Description of a pin-pulling process with aid of dimensional analysis

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samenvatting

Summary

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1. The thermal behaviour of an electrically heated piece of wire clamped on both ends.
2. The construction occurring when the wire is overstretched, and many interrelated effects such as change in dimension because of plastic flow, change in heat intensity resulting in different temperature-time relations at different places.

Direct mathematical analysis is very difficult; therefore an empirical approach is used, whereby the test results are processed for practical application by means of dimensional analysis. The following process-description shows a way to determine the required current, warming-up time and tensile force for different materials.

Though the experiments have been performed in the sphere of the factory practice and thus could not get that kind of attention that is usual for laboratory tests, the question if it is possible to describe this process with aid of dimensional analysis seems answered to us quite well in the affirmative.

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DESCRIPTION OF A PIN-PULLING PROCESS
WITH AID OF DIMENSIONAL ANALYSIS

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Materialien.

Obgleich die Versuche unter Betriebsverhältnissen durchgeführt wurden, und daher keine labormässige Aufmerksamkeit in Anspruch nehmen konnten, haben die Aussichten auf eine dimensions-analytische Beschreibung dieses Prozesses sich unseres Erachtens verhältnismässig gut bestätigt.

Sommaire

Le procédé de "pin-pulling" se compose de deux processus principals:

1. la conduite thermique d'une piece de fil chauffée electriquement et fixée par serrage à deux côtés.
2. la contraction se présentant en cas que le fil sera surtendu et beaucoup d'effets se tenant se produisent, comme modification de dimension en conséquence de fluidité plastique, modification d'intensité de chaleur, concentrant en temperature-temps relations différentes à places differentes.

L'application de l'analyse mathématique directe est difficile; pour cette raison une méthode empirique est choisie pour les résultats d'essai applicables pratiquement, et bien l'analyse dimensionelle.

Le procédé concernant fait voir une voie de fixer le courant requis, le temps de chauffage et la force de tension pour des materiaux différents.

Bien que les expériences sont faites au millieu de l'organisation d'atelier, impliquant que cela n'appelle pas l'attention désirée pour les résultats, la question de la possibilité de résoudre ce procédé à l'aide de l'analyse dimensionelle doit être répondu affirmativement.

Summary

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2. The construction occurring when the wire is overstretched, and many interrelated effects such as change in dimension because of plastic flow, change in heat intensity resulting in different temperature-time relations at different places.

Direct mathematical analysis is very difficult; therefore an empirical approach is used, whereby the testresults are processed for practical application by means of dimensional analysis. The following process-description shows a way to determine the required current, warming -up time and tensile force for different materials.
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Zusammenfassung

Der gesamte Stift-Ziehproces setzt sich zusammen aus zwei wichtigen Teilvorgängen,

1. dem thermodynamischen Verhalten eines elektrisch geheizten Drahtstückes, dass mit beiden Seiten eingeklemmt ist.
2. der eintretenden Einschnürung bei stossartiger Überbelastung des Drahtes und mehreren damit zusammenhangenden Effekten, wie z.B. plastische Massänderung und örtliche Unterschiede in der Heizwirkung, woraus sich von Ort zu Ort ungleiche Temperatur-Zeitbeziehungen ergeben.

Eine unmittelbare mathematische Analyse ist mit grossen Schwierigkeiten verbunden; daher wurde versuchsmässig an die Aufgabe herangetreten. Die Versuchsergebnisse wurden mittels Dimensionsanalyse für praktische Verwendung zugänglich gemacht. Die Prozessbeschreibung zeigt eine Möglichkeit zur Bestimmung des erforderlichen Stromes, der Erwärmungsdauer und der benötigten Zugbelastung für verschiedene

Introduction

In the electronic component industry pins are widely used as parts for radio tubes and transistors. The pins vary in diameter from 0.2 to 2.0 mm and in length from 8 to 72 mm. If they are to be handled by vibratory hoppers and inserting equipment, the pins must meet the following requirements:

- The pin must have pointed ends and a sufficiently smooth point surface.
- Length variation of the pin must be limited (normal tolerance $\pm$ 0.2 mm).

Drawing of a pin is shown in fig. 1.

These pins can be manufactured by various methods such as cutting, rolling and pulling. Of these three methods the last will be dealt with more in detail. The machine used for pulling apart the wire, works on the following principle: A length of wire is clamped between two chucks that can be moved in relation to each other. A current is passed via the chucks through the wire as a result of which its temperature will increase. The heated wire is stretched and separated by moving the chucks apart.
Two different processes are involved, viz.

a. The thermal behaviour of an electrically heated piece of wire clamped on both ends.
b. The constriction occurring when the wire is overstretched.

The two processes are interrelated by a number of effects such as change in dimension because of plastic flow, change in heat intensity resulting in different temperature-time relations at different places.

For different products the material and pin dimensions are given within certain limits.

