

Cutting tool temperature : an analysis of experimental results

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CUTTING TOOL TEMPERATURE
AN ANALYSIS OF EXPERIMENTAL RESULTS

by

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Symbols and Units.

v	cutting speed	m/s
t	feed, chip thickness	m/rev.
d	depth of cut, chip width	m
l_c	chip contact length	m
F_v	cutting force	N
P_v	thrust force	N
τ_s	average shear stress	N/m ²
Φ	shear angle	deg.
β	friction angle	deg.
γ	rake angle	deg.
μ	coefficient of friction	-
λ	chip ratio	-
$\tan \gamma_s$	shear strain	-
Θ_m	temperature as measured	°C
Θ_t	theoretical value of temperature	°C
k	conductivity of heat	W/m.°C
ρc	volumetric specific heat	J/m ³ .°C
K	diffusivity of heat	m ² /s
\bar{A}	aspect ratio	-
U_f	specific frictional energie	W/m ³
A, B, X, Y	thermal-dynamometric functions	
f_1, f_2	correction factors	

Summary.

This report deals with the measurement of cutting-tool temperature using the Gottwein-Herbert method modified for the application of carbide throw-away tips. It is shown that when performing thermometry in connexion with a dynamometric program of investigation, in order to obtain information about the behaviour of dynamometric quantities in dependence on cutting conditions, the experimental temperature data differ in a systematic way with those predicted when applying Loewen and Shaw's (1) analysis.

As a matter of fact in the present analysis all dynamometric quantities have been related to the friction-angle instead of the shear-angle by introducing a shear-angle relationship as derived earlier (2), thus avoiding the uncertain indirect measurement of the shear-angle from chip geometry.

Zusammenfassung.

Diese Veröffentlichung enthält Ergebnisse einer Forschungsarbeit auf dem Gebiete der Schnitttemperaturmessung beim Drehen.

Das direkte thermo-elektrische Kontaktverfahren nach Gottwein wurde, im Hinblick auf die Verwendung von Hartmetallwendeplättchen, weiter entwickelt.

Falls die Thermometrie im Zusammenspiel mit der Dynamometrie durchgeführt wird, so geht daraus die Abhängigkeit der Zerspanungsfunktionen von den gewählten Zerspanungskenngrößen hervor. Es wird gezeigt, dass die gemessenen Temperaturdaten systematisch abweichen von den Daten die mit Hilfe des Rechenverfahrens nach Loewen und Shaw (1) ermittelt werden können.

Tatsächlich sind in der vorliegende Arbeit alle dynamometrische Größen, wie schon früher veröffentlicht (2), mittels einer Scherwinkelgleichung bezogen auf den Reibungswinkel statt des Scherwinkels, wodurch die fragliche Messung des Spanstauches umgangen wurde. Die ganze Rechenarbeit bezieht sich dann unmittelbar auf die reine Kraftmessung.

Sommaire.

Ce rapport présente les résultats de la mesure de la température d'outil à couper par la méthode Gottwein-Herbert, modifiée pour l'application des mises à jeter. Il est montré qu'en cas de connexion entre la thermométrie et la dynamométrie dans le but d'obtenir des renseignements concernant le procédé des fonctions dynamométriques s'étant rattachées aux conditions de coupe, les données de la température expérimentale diffèrent par manière strictement systématique aux celles-ci en cas de mettre en usage les analyses Loewen et Shaw. (1)

En effet toutes les fonctions dynamométriques en cette analyse se rapportent à l'angle de frottement au lieu d'à l'angle de cisaillement au moyen d'introduire une résolution de l'angle de cisaillement comme conclue autrefois (2), ainsi évitant la mesure indirecte incertaine de l'angle de cisaillement de la géométrie de copeau.

Introduction.

In a program of research concerning the wear of cutting-tools considerable attention is paid to the problem of the measurement of tool temperature.

As elsewhere (3) has been chosen in favour of radiation techniques, the present authors continued the development of the thermo-electric contact method (4) by adapting it to the use of throw-away bits. To this purpose special tool holders have been constructed.

It appears that the temperature data obtained get a significant interpretation when connected with the results of dynamometric investigation.

For this reason a sensitive two-components dynamometer has been built *) as an improvement of the instrument as described by ten Horn and Schürmann (5).

So far only single point tools have been used.

Investigated is the combination of an annealed steel C45 as workpiece material and a carbide grade ISO-P20, type Coromant Sandvik 194.4-1623.

Troughout the experimental program a tool geometry (0-6-5-5-30-0-1.2) has been maintained and a depth of cut of 3 mm.

*) sensitivity : $22 \cdot 10^{-3}$ microstrain/N
mutual interaction of components : less than 1%
deviation of linearity and hysteresis : neglectable
natural frequency : 1,600 c/s
maximum load : $15 \cdot 10^3$ N

The measurement of temperature.

Both the experimental procedure of temperature measurement and the calibration of the thermo-electric characteristic of the tool material in combination with the workpiece material have been described earlier. (6, 7)

Fig. 1 shows the principle of the operation of the thermo-electric tool. It is obvious that the thermo-electric system generates an electric voltage as soon as a temperature difference exists between the spots "A" and "B", where the carbide contacts the same material C45. Here "A" represents the cutting contact region while in "B" the carbide tip contacts a stiff spring machined out of the workpiece material and mounted in the toolholder.

In the tip of the spring and hence in the very place of contact a thermo couple with a well-known characteristic has been clamped.

Thus at any moment the temperature in "B" is known and starting from this it is possible to determine the temperature in "A", as shown in fig. 2.

Once the thermo-electric calibration curve known the reading of the potentiometer recorder A can be reduced to terms of temperature difference. Adding of the temperature-reduced reading of both the recorders gives the temperature to be measured.

During cutting the temperature in "B" increases and the temperature difference between "A" and "B" decreases, but at any moment the sum of the values as recorded must correspond with the temperature of the cutting edge.

Thus a series of synchronous cross-sections through the recordings delivers a number of independant measurements of the tool temperature.

The average statistical error in a single measurement, including the readjustment of the cutting conditions and the use of different tool-bits in repeated cuts, proves to amount $\pm 2\%$.

The absolute accuracy of the measurement of course depends on the reliability of the calibration curve used.

However when choosing "B" as close as possible to "A" in order to minimize the temperature difference between "A" and "B" the importance of achieving extreme accuracy of calibration grows less, though still staying important.

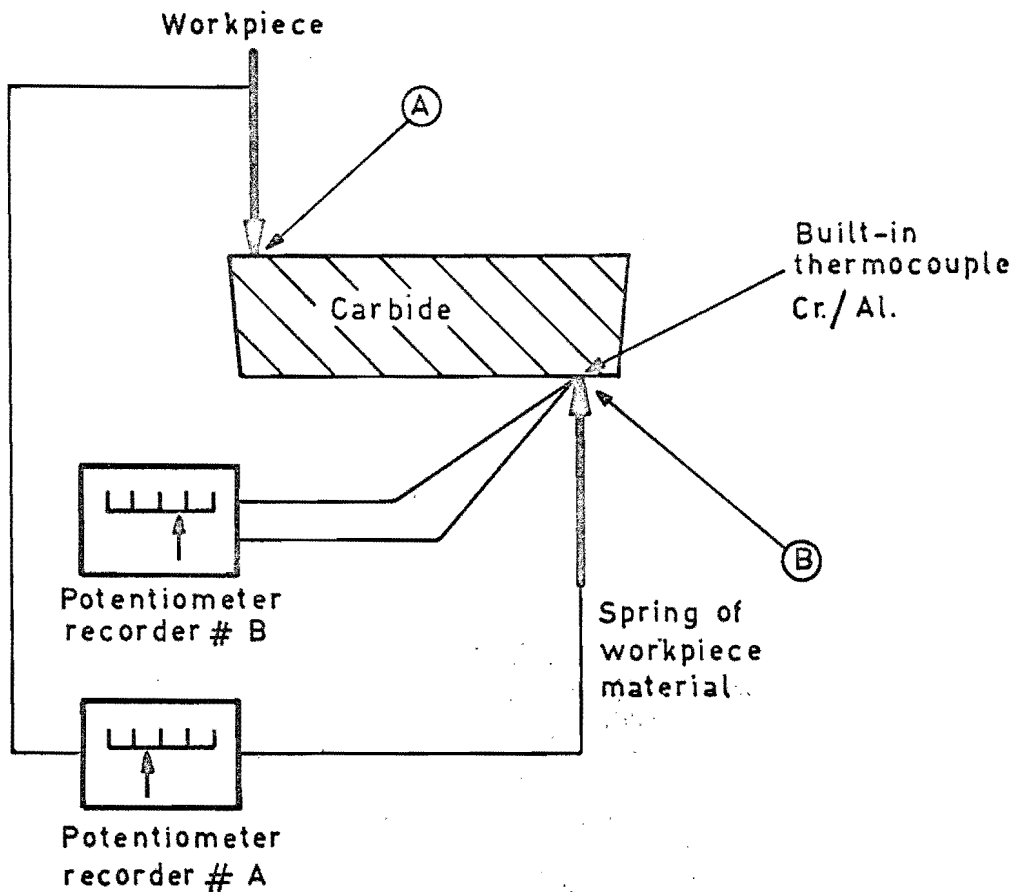


fig. 1 Principle of temperature measurement.

