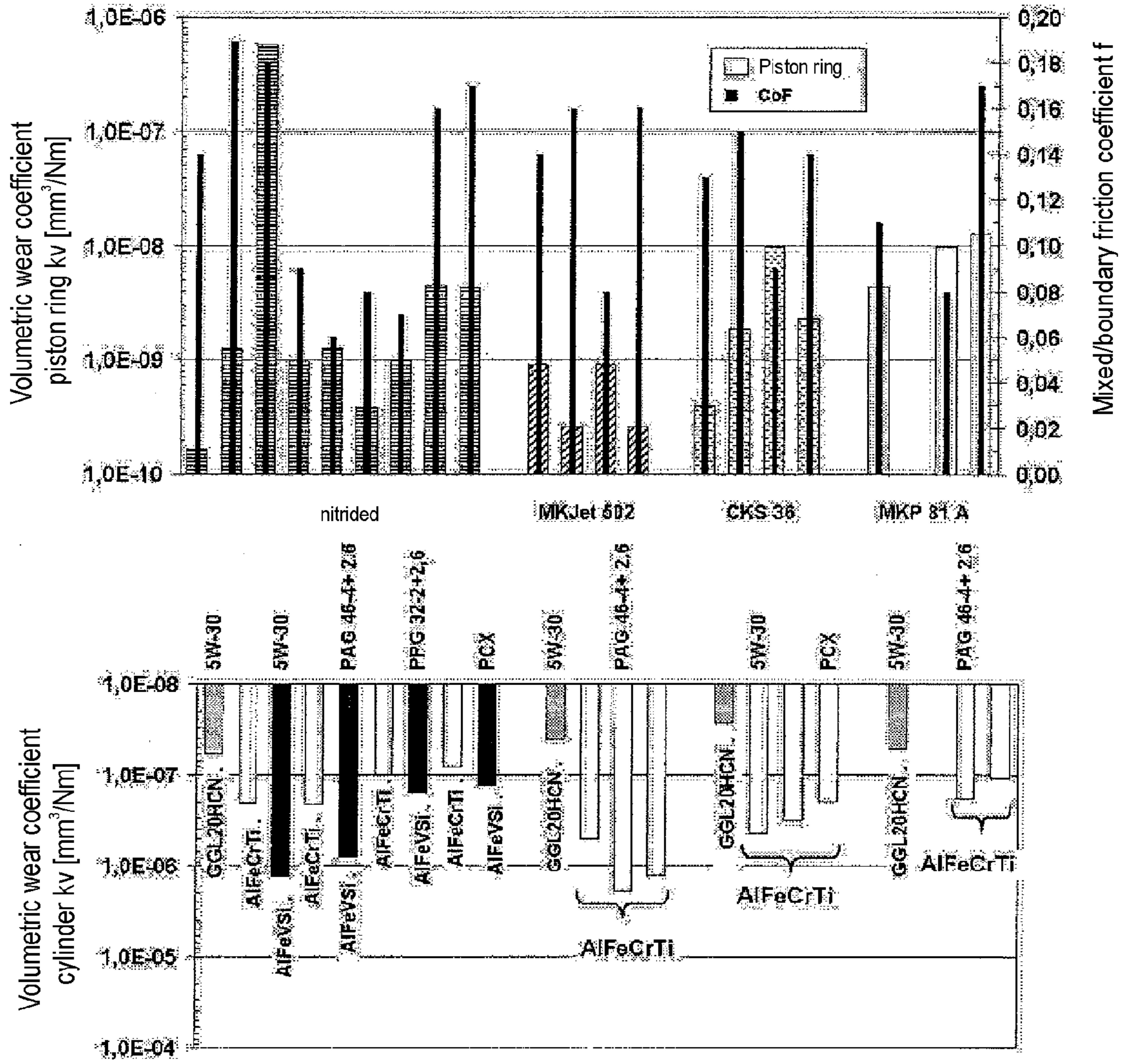


Fig. 15

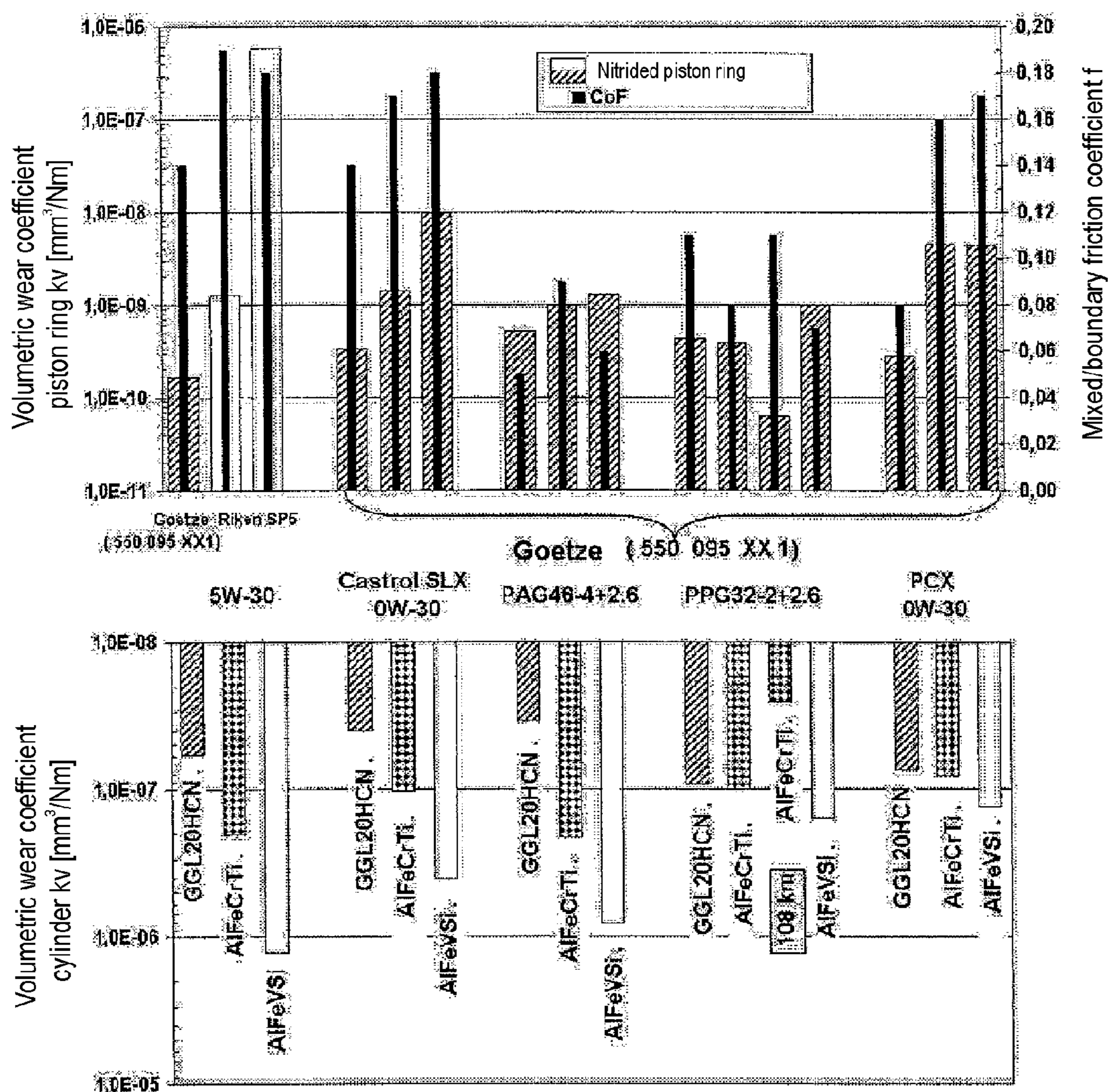


Fig.16

**METHOD FOR PRODUCING A
WEAR-RESISTANT ALUMINUM ALLOY, AN
ALUMINUM ALLOY OBTAINED
ACCORDING TO THE METHOD, AND USES
THEREOF**

TECHNICAL FIELD

[0001] The invention relates to a method for producing a wear-resistant aluminum alloy, to aluminum alloys produced according to the method, and to the use thereof.

BACKGROUND OF THE INVENTION AND
RELATED ART

[0002] Engine sliding couples having sliding elements produced from aluminum base alloy are found e.g. in a piston-piston ring-cylinder face assembly or a crankshaft-bearing shell assembly, especially in the form of crankshaft bearing shells, cylinder faces, piston rings, pistons and valve guides.

[0003] In addition, the sliding surfaces of the sliding elements can be coated or thermo-chemically treated. Since the thirties of the past century, cylinder faces made of eutectic AlSi alloys ("Silumin") with coarse Si primary crystals have been known and used in engines. They may include up to 1.3 wt % iron. The material matrix in these concepts is based on aluminum and silicon. With regard to the functional design of the cylinder face surface, an essential point is to recess the aluminum matrix by 0.5-2 μm by subjecting the faces to chemical or mechanical treatment, so that the hard silicon crystals (Hv \sim 12-14 GPa) would form the supporting component.