The practical problem was to find

1. the optimal conditions for the process
2. a practical way to bring the machine setting as close as possible to these conditions.

First the stretching process will be studied; the results will then be worked out to dimensionless numbers. With help of these numbers the setting of the machine in practical cases can be done more systematically.

The method chosen to solve the problem

As was already outlined above, the total process consists of many interrelated effects. Direct mathematical analysis is very difficult; therefore an empirical approach is used, whereby the testresults are processed for practical application by means of dimensional analysis.
Readers are referred concerning this method to lit. 1, 2.
The use of dimensional analysis for a practical problem depends on the hypothesis that its solution can be expressed in terms of certain variables by means of a homogeneous (dimensional) equation. This hypothesis is based on the trivial fact that physical equations are homogeneous in dimension and that relations can be deduced from these equations and must therefore be homogeneous in dimension too.
However, if an equation is homogeneous in dimension, it can be reduced to a relation between a complete set of dimensionless products (Buckingham theorem). It is obviously necessary that an adequate physical model is used in which all important relevant factors are taken into consideration.

The physical model

Constriction of the wire begins once the stress has exceeded a certain critical value. This stress is temperature dependent and, generally speaking, it may be said that the required critical stress decreases with increasing temperature. As the temperature reaches a maximum in the plane of symmetry, the critical value will be exceeded first in this plane. The physical quantities determining the temperature at a certain place are:

a. the power supplied P
b. the dissipated heat Q
c. the heat capacity C

all related to the material element under consideration

If we now consider the total length of wire between clamping points and simplify the situation by using average values of temperature etc., then the power supplied

$$\left(P_{tot} = I^2 R = \frac{I^2 \rho \cdot l}{\pi/4\ d^2}\right) \text{ will depend on}$$

1. ρI^2
2. l
3. d

with ρ = electrical resistivity
I = current
l = distance between the chucks
d = wire diameter

For the purpose of finding dimensional quantities this simplification may be justified. The wire temperature is considered to be only variable with x and the time t.

The dissipated heat for an element in the middle of the wire $\left(Q = \lambda . A . \frac{dT}{dx} . t\right)$ will depend on

1. λ with λ = heat conductivity
2. T — T = temperature of the middle of the wire
3. t — t = warming-up time
4. l — l = distance between the chucks
5. d — d = wire diameter

The constriction is determined by
1. the deformation energy / unit volume E
2. the tensile strength at T°C σ_T

$$E = \frac{F}{A} . \varepsilon$$

The deformation energy depends on:

1. F with F = applied force
2. A — A = surface of a plane, perpendicular on the wire
3. ε — ε = strain

In considering these simplified equations, we supposed to have the following variables to be of importance for our dimensional analysis.

1. I^2 in Watt.m — $M.L^{-3}.T^{-3}$

   It is permissible to combine I with ρ, because they are the only variables containing the electrical basic units of charge for current.

2. E = deformation energy / unit volume in Nm/m^3 — $M.L^{-1}.T^{-2}$
3. C = heat capacity / unit volume in $Nm/m^3\,°C$ — $M.L^{-1}.T^{-2}.\theta^{-1}$
4. λ = heat conductivity in Nm/msec°C — $M.L.T^{-3}.\theta^{-1}$
5. d = wire diameter in m — L
6. l = distance between the chucks in m — L
7. T = temperature of the middle of the wire — θ
8. t = warming-up time in sec. — T
9. σ_T = tensile strength of the wire at T°C — $M.L^{-1}.T^{-2}$

Table 1. Dimensional matrix of the variables

	E	ρI^2	t	T	d	C	λ	l	σ_T
mass	1	1	0	0	0	1	1	0	1
length	-1	3	0	0	1	-1	1	1	-1
time	-2	-3	1	0	0	-2	-3	0	-2
temperature	0	0	0	1	0	-1	-1	0	0

From these variables the following complete set of dimensionless products can be formed.

$$V_1 = \frac{\lambda . t}{C l^2}$$

$$V_2 = \frac{\lambda . T l^2}{\rho I^2}$$

$$V_3 = \frac{l}{d}$$

$$V_4 = \frac{F}{A\,\sigma_T}$$

$$V_5 = \frac{\rho I^2 t}{F l^2}$$

The following physical significance can now be given to the dimensionless numbers.

V_1 = dissipated heat / heat capacity

V_2 = dissipated heat / generated heat

V_3 = geometrical proportion

V_4 = force applied / force required

V_5 = energy supplied / mechanical energy

In order to determine the relations between these numbers, it will be necessary to measure some variables by tests on the production machines.
From the literature (see lit. 3 and lit. 4) we derive the following as a function of temperature.

1. the specific electrical resistivity
2. the specific heat
3. the heat conductivity
4. the tensile strength at temperature T

The other variables are measured at the machine. The following five materials are at our disposal.

1. Nickel
2. Nickel-Iron 50/50
3. Nickel plated Iron
4. Copper + 2 % Ag
5. Molybdenum

All with a diameter of 1 mm.