The carbide tip is contacted in "A" by the workpiece (chip and machined surface). In "B", it is contacted by a spring built-in in the toolholder and manufactured out of the workpiece material.

The thermocouple (A-B) is active as soon as a temperature difference exists between "A" and "B" and its e. m. f. is measured by the recorder A.

In "B" a thermocouple with a known characteristic is mounted in the tip of the spring, which allows for the measurement of the temperature in "B" by means of the recorder B.

The temperature in "A" is found by adding the reduced reading of A to the temperature indicated by B.

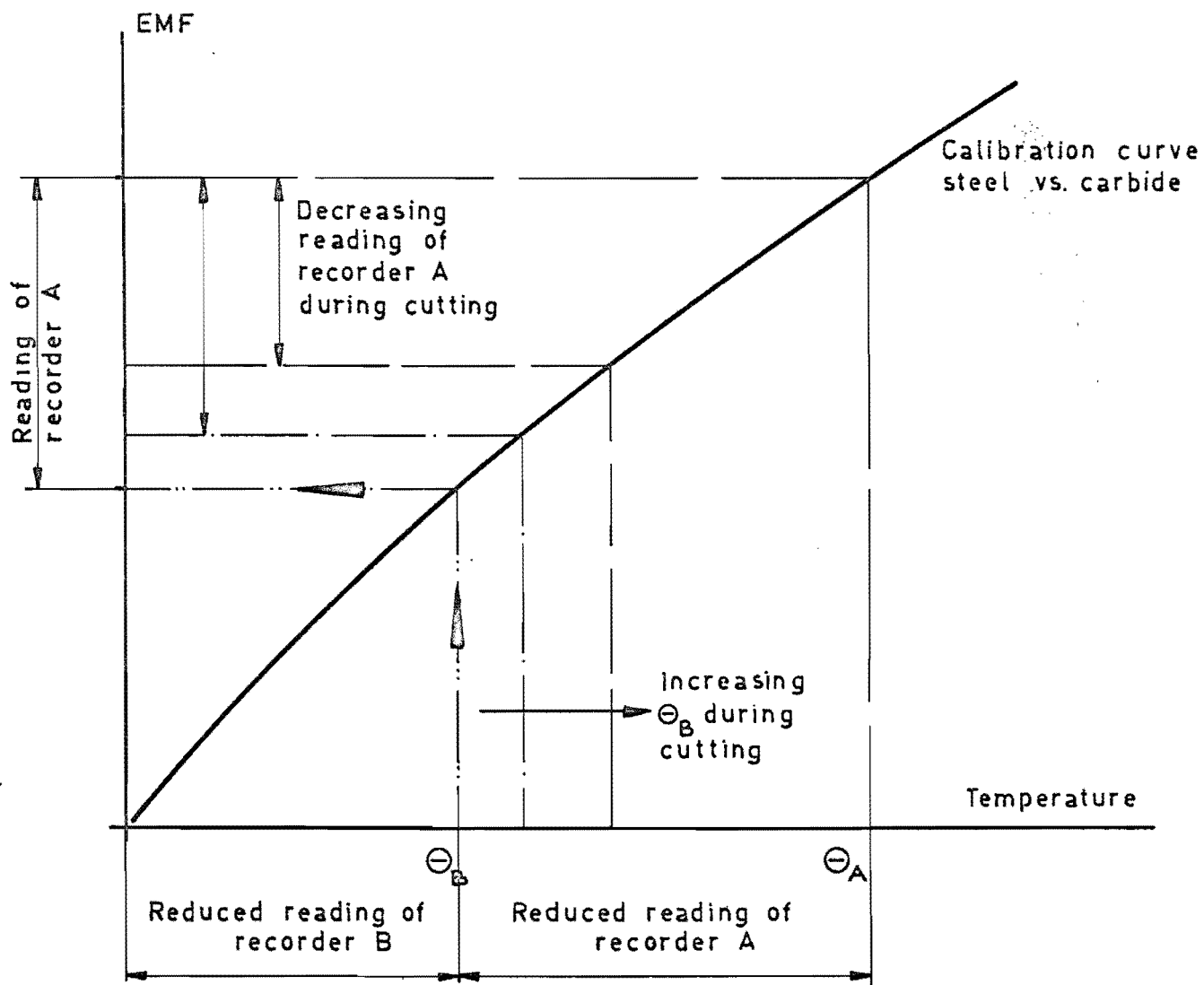


fig. 2 The reading of recorder A is reduced to a temperature difference when using the thermo-electric characteristic of the tool-workpiece combination investigated. Adding of the reduced readings of the recorders gives the cutting temperature Θ_A . During cutting Θ_B increases by through-heating of the carbide tip. In the meantime the reading of recorder A decreases. The sum of the reduced readings proves to be constant.

Analysis of experimental results.

The final result of Loewen and Shaw's analysis (1) is:

$$\overline{\Delta \Theta} = \tau_s \left[A \mu \left(\frac{t \sec \gamma}{l_c} \right)^{\frac{1}{2}} + B \right] \left[\frac{vt \tan \gamma_s}{(k \rho c)} \right]^{\frac{1}{2}} \quad \text{----- 1)}$$

where :

$$A = \frac{0.754}{X} \quad \text{----- 2)}$$

$$B = \frac{1}{X.Y}$$

and :

$$X = 1 + \frac{0.754}{A} \frac{k^1}{k} \left[\frac{K \cdot \lambda}{l_c v} \right]^{\frac{1}{2}} \quad \text{----- 3)}$$

$$Y = \left[\frac{vt}{K_o \tan \gamma_s} \right]^{\frac{1}{2}} + 1.328$$

The relation 1) suggests a square root relationship between temperature rise on the one hand and cutting speed and feed on the other.

This however is only seeming because of the fact that implicate relations exist between the dynamometric quantities τ_s , μ , $\tan \gamma_s$, l_c , λ and cutting conditions.

These effects results in a far less sensitive dependence of temperature with respect to cutting conditions, as is expressed by the approximate logarithmically linearized experimental relation:

$$\overline{\Delta \Theta} \approx 800 \cdot v^{0.3} \cdot \left[t \cdot 10^3 \right]^{0.1} \quad \text{----- 4)}$$

as derived from the experimental data shown in the figs. 3 and 4.