[0004] The lowest system wear (piston ring and cylinder face) is achieved with AlSi faces against nitrided piston rings, which can be identical with or in some cases even better than the expected wear of high-carbon gray iron cylinder faces (3.3-3.8 wt % C). The patent document U.S. Pat. No. 6,030,577 discloses AlSi (17-35 wt % Si) with 3-5 wt % Fe.

[0005] In total, however, it has been found that this well-tried couple of AlSi alloys can no longer withstand the load of new or future supercharged and/or hydrogen-operated engines in tribological terms. As it turned out, this applies to both AlSi17 (Alusil) and AlSi25 alloys ("SILITEC"). Regarding the tribological high-pressure properties, the AlSi alloys are also limited in their tribological OK load or scuffing load.

[0006] The highly castable material system Al—Si—Mg, e.g. Al-9.0Si-0.5Mg (A359) is remarkable for a strength rapidly decreasing with temperature and for the following eutectic equilibria at low temperature:

- a. Al—Mg₂Si—Mg with a melting temperature of 555° C.,
- b. Al—Mg₂Si—Al₃Mg₂ with a melting temperature of 451° C., or
- c. Al_{30.9}Mg_{69.1} \leftrightarrow Mg+Mg₁₇Al₁₂+Mg₂Si with a melting temperature of 437° C.