Tabel 2. Results of measurement

	Nickel	Nickel-Iron 50/50	Nickel-Plated Fe	Copper + 2 % Ag	Molybdenum
I av. Amp.	396	240	297	1131	707
F N	80	70	70	75	110
T °C	572	607	465	310	705
t sec.	0.08	0.08	0.08	0.04	0.04
$C.10^6$ $Nm/m^3\,°C$	4.63	4.58	5.02	3.74	2.78
λ $Nm/msec°C$	50.2	21.4	42	369	113
$\rho.10^8$ m	36.5	11.5	53	88	23.3
$\sigma_T.10^6$ N/m^2	250	350	250	88	240
1.10^3 m	2	1.94	1.94	2.0	2.24

Dimensionless numbers that are useful in practice

The dimensionless numbers V_1 to V_5 incl. are calculated for the five materials mentioned above and are shown in the table below.

Table 3. Values of the dimensionless numbers

	V_1	V_2	V_3	V_4	V_5
Ni	0.218	2,00	0.463	0.40	14.3
NiFe	0.1	0.732	0.515	0.246	19
Fe	0.178	1.58	0.515	0.356	14.1
Cu	0.986	12.2	0.5	1.08	5.0
Mo	0.325	3.42	0.446	0.53	8.4

Represented on log-log paper the relations between

V_4 and V_5 fig. 3

V_2 and V_5 fig. 4

V_1 and V_2 fig. 5 are linear.

Simple graphical means deliver the following relations.

$$V_4 = 5.4\ V_5^{-1}$$

$$V_2 = 271\ V_5^{-2}$$

$$V_1 = 0,13\ V_2^{0,8}$$

Substitution in the equations leads to the following expressions.

$$\frac{F}{A\sigma_T} = 5.4\left(\frac{\rho I^2 t}{F l^2}\right)^{-1}$$

$$\frac{\lambda T l^2}{I^2} = 271\left(\frac{\rho I^2 t}{F l^2}\right)^{-2}$$

$$\frac{\lambda t}{C l^2} = 0.13\left(\frac{\lambda T l^2}{\rho I^2}\right)^{0,8}$$

The varables occurring in the above relations are:

1. $\lambda = \lambda(T)$ o
2. $C = C(T)$ o
3. $\rho = \rho(T)$ o
4. σ_T o
5. T o
6. l *
7. d *
8. $A = \pi/4\ d^2$ *
9. F
10. t
11. I

As a practical example of the use of experimental data the following may serve.
The starting point is wire of a certain diameter. What values must the current, the warming-up time, the tensile force and the distance between the chucks have to obtain the desired shape of the pointed ends? If we proceed from wire with a given diameter, as in our case, the magnitudes marked with * are given. If we, moreover, assume that the temperature as measured is the only one at which the process can properly take place, the temperature i.e. the magnitudes marked with o are also determined.
However, we still have three equations and three unknown variables, so we can calculate F, t and I as a function of the diameter.

We find: $l = l(d)$ from fig. 6
$F = F(d)$ " fig. 7
$t = t(d)$ " fig. 8

The results of the above data with $\frac{d}{l} \approx 0{,}5$ are given below.

Table 4. F, t and I as a function of the diameter

	I in Amp.	t in sec.	F in N	d in mm
Ni	428 d	$7.41\ 10^{-2}$ d	98 d^2	
NiFe	243 d	$7.93\ 10^{-2}$ d	77 d^2	
Fe	322 d	$7.25\ 10^{-2}$ d	23.3 d^2	
Cu	1110 d	$3.52\ 10^{-2}$ d	141 d^2	
Mo	747 d	$3.91\ 10^{-2}$ d	108 d^2	

Discussion of the results

From this limited amount of measuring points, it cannot be expected that more accurate proportions can be determined between the dimensionless numbers.
The graphical working out for that purpose has to be limited to the primary stage.
Moreover, the values for σ_t in the various text books vary rather considerably.
Nevertheless in practice these numbers give some improvement over the trial and error method applied up till now.

Conclusion

The foregoing dimensional analysis has shown a way to determine the required current, warming-up time and tensile force of different materials. In order to decrease the inaccuracy in the data available up till now, more experimental work of the type described has to be performed to come to sufficient accurate results.
In this further set of investigations it will be necessary not only to increase the number of materials, but also to vary the diameter.
It may turn out that with those materials a useful shape of the pointed ends can also be obtained at temperatures other than those at which the experiments were done.
However, this could not be verified from testresults taken from the available production machine, which was not at all intended for fundamental experiments.
Further tests on machines built specifically for experiments, may be useful for this purpose.