All the calculations connected with the solution of eq. 1 have been performed in a computer program according the next schedule:

- the coefficient of friction is determined by measurement of the main cutting force F_v and the thrust force P_v , from which with $\gamma = 6^\circ$ follows:

$$\tan (\beta - 6) = \frac{P_v}{F_v}$$

and : $\mu = \tan \beta$

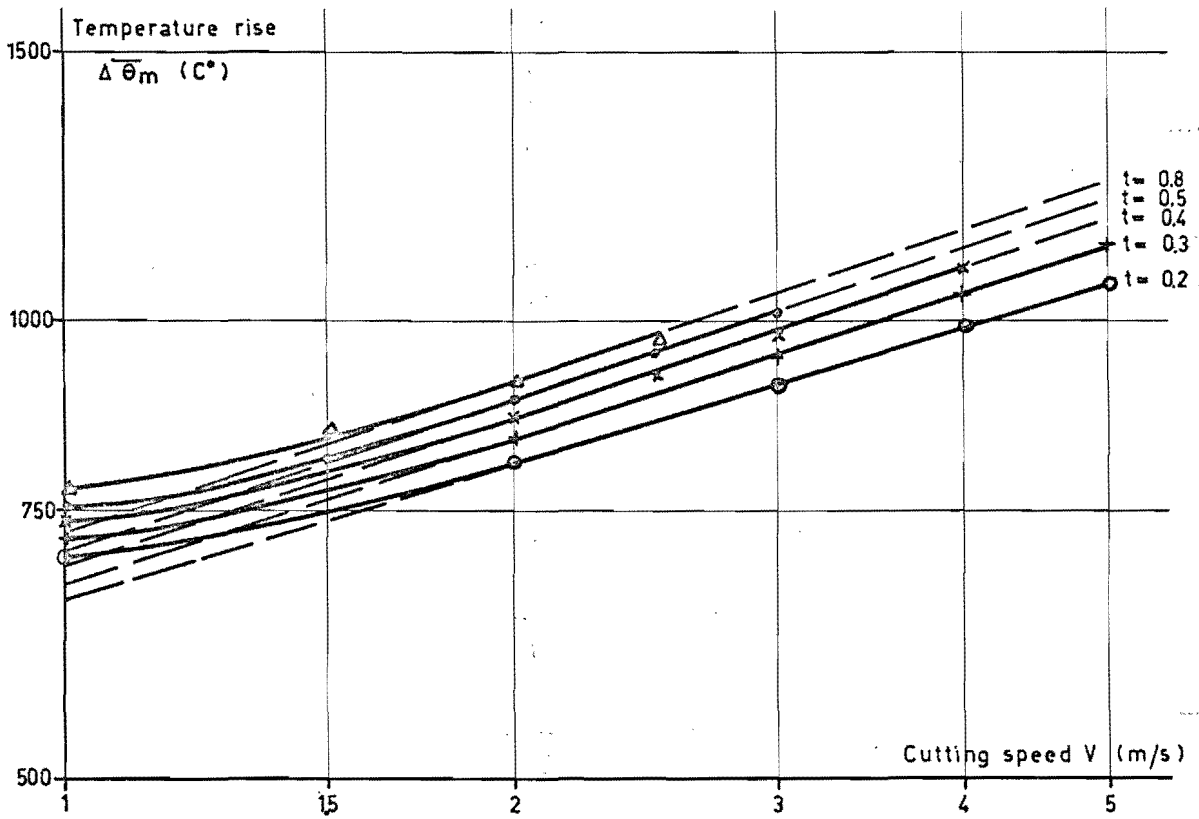


fig. 3 The experimental relation between cutting temperature and cutting speed with the feed as a parameter.
Approximately holds:

$$\Delta \bar{\Theta}_m \approx 800 v^{0.3} [t \cdot 10^3]^{0.1}$$

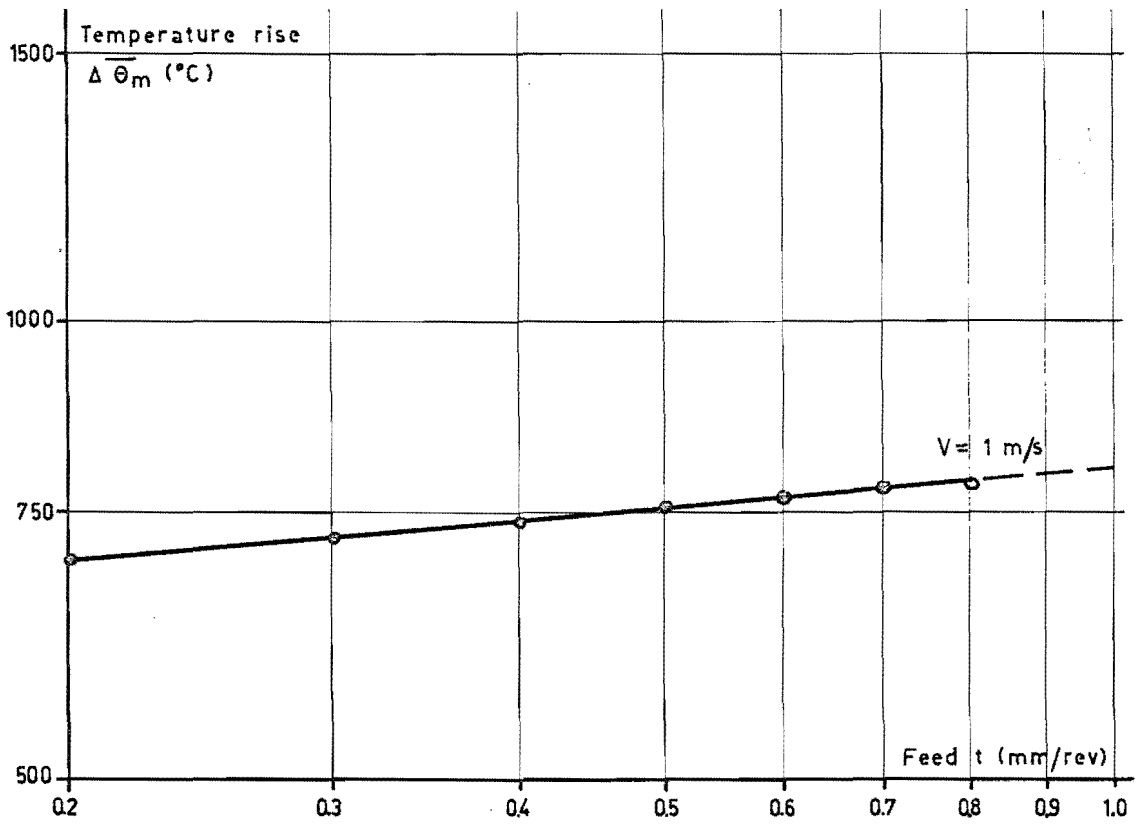


fig. 4 The experimental relation between cutting temperature and feed at a cutting speed $v = 1$ m/s.

- the shear strain has been calculated from:

$$\tan \gamma_s = \frac{\cos \phi}{\sin \phi \cos (\phi - \beta)}$$

where the shear-angle is introduced according to the shear-angle solution (2):

$$2 \tan (\phi + \beta - \alpha) = \tan (\phi - \alpha) + \cot \phi$$

- the average shear stress is obtained by applying:

$$\tau_s = \frac{F_v}{t.d. \left[\cot \phi + \tan (\phi + \beta - \alpha) \right]}$$

- the chip ratio factor follows from:

$$\lambda = \frac{\cos (\phi - \alpha)}{\sin \phi}$$

- the behaviour of the chip contact length has been investigated in a separate program of research. Regression analysis of the experimental values shows a dependence on both cutting speed and feed according to (8):

$$l_c = 0.783 \cdot 10^{-3} + 0.85 t - 0.029 \cdot 10^{-3} v.$$

- the aspect ratio \bar{A} is a function of the ratio t/l_c and has been calculated in ref. (1).

- the thermal quantities of the steel machined have been taken from ref. (9).

The numerical values are given in the figures 5, 6 and 7.

The product $(k \rho c)$ shows an approximate constant value in the region of actual cutting temperatures. However between 600°C and 800°C the values are very doubtful.

Ipsa facto the latter refers also to the values of both the thermal diffusivity K and the thermal conductivity k .

The thermal conductivity of the tool material according to manufacturers data amounts $k^1 = 41.9$ W/m. deg and is considered being independant of temperature. Fortunately the uncertainties thus introduced do not seriously affect the final results because of the fact that in the function X , eq. 3, the thermal dependant term proves to be relative small.