[0007] Similar phase equilibria also exist in the material system Al—Cu—Zn.

[0008] The heat resistance of AlSi alloys can be improved by ceramic fibers, particles and/or platelets, such as AlSiMg 30 vol. % SiCp (Lanxide Corp., Al-7.0Si-0.3Mg) or A359 20 vol. % SiCp (p=platelet), or enhanced by particles of silicon carbide, such as DURALCAN F3S.20S, 20 wt % SiC) or AA6061+40 vol. % Al₂O₃ (Al-1% Mg+30 wt % Al₂O₃ (PRIMEX™)). However, the ceramic phases have a highly adverse effect on the piston ring wear.

[0009] For optimum establishment of combustion in H₂-operated engines, the high thermal diffusivity of aluminum ($K^{RT} \sim$ 60-80 mm²/s) is essential, thereby ruling out cylinder face coatings with engineered ceramics, ceramets or hard metals, despite established improved wear resistance. For comparison: a lamellar gray iron including 3.7 wt % C has $K^{RT}=16.6$ mm²/s.

[0010] The patent document U.S. Pat. No. 4,948,558 discloses an AlFeXY material system. Apart from intermetallic phases, the structural morphology of the rapidly solidified Al special alloys is characterized by amorphous and crystalline aluminum phases. To date, these heat-resistant special alloys, e.g. Al88.5Fe8.5V1.3Si1.7 or Al84.5Fe7Cr6Ti2.5, have been rapidly solidified by melt spinning in a technological complex manner and subsequently compacted and extruded, or produced using powder metallurgy. Up to now, the alloys have neither been mentioned in the context with components subject to wear, nor produced using "classical" casting under the influence of gravity or under pressure in molds or ingot molds.

[0011] The patent document U.S. Pat. No. 5,318,641 by ALCOA discloses the alloy X8019 of an Al—Fe—Ce material system, which has a tensile strength of up to 1,600 MPa at RT and crystalline nanoparticles deposited in a partially amorphous matrix. The amorphous or partially amorphous structure recrystallizes above 300-450° C. (Al90.8Fe6.2Nb1.0Si2.0 (at. %), at 450° C.), causing loss of the high strengths and entailing grain coarsening. Using powder spinning, melt spinning or spray compacting with subsequent compacting and/or extruding, economic large-scale production of cylinder faces or engine blocks is not possible, especially when compared to competitive solutions such as thermal spraying or laser nitriding of gray iron.

[0012] All ultrahigh-strength Al special alloys with 800 MPa < σ_{tens}^{RT} = 1,600 MPa are produced using either powder metallurgy or powder spinning or a melt spinning process or spray compacting. They have a high volume share of intermetallic phases which, owing to rapid solidifying, are present in the form of fine dispersoids smaller than 50-100 nm in size.

[0013] The patent application US 2003/0185701 (K. L. Sahoo et al.) discloses casting parameters for the Al—Fe—V—Si material system. The casting temperatures mentioned therein are 800-1,000° C., with casting being effected in an ingot mold preheated to 350-500° C. The inoculum for grain refinement consists of <1.0 wt % Mg/Ni. A relation to tribologically loaded surfaces is neither made obvious nor disclosed, which also applies to the casting temperatures according to the invention.

[0014] The publication by Sahoo et al., J. of Materials Processing Technology 135 (2003) 253-257, presents the mechanical properties and structural morphologies of an Al-8.3Fe-0.8V-0.9Si alloy, grain-refined with 0.18 wt % Mg, which solidified with 1 K/s to 14 K/s.

[0015] The Al-8.3Fe-0.8V-0.9Si alloys produced according to US 2003/0185701, with and without grain refinement by means of 0.1-1.0 wt % Mg, achieved a Vickers hardness between 43 and 143, which is significantly lower than that of the alloys according to the invention.

[0016] The Chinese publication by Z. H. Chen et al., J. Cent. South Univ. Technol. Vol. 7, No. 4, December 2000, presents the production of components of an AA8009 alloy according to the OSPREY process. A relation to tribologically loaded surfaces is neither made obvious nor disclosed.

[0017] The patent application US 2004/0156739 discloses aluminum alloys with up to 20 wt % rare earths for turbine uses, cast with cooling rates of 10-100 K/s. A relation to tribologically loaded surfaces is neither made obvious nor disclosed.

[0018] The patent application US 2004/0261916 discloses a dispersion-solidifying Al—Ni—Mn material system, wherein the alloys consisting of 0.5-6.0 wt % Ni and 1.0-3.0 wt % Mn with up to 0.3 wt % Zr and/or Sc can be grain-refined. A relation to tribologically loaded surfaces is neither made obvious nor disclosed.