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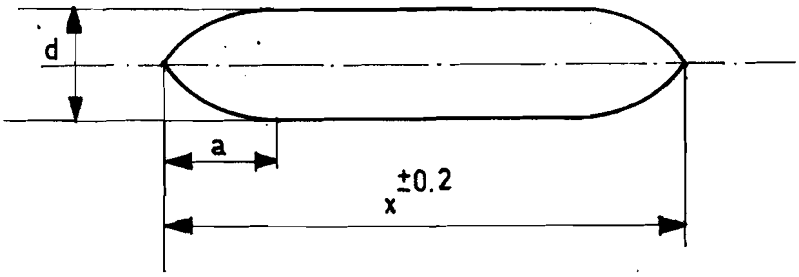

Fig.1 Product drawing.

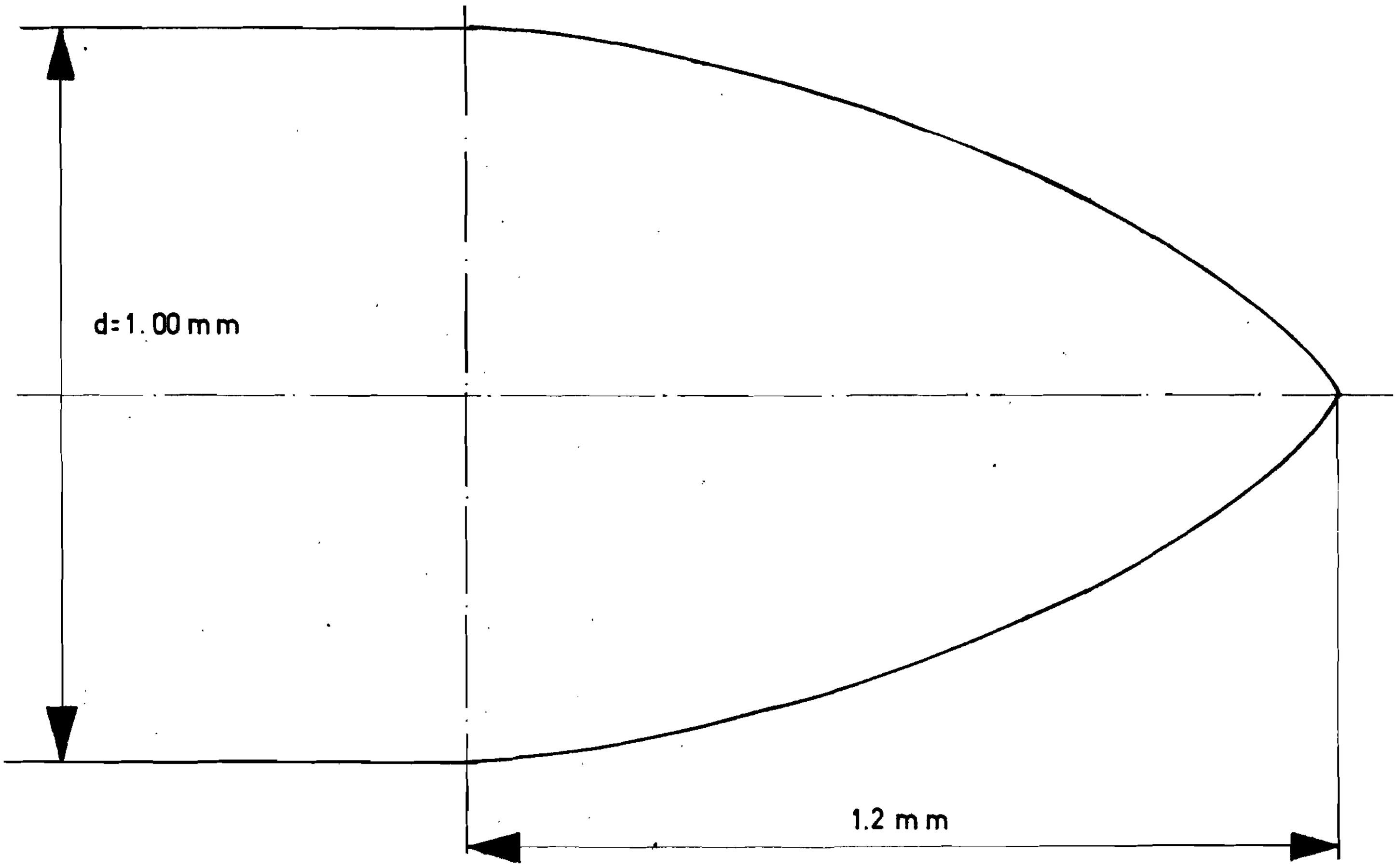

Fig.2 Empirically determined ideal shape of the pointed ends.

Fig 3. The relation between the dimensionless numbers V_4 and V_5.