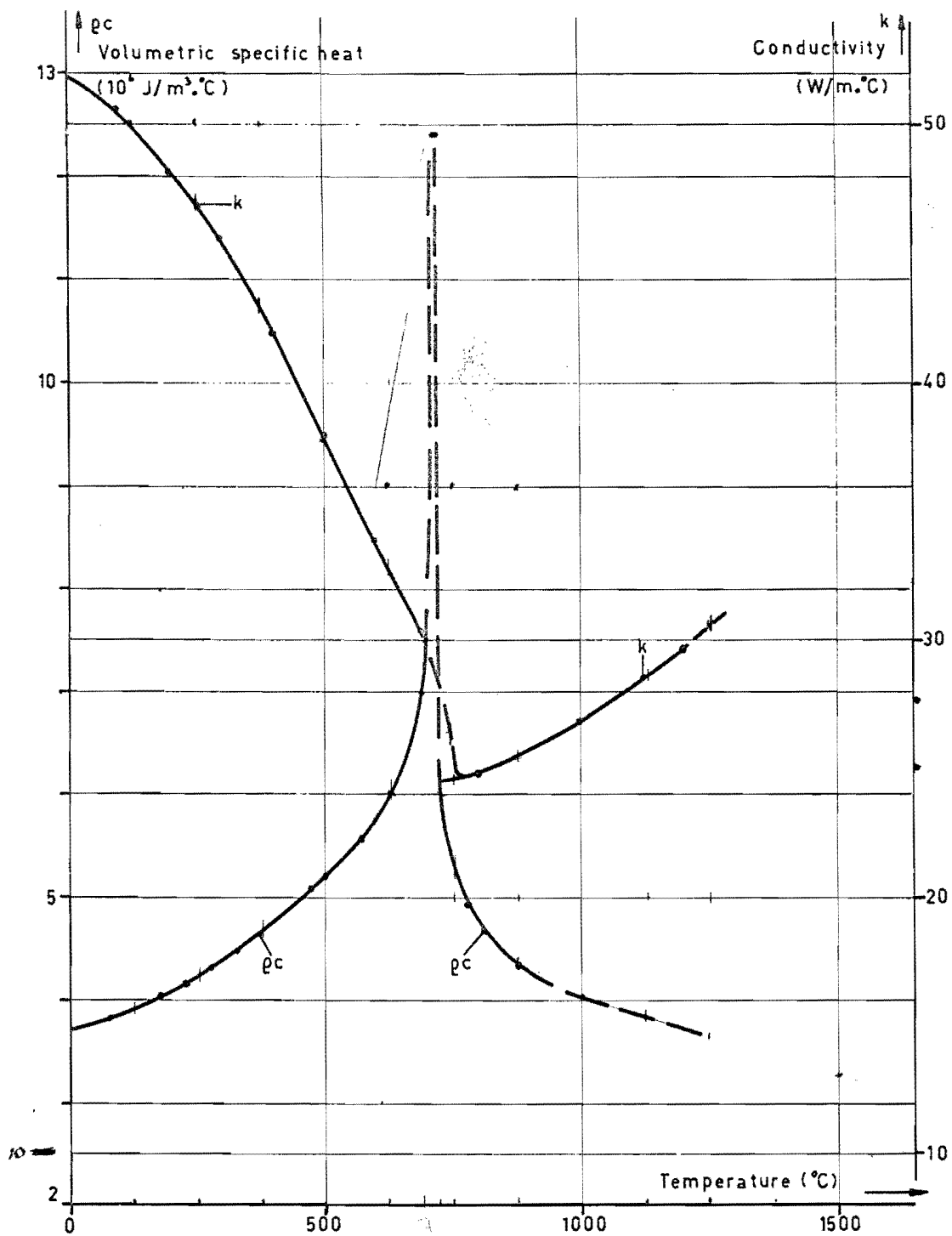


fig. 5 The behaviour of the volumetric specific heat and the conductivity as a function of temperature.
Steel 0.415%C, 0.643% Mn. (ref. 9)

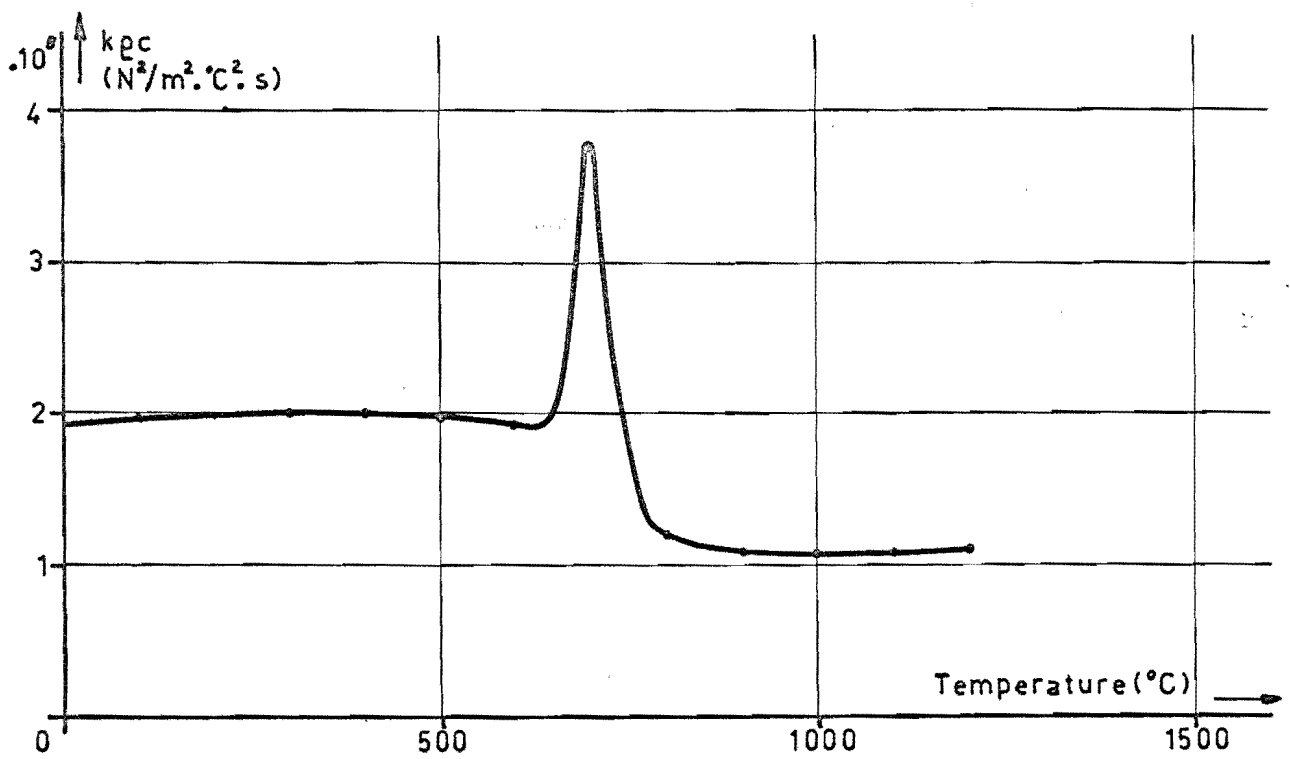


fig. 6 The quantity $(k \rho c)$ as a function of temperature.