[0019] The patent application US 2004/0140019 discloses a dispersion-solidifying Al+<11 wt % (Mg, Li, Si, Ti, Zr) material system enriched with up to 0.3 wt % nitrogen by low-temperature grinding. It is used in US 2004/0255460 for the production of tubes conducting cryogenic media. A relation to casting technologies or tribologically loaded surfaces is neither made obvious nor disclosed.

[0020] Accordingly, there is a continuing demand for a material which overcomes the above-described limitations of the prior art.

SUMMARY OF THE INVENTION

[0021] A first aspect of the invention that contributes to a solution of the problem being posed lies in providing a method for producing a wear-resistant aluminum alloy. The method according to the invention comprises the steps of:

[0022] (i) providing an aluminum alloy having the composition

[0023] Fe: 3-10;

[0024] X: 3-10;

[0025] Y: 0-1.5;

[0026] Z: 0-10;

wherein

X represents an element or combination of elements

[0027] (a) V and Si;

[0028] (b) Cr and Ti;

[0029] (c) Ce; or

[0030] (d) Mn;

each time with the proviso that the proportion of the individual elements in the combinations of elements (a) and (b) is at least 0.5 wt %;

Y represents one or more grain-refining elements selected from the group of B, Ce, Sr, Sc, Mg, Nb, Mn and Zr, unless already present as X;

Z represents one or more additives increasing the heat resistance, selected from the group of ceramic fibers, particles and platelets,

the figures referring to % by weight in the alloy, and Al and production-related impurities representing the remaining proportion in the alloy to make 100 wt %, with the proviso that the proportion of Al in the alloy is at least 80 wt %;

[0031] (ii) melting the aluminum alloy, dissolving and homogenizing the alloy elements at temperatures of from 650° C. to 1,000° C.; and

[0032] (iii) casting the melt into a casting mold at a casting temperature ranging from the melting temperature of the alloy up to a temperature 150° C. above the melting temperature.

[0033] The present invention improves the wear resistance, the tribological load-bearing capacity and the heat resistance of aluminum base alloys. This may be caused by intermetallic phases deposited within the structure, such as AlFe₃, Al₃Fe (H_v ~9.8 GPa, Θ, Al₅Fe₂ (η, H_v ~10.5 GPa), Al₆Fe, Al₁₃Fe₄,

Al₅Fe₂ (η, H_v ~10.5 GPa), Al₃(Ti, Cr), Al₃Ti, Al₄(Cr, Fe), Al₁₀(Cr, Fe), AlSi₂ or Al₈Fe₂Si having microhard-nesses of from 4,000 to 8,000 MPa.

[0034] Eutectic melting equilibria with liquids temperatures below 600-620° C. are not formed in the metallurgy according to the invention. Therefore, the silicon content preferably should not be higher than 2.0 wt %, more preferably not higher than 1.0 wt % Si. The intermetallic phases are formed from eutectic (α—Al ↔ Al₃Fe) and peritectic phase equilibria.

[0035] A predominant morphological difference of the alloys according to the invention is the form of the dendrites generated from intermetallic phases compared to the silicon crystals deposited in well-known AlSi alloys. The silicon crystals in aluminum alloys are present as individual single crystals, while a dendritic network allows excellent incorporation in the matrix to absorb shear stress from tribological load. Unambiguous characterization of the alloys according to the invention is possible via the production process thereof.

[0036] Furthermore, a specific object of the present invention is to prepare the alloy elements, such as Fe, Ti, Cr, Mo or V, which, in solid state, are insoluble or barely soluble in aluminum, in the form of homogeneous structures free of segregation, using straightforward casting technology. More specifically, this is achieved by grain refinement using an element selected from the group of B, Ce, Sr, Sc, Mg, Nb, Mn and Zr and by using specific casting temperatures.

[0037] A mold form in the meaning of the invention may encompass any form suitable for metal casting technology. For test purposes, graphite ingot molds can be used, for example.

[0038] It should be noted that predicting the formation of intermetallic phases or dendrites during casting is not possible, but it is precisely the presence thereof that has a considerable influence on the tribological material properties. Lacking predictability of intermetallic phases, morphology and composition of the individual components in the structure, as well as problems arising from the formation of eutectic phases lead to the conclusion that purely theoretical considerations are not suitable for predicting suitable materials. It has now been found in experiments that holding the temperature of the melt above 650° C. causes establishment of a phase equilibrium over the entire volume of the material within a period of time reasonable for commercial applications.

[0039] Following melting and homogenizing, between 0.5 and 0.8 wt % of one or more elements selected from the group of B, Ce, Sr, Sc, Mg, Nb, Mn or Zr can preferably be alloyed for grain refinement. Grain refinement predominantly reduces the size of the dendrites of intermetallic phases deposited during solidification, but also results in an increase of the crystal germ number/density during primary crystallization of aluminum.

[0040] A higher cooling rate of >100 K/s achieves the same effect, so that grain refinement can be used with advantage to obtain a uniform structural pattern when the wall thickness of the cast parts is larger. The dendrites, still being relatively large, are favorable to the tribological sliding load and binding of the intermetallic phases within the structure, but unfavorable in supplementing the solidification front with melt. For this reason, the size thereof must be optimized by grain-refining elements, optionally with the aid of magnetic stirring.