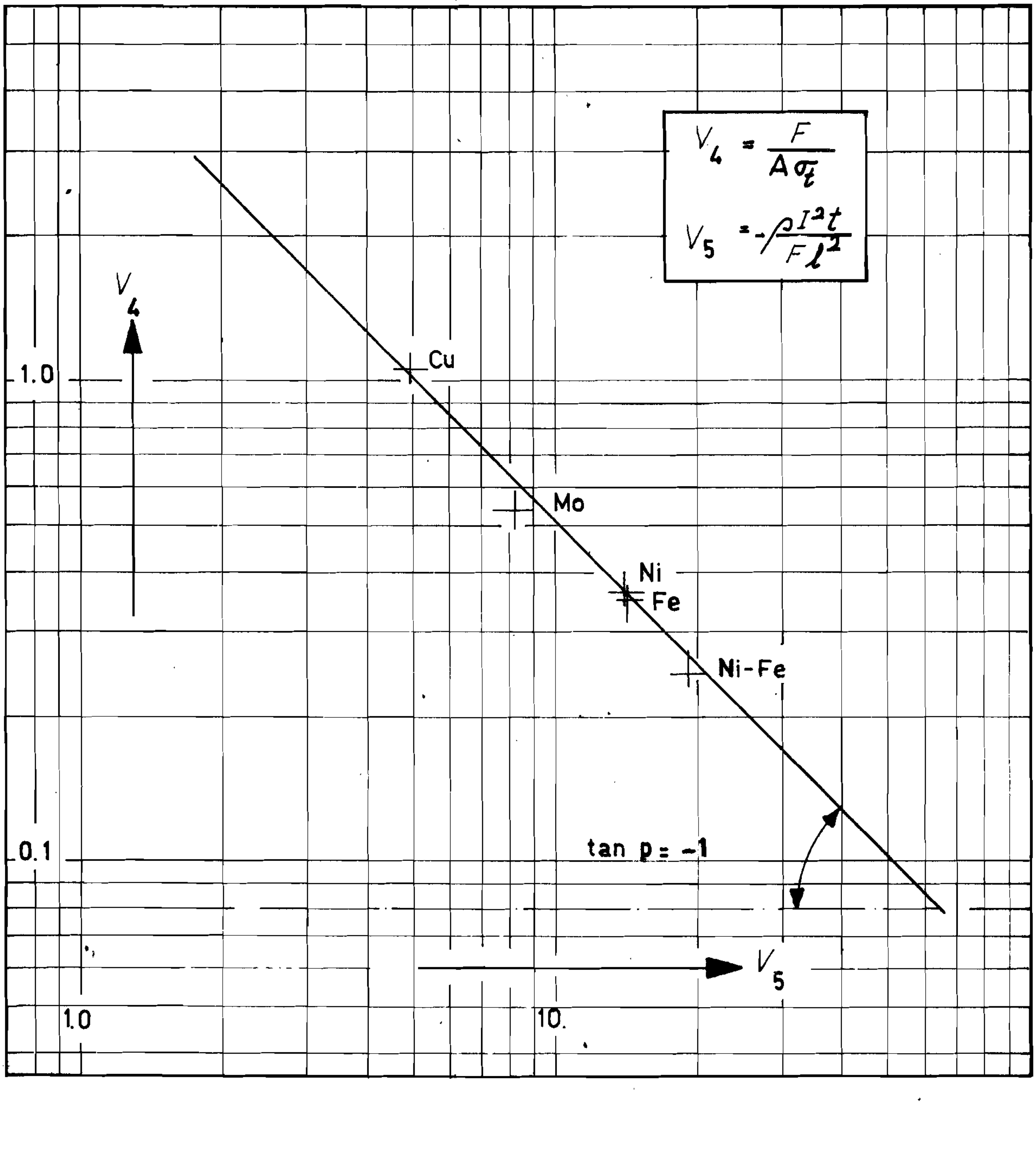

Fig 4. The relation between the dimensionless numbers V_2 and V_5.