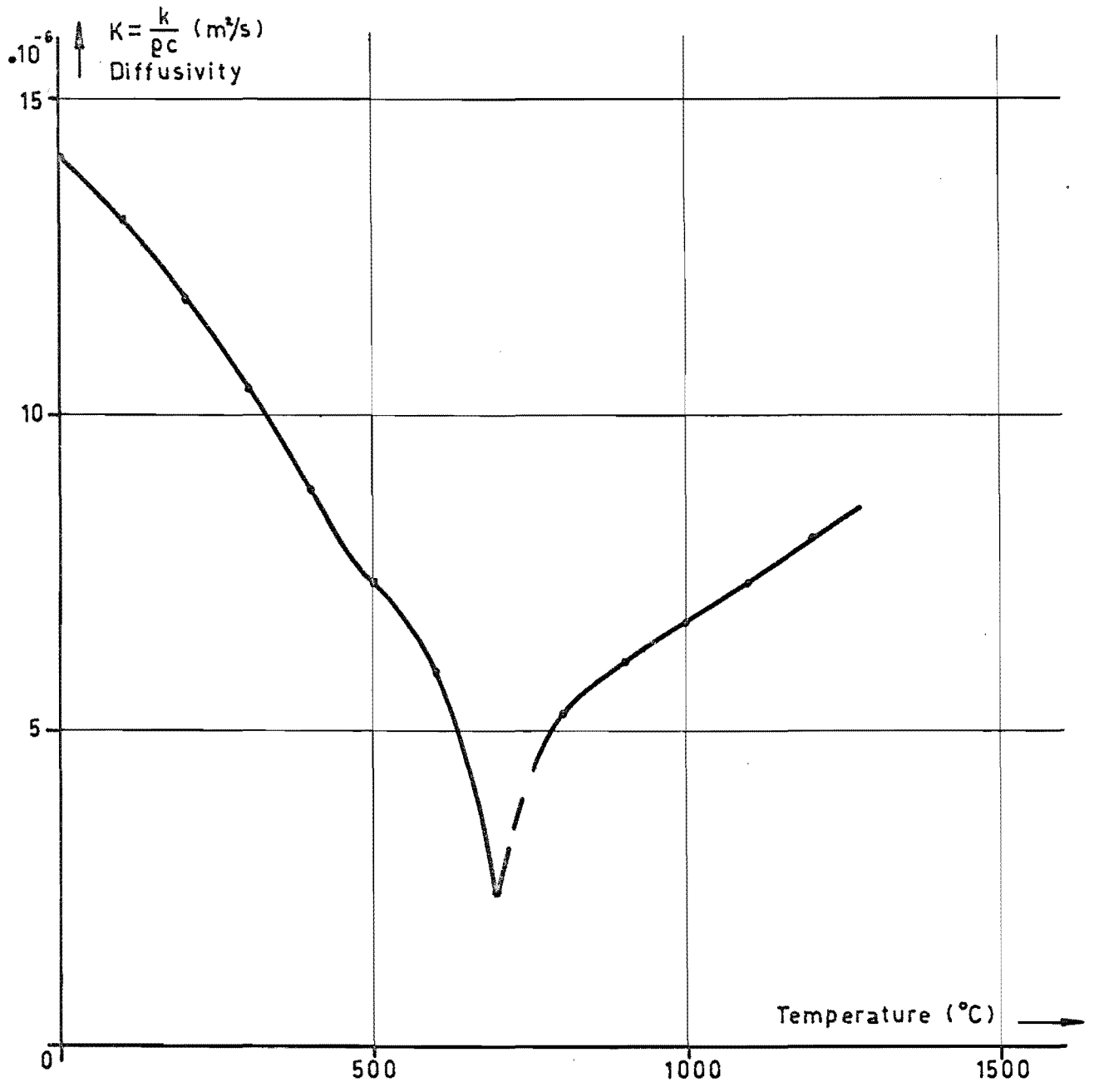


fig. 7 The diffusivity as a function of temperature.

The value of the thermal diffusivity K_0 in the function Y, eq. 3, must be determined at a temperature averaging shear-plane temperature and room temperature.

This can be done by applying an iteration procedure as described in ref. (1). The calculations converge very rapidly because of the fact that changing of cutting conditions interacts very weakly with the average shear plane temperature.

It proves that the value of K_0 changes between $12.00 \cdot 10^{-6}$ and $12.50 \cdot 10^{-6} \text{ m}^2/\text{s}$ within the range of cutting conditions investigated, which has a very low order influence on the final results.

As a matter of fact eq. 1 is based on rather a rough approximation of the specific frictional energy dissipated on the rake of the tool.

It is easy to show that this energy amounts:

$$U_f = \frac{\mu \tau_s \cos \beta}{\lambda \sin \Phi \cos (\Phi + \beta - \gamma)} \quad \text{----- 5)}$$

for which reason the factor A eq. 2 has to be multiplied by the factor:

$$f_1 = \frac{\cos \beta}{\cos (\Phi + \beta - \gamma)} \quad \text{----- 6)}$$

which in most cases is clearly different from one.

Further investigation into the derivation of eq. 1 shows that the quantity B ought to be multiplied by a factor:

$$f_2 = \left[\frac{\{k \rho c\}}{\{k \rho c\}_0} \right]^{\frac{1}{2}} \quad \text{----- 7)}$$

where the denominator refers to the shear-plane, while the numerator does so for the rake face of the tool.

From fig. 6 it is clear that the value of eq. 7 is close to a constant $f_2 = 0.75$ in all practical cutting conditions.

In table I both the temperature measured in a direct way relative to room temperature:

$$\Theta_m = \Delta \Theta_m + 20$$

and the temperature based on measurement of cutting forces and using eqs. 1 upto 7:

$$\Theta_t = \Delta \Theta_t + 20$$

have been listed.

TABLE I

v m/s	t m 10 ⁻³	P _v N	F _v N	Θ _m °C	μ	l _c m 10 ⁻³	φ	$\bar{\tau}_s$ N/m ² 10 ⁸	λ	tan γ _s	Y	\bar{A}	X	A	B	Θ _t °C	Δ %
1	0,2	857	1432	719	0,75	0,92	22,6	6,35	2,50	2,70	4,01	1,57	1,10	0,684	0,226	712	- 0,97
2		649	1363	831	0,61	0,90	25,4	6,81	2,20	2,46	5,40	1,59	1,07	0,705	0,173	848	+ 2,0
3		560	1334	928	0,55	0,87	26,9	7,06	2,07	2,35	6,48	1,61	1,05	0,715	0,146	945	+ 1,8
4		514	1304	1008	0,52	0,84	27,6	7,09	2,01	2,31	7,36	1,63	1,05	0,720	0,130	1026	+ 1,7
5		492	1275	1076	0,51	0,81	27,8	6,98	1,99	2,30	8,09	1,65	1,04	0,724	0,119	1103	+ 2,5
1	0,3	915	1903	740	0,62	1,01	25,3	6,31	2,21	2,47	4,77	1,52	1,10	0,688	0,191	768	+ 3,8
2		702	1814	856	0,51	0,98	27,8	6,62	1,99	2,30	6,44	1,54	1,06	0,708	0,146	916	+ 7,0
3		612	1765	964	0,47	0,95	29,0	6,72	1,90	2,23	7,72	1,56	1,05	0,716	0,123	1021	+ 5,9
4		565	1741	1060	0,44	0,92	29,7	6,78	1,85	2,19	8,80	1,57	1,04	0,722	0,109	1117	+ 5,4
5		541	1716	1144	0,43	0,89	30,0	6,75	1,83	2,18	9,72	1,59	1,04	0,725	0,099	1208	+ 5,6
1	0,4	951	2300	760	0,54	1,09	27,1	6,12	2,05	2,34	5,38	1,48	1,09	0,690	0,170	798	+ 5,0
2		738	2231	883	0,45	1,07	29,5	6,47	1,86	2,20	7,31	1,49	1,06	0,710	0,129	963	+ 9,1
2,5		685	2207	941	0,43	1,05	30,1	6,54	1,82	2,17	8,09	1,50	1,05	0,715	0,117	1024	+ 8,8
3		645	2187	997	0,41	1,04	30,6	6,59	1,79	2,15	8,80	1,51	1,05	0,718	0,108	1079	+ 8,2
4		597	2162	1105	0,39	1,01	31,2	6,65	1,74	2,12	10,04	1,52	1,04	0,723	0,096	1184	+ 7,1
1	0,5	979	2687	775	0,49	1,18	28,5	6,02	1,94	2,26	5,92	1,43	1,09	0,693	0,155	822	+ 6,1
1,5		853	2667	844	0,44	1,16	29,8	6,27	1,84	2,19	7,09	1,44	1,07	0,704	0,132	927	+ 9,8
2		777	2648	908	0,41	1,15	30,7	6,40	1,78	2,15	8,09	1,45	1,06	0,711	0,117	1008	+ 11,0
2,5		724	2638	970	0,39	1,14	31,3	6,50	1,74	2,12	8,97	1,45	1,05	0,716	0,106	1079	+ 11,1
3		685	2628	1028	0,38	1,12	31,8	6,58	1,71	2,10	9,76	1,46	1,05	0,719	0,098	1142	+ 11,0
1	0,6	1016	3084	788	0,45	1,26	29,5	5,98	1,86	2,20	6,41	1,39	1,09	0,694	0,144	849	+ 7,7
1,5		873	3079	858	0,40	1,25	31,0	6,27	1,76	2,13	7,71	1,40	1,07	0,706	0,121	955	+ 11,3
2		804	3074	920	0,38	1,24	31,7	6,40	1,71	2,10	8,81	1,41	1,06	0,712	0,107	1047	+ 13,8
2,5		765	3070	979	0,36	1,22	32,2	6,48	1,69	2,08	9,76	1,41	1,05	0,717	0,097	1131	+ 15,4
3		745	3065	1034	0,36	1,21	32,4	6,51	1,67	2,07	10,61	1,42	1,05	0,720	0,090	1213	+ 17,2
1	0,7	1059	3560	798	0,42	1,35	30,5	6,12	1,79	2,15	6,90	1,36	1,08	0,696	0,134	888	+ 11,3
1,5		919	3560	870	0,37	1,33	31,9	6,38	1,71	2,09	8,31	1,36	1,07	0,707	0,113	1003	+ 15,3
2		864	3560	930	0,36	1,32	32,4	6,49	1,67	2,07	9,48	1,37	1,06	0,713	0,100	1109	+ 19,2
2,5		838	3560	985	0,35	1,31	32,7	6,54	1,66	2,06	10,50	1,38	1,05	0,717	0,091	1209	+ 22,6
1	0,8	1093	4060	798	0,39	1,43	31,5	6,29	1,72	2,11	7,37	1,32	1,08	0,697	0,125	924	+ 15,8
1,5		984	4060	870	0,36	1,42	32,4	6,48	1,67	2,07	8,85	1,33	1,07	0,707	0,106	1058	+ 21,6
2		944	4060	931	0,35	1,41	32,7	6,54	1,65	2,06	10,09	1,34	1,06	0,714	0,094	1180	+ 26,7
2,5		929	4060	990	0,34	1,39	32,9	6,57	1,64	2,05	11,17	1,34	1,05	0,718	0,085	1294	+ 30,7