[0041] Formation of dendrites from the intermetallic phases can also be prevented by magnetic stirring. In this way,

magnetic stirring improves feeding the solidification front with fresh melt and aids in preventing voids (pores).

[0042] The casting temperature in step (iii) is preferably in the range of 1° C. to 80° C., particularly in the range of 10° C. to 50° C. above the melting temperature of the alloy. The casting temperatures are preferably below 800° C.

[0043] According to another preferred variant of the method, an alloy having 4-8 wt % Fe and/or 3-5 wt % X is provided. It is also preferred to preset X for the combination of elements (a) in such a way that the share of Si is smaller than or equal to 2 wt %, particularly smaller than or equal to 1 wt %. The measures mentioned above result in aluminum alloys having particularly favorable tribological behavior.

[0044] In a preferred fashion, the steps (ii) and (iii) form part of a metallurgic melt casting process selected from the group of sand casting, pressure casting, continuous casting, thin-strip casting, centrifugal casting and cold crucible process. The above-mentioned processes are particularly easy to accomplish in cooperation with the method according to the invention. In a preferred fashion, the workpiece consisting of the alloy can be treated by die-forging wherein the workpiece is completely surrounded by the closed mold, i.e. the forging die, and the cavity incorporated in the forging die determines the shape of the finished molding.

[0045] Finally, the temperature of the casting mold preferably ranges from 450° C. to 600° C. In this way, it is possible to produce aluminum alloys having particularly favorable tribological behavior.

[0046] A second aspect of the invention relates to an aluminum alloy produced or obtainable according to the method described above.

[0047] A third aspect of the invention relates to the use of the above-mentioned aluminum alloy in the production of sliding elements in crankshaft bearing shells, cylinder faces, piston rings, pistons, valve guides, bearing bushes or bearing shells.

[0048] With reference to the examples and associated drawings, the invention will be illustrated in more detail below.

[0049] FIGS. 1 to 3 show sample cross-sections of AlFeVSi alloys;

[0050] FIGS. 4 and 5 show REM images of an etched and non-etched 88.5Al8.5Fe1.3V1.7Si alloy;

[0051] FIG. 6 shows a sample cross-section of an AlFeCrTi alloy;

[0052] FIGS. 7 to 9 show REM images of the AlFeCrTi alloy;

[0053] FIG. 10 shows an LOM image of the AlFeCrTi alloy;

[0054] FIG. 11 shows an LOM image of a rapidly cooled AlFeCrTi alloy with residual melt;

[0055] FIGS. 12 and 13 show LOM images of an Al84.4Fe7Cr6Ti2.5Mg0.1 alloy; and

[0056] FIGS. 14 to 16 show test results relating to the tribological behavior of the alloys.

[0057] The following FIGS. 1-13 describe the production parameters under the established conditions and the structural morphologies of inventive alloys on the basis of AlFeVSi and AlFeCrTi in argon atmosphere.

EXAMPLE 1

AlFeVSi Alloys

[0058] FIGS. 1-3 show sample cross-sections of AlFeVSi alloys cast under varying conditions. The 12 mm sample cross-section of FIG. 1 shows an Al88.4Fe8.5 V1.3Si1.7Zr0.1 alloy cast at a melting temperature of 750° C. into a graphite ingot mold preheated to 600° C. and added with Zr as grain-refining element. The sample cross-section (14 mm) of FIG. 3 is based on an Al88.5Fe8.5V1.3Si1.7 alloy cast at a melting temperature of 700° C. into a graphite ingot mold without preheating. FIG. 2 shows the same alloy, but with use of a process variant wherein the melting temperature was 750° C. and the graphite ingot mold was heated to 500° C. The latter alloy presented an E-modulus at room temperature (RT) of $E^{RT}=85.7$ GPa, which still was $E^{500^\circ C.}=65$ GPa at 500° C. Hence, such E-modulus values are comparable to those of a high-carbon lamellar gray iron (~3.7 wt % C, GL11) and significantly higher than those of AlSi alloys. Referring to both of the exemplary Al cast alloys according to the invention, it should be noted that the high E moduli were achieved without addition of ceramic fibers, particles or platelets. By virtue of their high E-moduli alone, the alloys according to the invention are capable of substituting gray iron in terms of material mechanics because—in addition—the moduli decrease with increasing temperature in a similar manner as in high-carbon gray iron. Moreover, the decline in strength of the alloys according to the invention is shifted towards higher temperatures.

[0059] As seen in FIGS. 1-3, a graphite ingot mold preheated to 500° C. achieves uniform formation of the structural pattern of the Al88.5Fe8.5V1.3Si1.7 alloy across the cross-section, but these conditions promote growth of large dendrites of Al₃Fe (Index of X-ray diffraction data JCPDS No. 001-1265) several millimeters in length. It is only by grain refinement using 0.1 wt % Zr, a graphite ingot mold preheated to 600° C., together with a casting temperature of 750° C., that a significantly finer structural pattern is achieved, which is formed homogeneously across the cross-section.