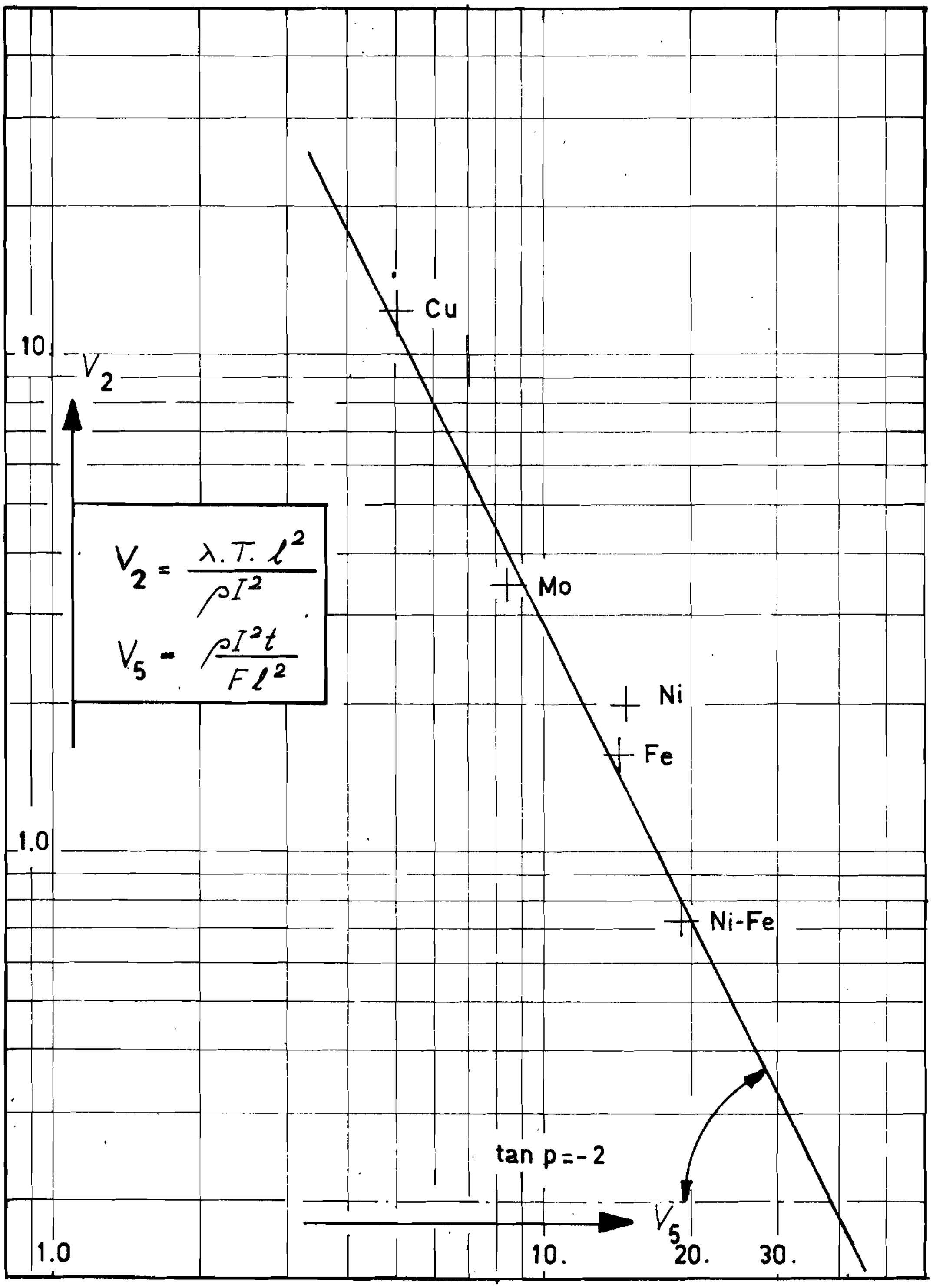

Fig. 5 The relation between the dimensionless numbers V_1 and V_2.