The numerical values of the main intermediately used functions also have been tabulated.

It is remarked that every experimental value is an average of a number of at least five observations.

The statistical error in a single dynamometric measurement amounts $\pm 2\%$, which roughly causes an average uncertainty of $\pm 2\%$ in the theoretical value of the temperature based on a number of 5 independent measurements. This figure is to be compared with the statistical uncertainty of $\pm 1\%$ of the temperature measured in a direct way as an average of 5 observations.

Cutting forces and temperature have not been determined at the same time and often neither refer to the same tool bit nor to the same piece of material, because of the fact that so far no combined dynamometer-thermometer is at our disposal. An instrument of this kind is in development in order to continue the gathering of experimental values on a routine basis.

Once the computer program being prepared the numerical evaluation is to be considered as a part of this routine.

DISCUSSION AND CONCLUSIONS.

- From table I and the fig. 8 it is clear that a fair agreement exists between experimental and theoretical data as long as the region of low loads on the tool is concerned.
However as soon as the load increases, particularly in terms of feed (chip cross-section) the differences grow to discrepancies.
- The background of this becomes quite clear when calculating from table I the net input power to the tool by multiplying cutting speed and main cutting force and plotting the data obtained against the temperatures Θ_t and Θ_m .
The results are shown in table II and in the figs 9 and 10.

TABLE II

input power W	temp. measured Θ_m °C	temp. calculated Θ_t °C	chip production mm ³ /s
feed t = 0.2			
1432	719	712	600
2726	831	848	1200
4002	928	945	1800
5216	1008	1026	2400
6375	1076	1103	3000
feed t = 0.3			
1903	740	768	900
3628	856	916	1800
5295	964	1021	2700
6964	1060	1117	3600
8580	1144	1208	4500
feed t = 0.4			
2300	760	798	1200
4462	883	963	2400
5518	941	1024	3000
6561	997	1079	3600
8648	1105	1184	4800

input power W	temp. measured Θ_m °C	temp. calculated Θ_t °C	chip production mm ³ /s
feed t = 0.5			
2687	775	822	1500
4000	844	927	2250
5296	908	1008	3000
6595	970	1079	3750
7884	1028	1142	4500
feed t = 0.6			
3084	788	849	1800
4618	858	955	2700
6148	920	1047	3600
7675	979	1131	4500
9195	1034	1213	5400
feed t = 0.7			
3560	798	888	2100
5340	870	1003	3150
7120	930	1109	4200
8900	985	1209	5250
feed t = 0.8			
4060	798	924	2400
6090	870	1058	3600
8120	931	1180	4800
10150	990	1294	6000

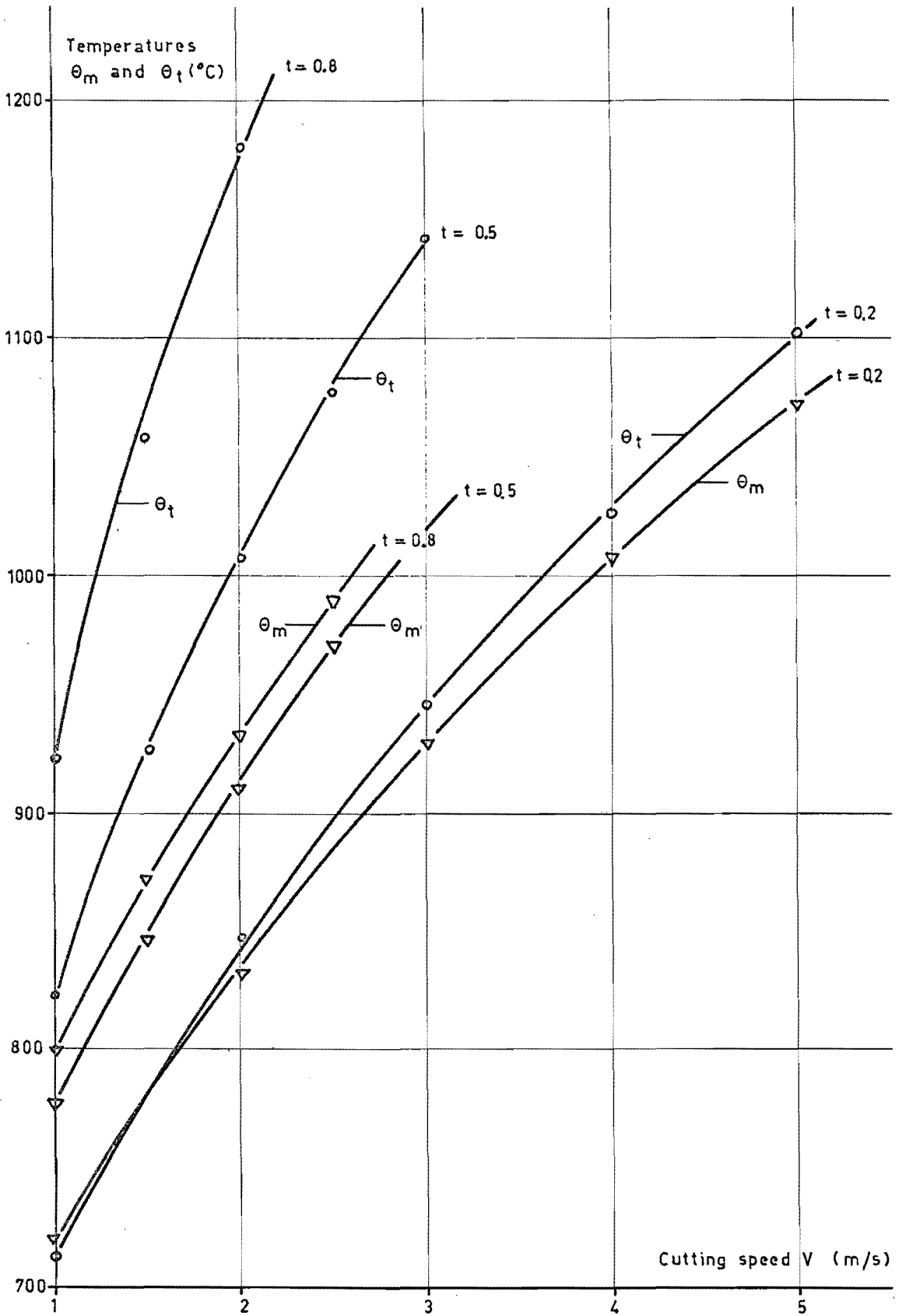


fig. 8 Comparison between the theoretical values of temperature according to eq. 1 and the data experimentally obtained (table I).