[0060] In addition to deposition of primary dendrites of Al₃Fe (001-1265) and Al80V12Fe7.5 (JCPDS No. 040-1229) in the 88.5Al8.5Fe1.3V1.7Si alloy, the REM images of FIG. 4 (non-etched) and FIG. 5 (etched) show the fine “perlite-like” pattern from eutectic decomposition of the residual melt, which consists of AlSi₂ (aluminum disilicide). It represents the key to generating the high heat resistance of a “classically” cast AlFe—XY alloy without the use of rapid solidification processes.

EXAMPLE 2

AlFeCrTi Alloys

[0061] FIG. 6 shows the structural morphology of an Al84.5Fe7Cr6Ti2.5 alloy cast at 700° C., in which case the alloy had no grain-refining elements added and casting was effected in a non-preheated graphite ingot mold (Ø=14 mm). The Al84.5Fe7Cr6Ti2.5 alloy had an elasticity modulus of $E^{RT}=104.1$ GPa, which declined to $E^{500^\circ C.}=83$ GPa at 500° C.

[0062] Similarly, the Al84.4Fe7.0Cr6.0Ti2.5 alloy system deposits a dense, yet closed, primary dendrite network (see FIG. 6) analyzed as Al₄(Fe, Cr) by means of EDX. The REM images (FIG. 7 (non-etched); FIG. 8 (etched)) reveal deposits of Al₄(V,Fe) in addition to the Al₃Fe dendrites. A globular

substructure is found within the lamellar dendrites. In addition, deposits of $\text{Al}_3(\text{Ti}, \text{Cr})$ are found in the same structure (FIG. 9; REM image, etched).

[0063] As is the case with the 88.5Al8.5Fe1.3V1.7Si alloy, the AlFeCrTi alloy shows a fine, “perlite-like” pattern from eutectic decomposition of the residual melt of the Al84.4Fe7.0Cr6.0Ti2.5 alloy (FIG. 10). For comparison, FIG. 11 shows an LOM image of the lamellar dendrites from intermetallic phases in a rapidly cooled AlFeCrTi alloy with residual melt.

[0064] By reducing the difference between the casting and ingot mold temperatures to 250 K and grain refining using 0.1 wt % Mg, the dendrite network in an Al84.4Fe7.0Cr6.0Ti2.5Mg0.1 alloy appears somewhat finer (FIG. 12), which, in particular, is caused by branching or ramification thereof (FIG. 13). The Al84.4Fe7.0Cr6.0Ti2.5Mg0.1 alloy was cast at 750° C. into a graphite ingot mold (14 mm) preheated to 500° C. The 88.5Al8.5Fe1.3V1.7Si alloys tend to form asterisk-shaped crystals compared to the Al84.4Fe7.0Cr6.0Ti2.5Mg0.1 alloy which has a dendrite network.

[0065] In total, it has also been found that the AlFeXY alloys according to the invention can be cast with advantage at a slightly excessive temperature of 150 K at maximum above the melting temperature of the alloy.

Tribological Behavior

[0066] The outside-engine characterization of the tribological behavior of the AlFeXY alloys according to the invention was performed according to the BAM testing methodology which has been described in detail in the citation “Woydt M. and N. Kelling, Characterization of the tribological behaviour of lubricants and materials for the tribosystem piston ring/cylinder liner, in: ASTM STP 1404, “Bench testing of

[0067] FIG. 14 presents the obtained test results in the form of the wear coefficient of the base body (piston ring) separated from the counter-body (rotating specimen or cylinder face), together with the mixed/boundary friction coefficient associated to each couple. The SAE 5W-30 and SAE 0W-30 hydrocarbon-based initial-fill oils used in FIG. 14 have a high-temperature/high-shear viscosity (HTHS) of 3.0 mPas. GG20HCN is a gray iron with lamellar graphite, highly carbonized with 3.66 wt % carbon. The piston ring designations “MKP81A”, “MKJet502 (WC/Cr₃C₂, “superpoliert”)” and “CKS36” are brand names of Federal Mogul Burscheid GmbH. In the diagrams, “nitrided” represents a “standard nitriding” by Federal Mogul Burscheid GmbH. The atmospheric plasma-sprayed (APS) $\text{Ti}_n\text{O}_{2n-1}$ and $\text{Ti}_{n-2}\text{Cr}_2\text{O}_{2n-1}$ ring coatings represent experimental coatings for piston rings from CIE Automotive (Tarabusi, Barrio Urquizu 58, ES-48140 Igorre). The AlFeXY alloys, Al84.4Fe7.0Cr6.0Ti2.5Mg0.1 and 88.4Al8.5Fe1.3V1.7SiZr0.1, were cast under vacuum at 750° C. into a graphite ingot mold preheated to 600° C.

[0068] In the BAM test procedure, nitrided rings against AlSi17 (AlSi17Cu4Mg, “Alusil”, from Kolbenschmidt) or AlSi25Ni4 (“Silitec” from PEAK Werkstoff GmbH) are regarded as low-wearing up to 25 N normal force, i.e., a low-wear condition, passing to a high-wear condition above ~25 N (oil-dependent!). The mixed/boundary friction coefficients of AlSi alloys (subjected to chemical exposure) in the BAM test procedure ($T=170^\circ\text{C}$.; $s=24\text{ km}$; $v=0.3\text{ m/s}$) compared to Al84.4Fe7Cr6Ti2.5Mg0.1 can be inferred from the following table.