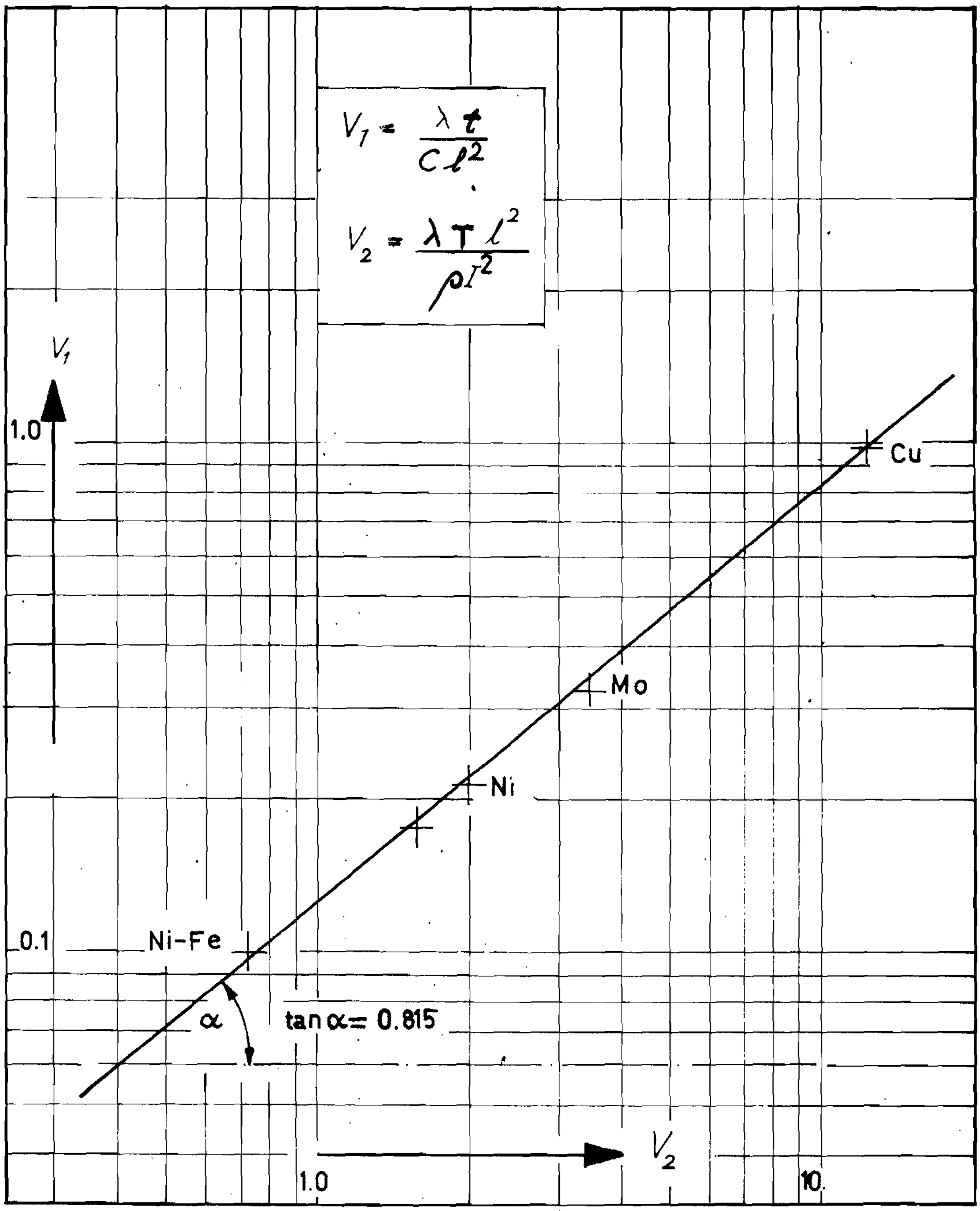

Fig. 6 The relation between the current I and the diameter d .