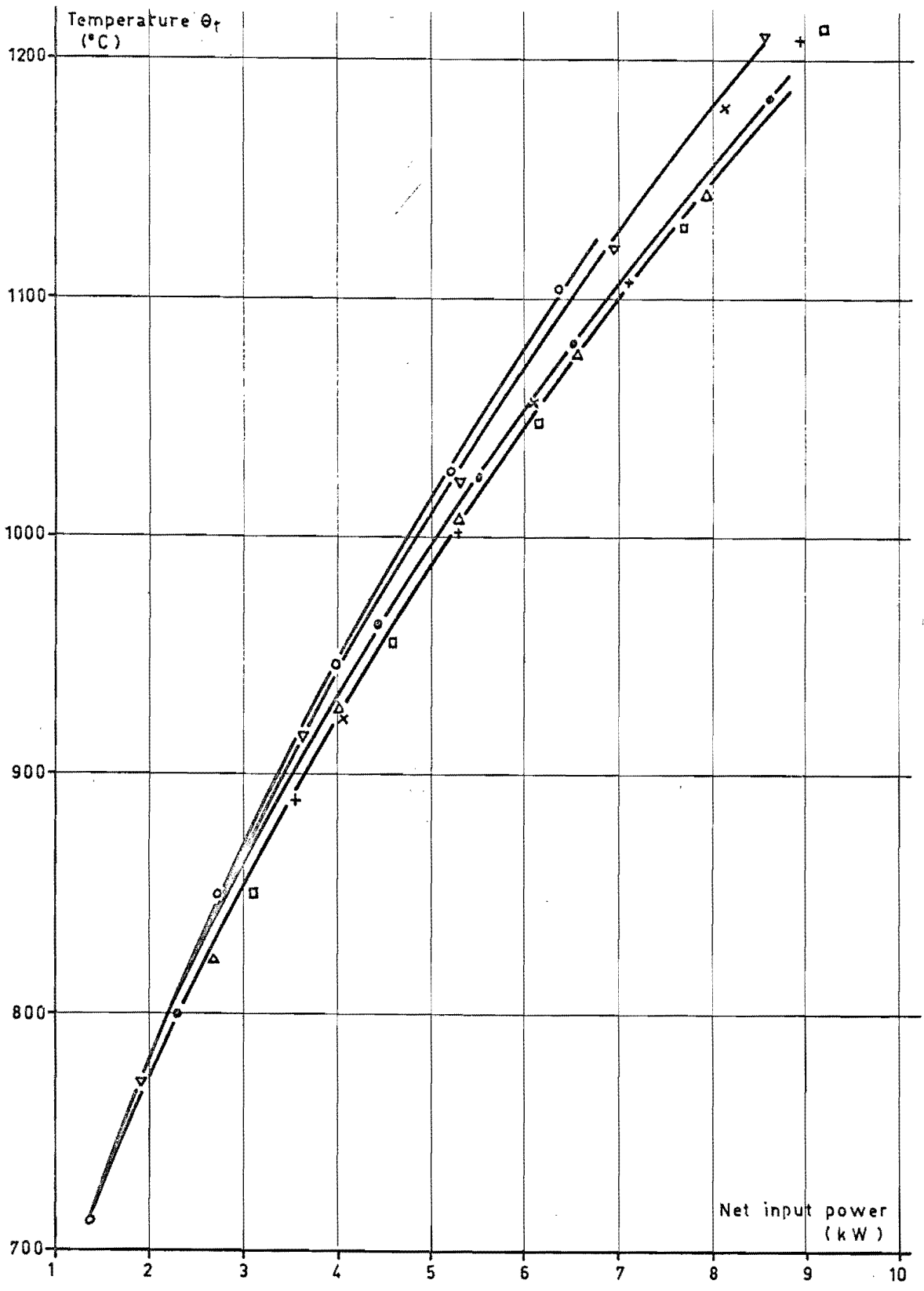


fig. 9 The calculated tool temperature as a function of the net input power to the tool, with the feed as a parameter.

- As shown in fig. 9 the calculated temperature of the tool is practically a function of the net input power only.

With an eye to the statistical errors in the dynamometric measurements it hardly can be justified deciding on a separate influence of feed on temperature at a given input power, the latter of course already implicitly being a function of feed.

- The data obtained experimentally lead towards a different conclusion, as shown in fig. 10.

Obviously a clear cut influence of both net input power and feed on temperature is present, as has been demonstrated in fig. 11.

Hence the temperature of the tool is not uniquely determined by the power fed into the tool but besides probably by some geometrical effect connected with chip dimensions.

- The differences may also be demonstrated by considering the volumetric chip production at different feeds and at a given tool temperature, as shown in fig. 12. The theoretical values show a rapid converging to a limiting value of the efficiency of chip production at a feed of approximately 0.8 mm/rev.

The experimental results show a steady increase of efficiency in the region of feeds investigated.

- At the present state of investigation it is not possible to formulate a definite solution of the problem encountered.

Obviously there is a choice of two possibilities:

1. the Herbert - Gottwein method badly underestimates the average tool temperature, particularly when considerable chip dimensions are involved.
2. the theoretical analysis according to eq. 1 incorrectly neglects some secondary chip-dimensional effect, resulting in an under-estimating of the amount of heat transported by the chip.

Theoretical analysis of the problem is continued.

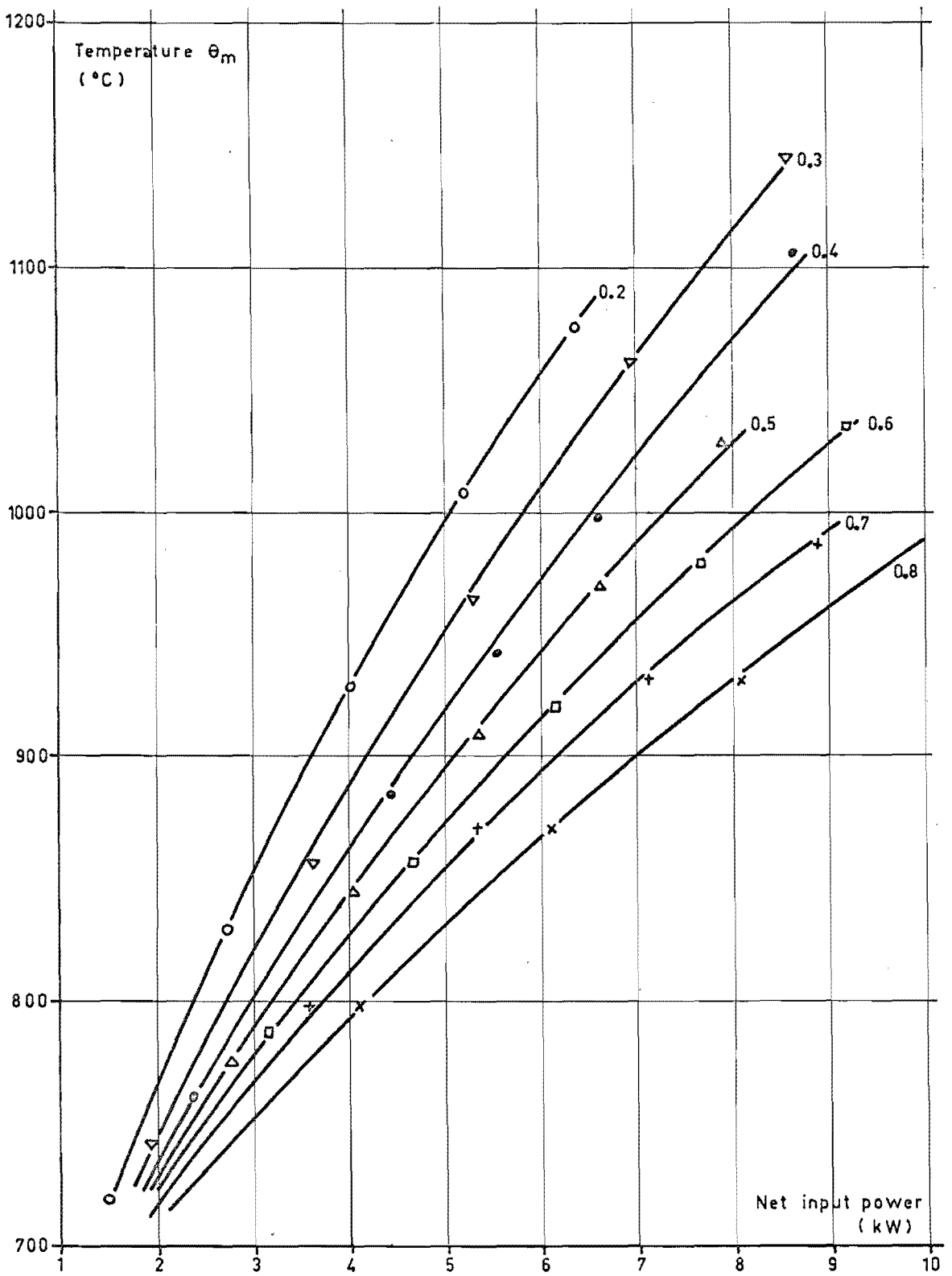


fig. 10 The tool temperature as measured as a function of the net input power to the tool, with the feed as a parameter.