Automobile piston ring	Face	Normal force [N]	Face wear coefficient [$10^{-9}\text{ mm}^3/\text{Nm}$]	Engine oil
Nitrided	GG20HCN	50	58	5W-30 Renault
Nitrided	Al84.4Fe7.0Cr6.0Ti2.5Mg0.1	50	200	5W-30 Renault
Nitrided	Al84.4Fe7.0Cr6.0Ti2.5Mg0.1	50	100	PPG32-2
Nitrided	Al84.4Fe7.0Cr6.0Ti2.5Mg0.1	50	80	5W-30 (“PCX”)
Nitrided	AlSi17Cu4Mg	25	7	0W-30
Nitrided	SILITEC (AlSi25)	50	5,000	(“SLX”)
		12.5	1	5W-30
		25	60	(“PCX”)
		50	110	

* Initial-fill oil

** Polypropylene glycol monobutyl ether engine oil formulation by BAM.

industrial fluid lubrication and wear properties used in machinery applications”, June 2000, Seattle, ISBN 0-8031-2867-3, p. 153”. FIG. 14 shows the wear coefficient of rotating specimen of two AlFeXY and various piston rings under mixed/boundary friction in SAE 0W-30 (FUCHS “PCX”) or 5 W-30 (Castrol “SLX”) initial-fill high-lubricity oils ($F_N=50\text{ N}$; $s=24\text{ km}$; $T=170^\circ\text{C}$.). Both AlFeXY alloys used in FIG. 14 were cast under vacuum, without exposing the intermetallic phases by chemical or mechanical treatment (honing). The tribological functional surfaces were lapped to $R_{PK}\sim 0.43\text{ }\mu\text{m}$ on Al88.4Fe8.5V1.3Si1.7Zr0.1 and $R_{PK}\sim 0.37\text{ }\mu\text{m}$ on Al84.4Fe7.0Cr6.0Ti2.5Mg0.1.

[0069] Using more than 200 tests with GGL20HCN high-carbon gray iron on an average, the mean wear coefficient of GGL20HCN in the BAM test procedure was $4.8\times 10^{-8}\text{ mm}^3/\text{Nm}$ at $F_N=50\text{ N}$. The wear resistance of the Al84.4Fe7Cr6Ti2.5Mg0.1 alloy grain-refined with 0.1 wt % Mg against the molybdenum-based MKP81A piston ring was comparable to the wear resistance and load-bearing/carrying capacity of high-carbon gray iron.

[0070] The higher friction coefficients with the SAE 5W-30 initial-fill oil under mixed/boundary friction of the AlFeXY alloys compared to GGL20HCN represent a remarkable feature in the table.

[0071] The relatively high mixed friction coefficients can be reduced by using a polyalkylene glycol (PAG46-4+2.6 Phopani, HTHS=3.6 mPas) or a polypropylene glycol monobutyl ether (PPG32-2+2.6 Phopani; HTHS=2.87 mPas) (see FIG. 15). The metal-free friction-reducing agent included in the SAE 0W-30 (“PCX”) initial-fill oil with a HTHS of 3.0 mPas fails to work with AlFeCrTi. As is clear from FIG. 15, the Al84.4Fe7.0Cr6.0Ti2.5Mg0.1 alloy face side against a nitrided piston, at an identical normal force of $F_N=50$ N, is comparable in its wear coefficient to the high-carbon gray iron ($s=24$ km; $T=170^\circ$ C.) within the boundaries of the precision limits of the test procedure. Particularly in PPG32-2, the overall wear of piston ring and face is comparable to that of GG20HCN.

[0072] Referring to the nitrided piston ring only, FIG. 16 shows that AlFeVSi, but particularly AlFeCrTi, has a wear resistance in FUCHS PCX 0W-30 and Polyglycol PPG32-2+2.6 Phopani oils that is comparable to that of the GGL20HCN high-carbon gray iron ($F_N=50$ N; $s=24$ km; $T=170^\circ$ C.). FIG. 16 also illustrates the wear coefficient in a long-term test (108 km), demonstrating a strong, wear-reducing run-in behavior of the AlFeCrTi alloy.