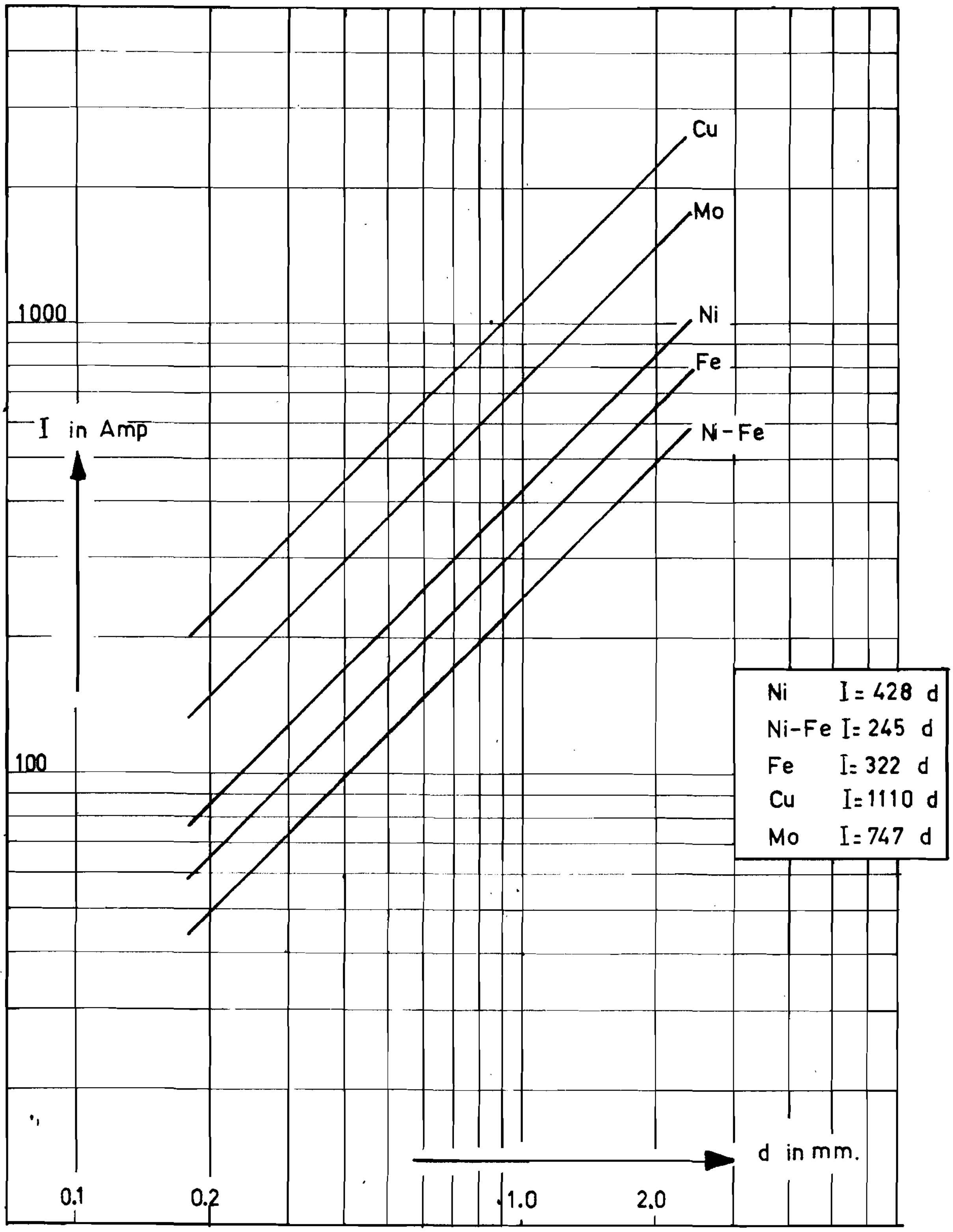

Fig 7 The relation between the tensile forse F and the diameter d.

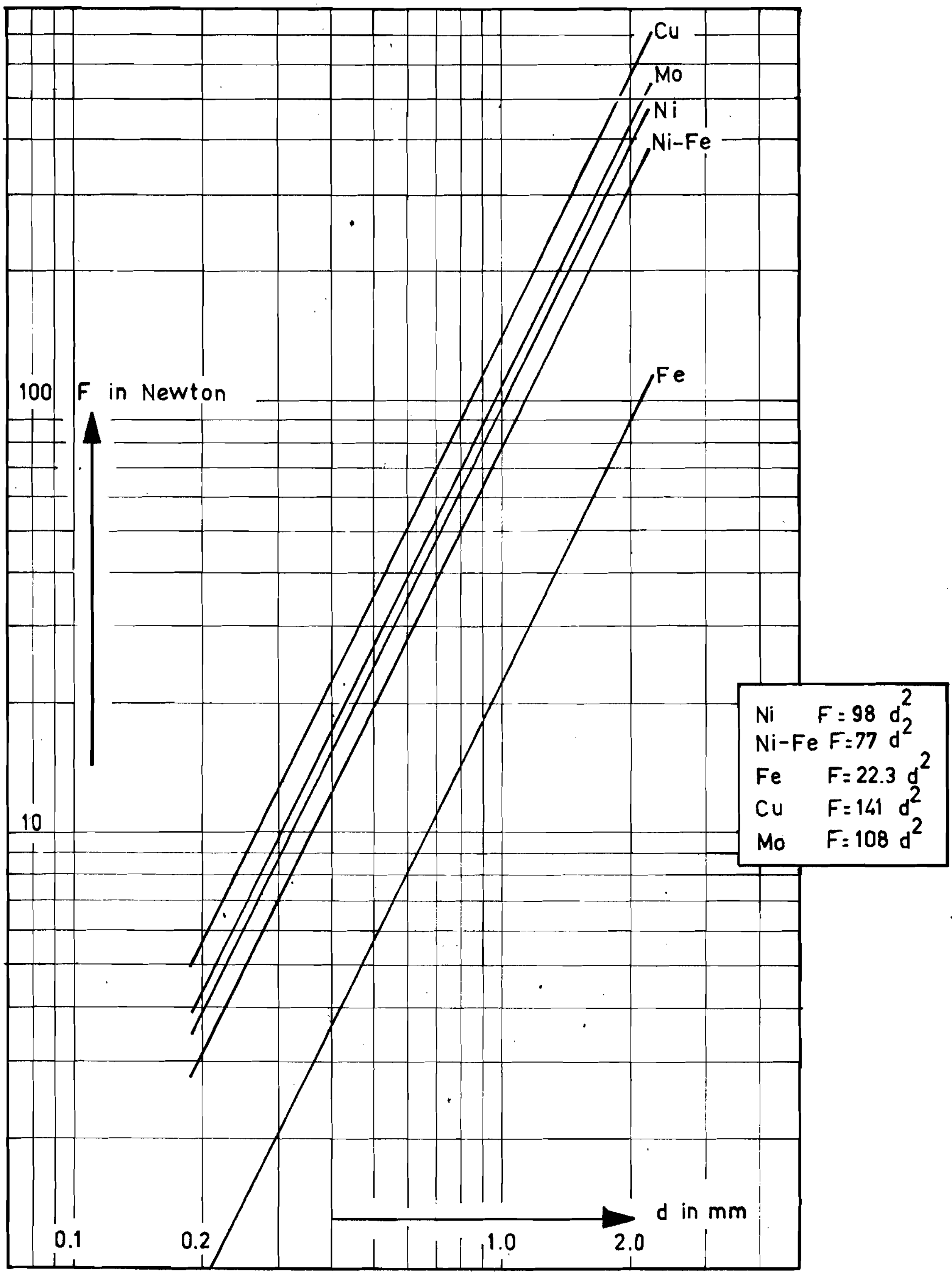

Fig. 8. The relation between the warming-up time t and the diameter d.