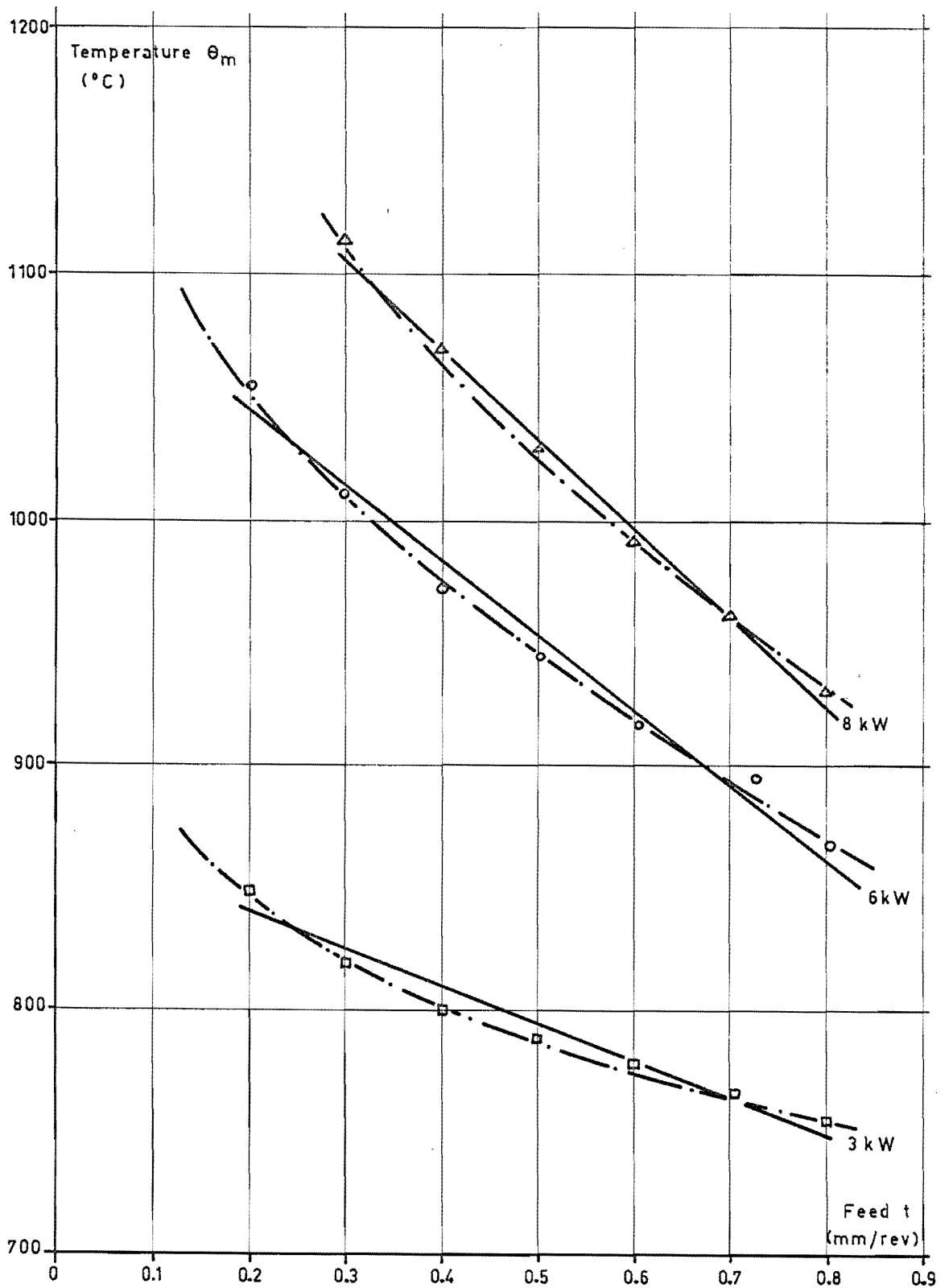


fig. 11 The tool temperature at a given net input power as a function of feed.

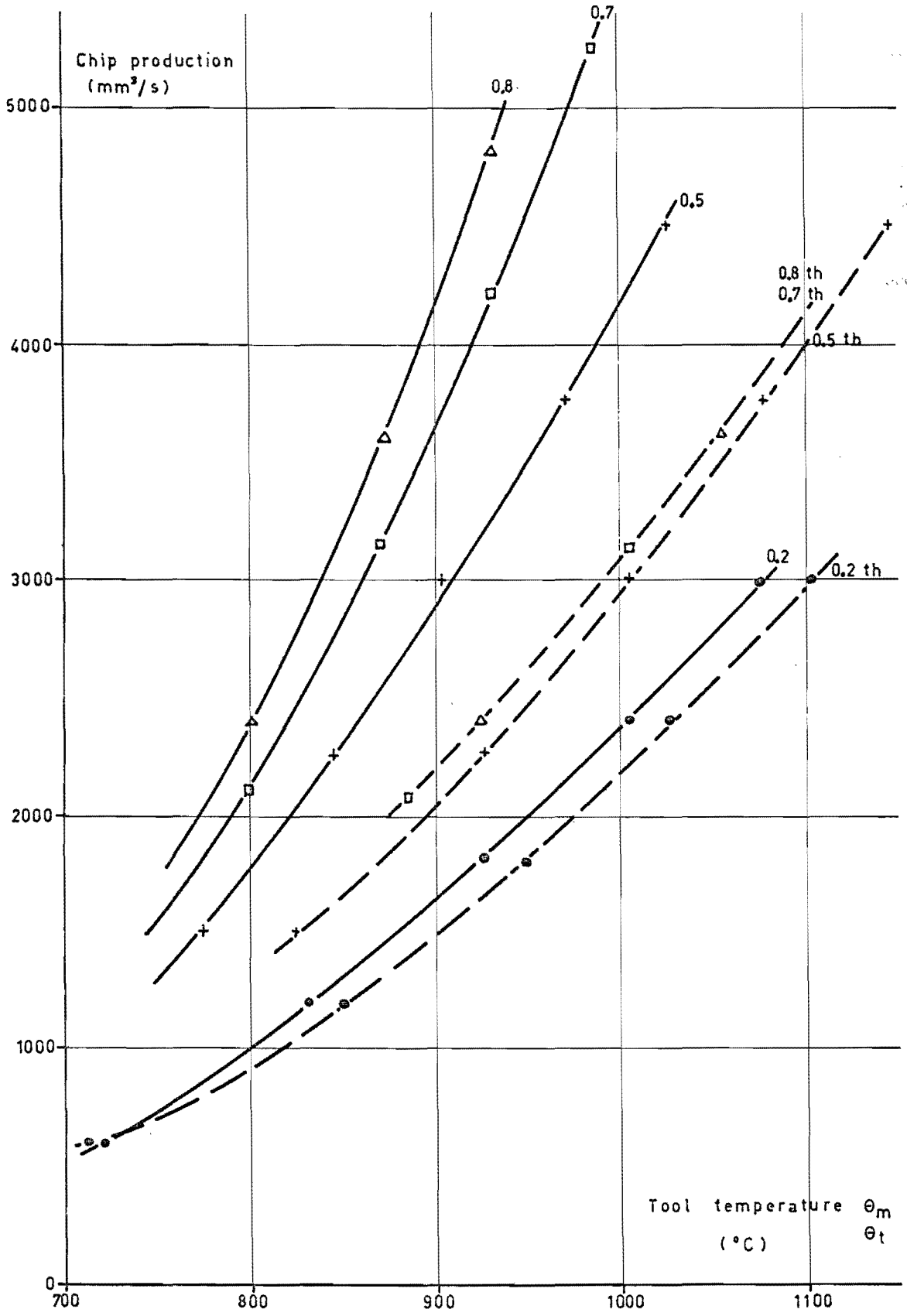


fig. 12 The chip production at different feeds as a function of tool temperature.
 Solid lines : experimental values
 Dotted lines : theoretical values.

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