[0073] Crankshaft slide bearing shells made of “eutectic” AlSi12CuNiMg (Karl Schmidt GmbH, KS 1275 (material number: 3210.9), now Kolbenschmidt AG, with 11-13.5% Si, 0.5-1.3 Cu, 0.8-1.3 Mg, 0.5-1.3 Ni, ~0.25 Zn, ~0.1% Cr, balance Al) were used in the BMW 801 double-row radial aircraft engine (Ing. Buske, Die Abhängigkeit der Lagerbelastbarkeit von der Lagerbauform, Report of the Schmierstoff-Tagung, Part 1: Reibung und Verschleiß, Kälteverhalten, Dec. 11/12, 1941, Berlin Adlershof, pp. 119-148), wherein the crankshaft journal was made of a nitrided steel with HRC 58. Since then, such a material solution has been unusual in the automotive and construction machinery industries. Current faces of slide bearing shells made of AlSn14Cu8, AlSn20, PbSn10Cu3, GZ-CuSn7ZnPb or lead bronzes, as well as friction-reducing lacquer coatings, require anti-corrosion additives for non-ferrous metals in the lubricants, significantly deteriorating the ecotoxicological properties. On the whole, AlSi or AlFeXY alloys are less endangered by corrosion, so that anti-corrosion additives are dispensable or can be used at significantly lower concentrations. Also well-known in the prior art is an Al96(Ni,Mn) alloy (Glyco-172) with a maximum allowable geometrical bearing load of 80 MPa, which is fatigue- and corrosion-resistant, but tends to show adhesive failure in the event of lacking lubrication, which is suppressed by virtue of the AlFeXY metallurgy.

[0074] The tribological load-bearing capacity limit of 100 MPa (geometrical surface load) of the sliding couple AlSi12CuNiMg/nitrided steel in the BMW 801 double-row radial engine at an oil inlet temperature of 99° C. of the fully synthetic lubricant “SS-1600” based on an adipic ester and ethylene oil is remarkable because, having a kinematic viscosity $\eta_{100C}\sim 6.2$ mm²/s, it was significantly “thinner” than current high-lubricity oils having $\eta_{100C}\sim 9-12$ mm²/s.

[0075] Another advantage to an AlFeXY system is that the anti-wear and high-pressure additives in engine and transmission oils—also as a consequence of the metallurgy of the specimen in tribometers—have been adjusted to iron rather than silicon.

[0076] Dissipating the heat from the valve shaft into the cylinder head, valve guides require high thermal diffusivity in association with an appropriate wear resistance. For this reason, valve guides are preferably made of copper base alloys

such as CuZn36Mn3Al2SiPb (\cong CuZn40Al2 according to DIN 17660 or CW713R) with $\lambda_{RT}\sim 63$ W/mK or $K^{RT}\sim 19.7$ mm²/s. Temperatures of 500° C. are not unusual on the surfaces of the lower part of the outlet valve guide. The aluminum alloys according to the invention offer a thermal diffusivity increased by 3-4 times, in association with the required temperature resistance and without melting equilibria up to $>600^\circ$ C.

[0077] Aluminum piston materials consist of eutectic AlSi2CuXX alloys or hypereutectic AlSi18CuXX alloys, likewise with up to 0.85 wt % iron. The thermal diffusivities range between 55 mm²/s $< K^{RT} < 61.7$ mm²/s.

1. A method for producing a wear-resistant aluminum alloy, comprising the steps of:

(i) providing an aluminum alloy having the composition

Fe: 3-10;

X: 3-10;

Y: 0-1.5;

Z: 0-10;

wherein

X represents an element or combination of elements

(a) V and Si;

(b) Cr and Ti;

(c) Ce; or

(d) Mn;

each time with the proviso that the proportion of the individual elements in the combinations of elements (a) and (b) is at least 0.5 wt %;

Y represents one or more grain-refining elements selected from the group of B, Ce, Sr, Sc, Mg, Nb, Mn and Zr, unless already present as X;

Z represents one or more additives increasing the heat resistance, selected from the group of ceramic fibers, particles and platelets;

the figures referring to % by weight in the alloy, and Al and production-related impurities representing the remaining proportion in the alloy to make 100 wt %, with the proviso that the proportion of Al in the alloy is at least 80 wt %;

(ii) melting the aluminum alloy, dissolving and homogenizing the alloy elements at temperatures of from 650° C. to $1,000^\circ$ C.; and

(iii) casting the melt into a casting mold at a casting temperature ranging from the melting temperature of the alloy up to a temperature 150° C. above the melting temperature.

2. The method according to claim 1, wherein the casting temperature in step (iii) is in the range of 1° C. to 80° C. above the melting temperature of the alloy.

3. The method according to claim 2, wherein the casting temperature in step (iii) is in the range of 10° C. to 50° C. above the melting temperature of the alloy.

4. The method according to claim 1, wherein the temperature of the casting mold ranges from 450° C. to 600° C.

5. The method according to claim 1, wherein the alloy includes 4-8 wt % of Fe.

6. The method according to claim 1, wherein the alloy includes 3-5 wt % of X.

7. The method according to claim 1, wherein the alloy includes 0.5-0.8 wt % of Y.

8. The method according to claim 1, wherein X represents the combination of elements (a) and the share of Si is smaller than or equal to 2 wt %.

9. The method according to claim **1**, wherein X represents the combination of elements (a) and the share of Si is smaller than or equal to 1 wt %.

10. The method according to claim **1**, wherein the steps (ii) and (iii) form part of a metallurgic melt casting process selected from the group of sand casting, pressure casting, continuous casting, thin-strip casting, centrifugal casting and cold crucible process.

11. An aluminum alloy, produced or obtainable according to the method of claim **1**.

12. Use of the aluminum alloy according to claim **11** in the production of sliding elements in crankshaft bearing shells, cylinder faces, piston rings, pistons, valve guides, bearing bushes or bearing shells.

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