# SURFACE AND SUB-SURFACE WORKHARDENING IN MACHINING OF DIFFICULT TO MACHINE ALLOYS

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## ABSTRACT

*Six different thermal resistance alloys, commonly used in aero-engine industry at annealed and heat treated states, were tested for their workhardening properties in orthogonal machining. The degree and depths of hardening were determined under simulated broaching conditions. The materials have been graded in the order of workhardening tendency. It was found that most thermal resistance alloys under test, while workhardening in the same manner as the soft materials, exhibit a lower workhardening tendency. The second part of the experiment involved machining of Incoloy alloy N901 at different cutting conditions. It was found that workhardening decreased with (a) decreased uncut chip thickness, (b) increased rake angle, (c) increased clearance angle, (d) decreased flank wear land and (e) application of cutting fluid. The ratio of the degree of workhardening to the depth of workhardening was found to be constant for a given material and heat treatment.*

## INTRODUCTION

This paper reports the result of a work undertaken in response to an expressed industrial need for information on the workhardening during machining heat resistant alloys commonly used in aero-engine industry. A survey of available literature indicates that little quantitative information is available in this regard.

Workhardening is a phenomenon where the bulk of the metal becomes harder when it is permanently deformed at a temperature lower than its recrystallization temperature. Metal cutting processes involve plastic deformation and hence the hardening of the chip and the workpiece. The workhardening produced in the chip has been related to the shear strain obtained in the cutting process [1] whilst that in the workpiece is related to the passage of work material under the cutting edge phenomena [2]. The latter may be viewed as an indentation process [3].

The life of a tool depends largely on the relative hardness of the work and the tool. Tool wear at the flank depends on the hardness of the tool relative to that of the workpiece. Thus if the machined surface is subjected to considerable hardening, the tool wear would be consequently higher. Workhardening has been found to be maximum on the surface and disappears altogether some way below the surface. In aircraft industry, it is found that when machining thermal resistance alloys, especially by broaching, metals tend to workharden. These workhardened alloys not only reduce the broach life, but also increase the broaching forces. In order to be able to predict workhardening, it is important to understand the various factors which influence it. The following work uses a slow speed planing operation to simulate the broaching operation. Hardness survey is carried out to obtain the workhardenability of different alloys.

## WORKPIECE MATERIALS

The following thermal resistance alloys have been tested:

(a) Incoloy 901 (N/901)
(b) Nimonic Alloy PK31 (N/PK31)
(c) Creep Resistance Ferritic Stainless Steel (S/SAV)
(d) Low Carbon 12 % Chromium Vac. Melted Steel (S/SJV)
(e) Commercially Pure Titanium (T/CP)
(f) Titanium, Tin, Zirconium Alloy (T/SZ)

CHEMICAL COMPOSITION

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (a) | N/901 | 13Cr, 34Fe, 6Mo, 2.5Ti, 0.2Al, 44Ni | | | | | | | | | | | |
| (b) | N/PK31 | 19Cr, 14Co, 1Fe, 4.5Mo, 2.5Ti, 6Al, 53Ni, 5.5Nb | | | | | | | | | | | |
| (c) | S/SAV | C | Mn | Si | S | P | Ni | Cr | Mo | Ve | Nb | Co | N |
| | Min | 0.06 | 0.60 | 0.2 | — | — | 0.2 | 9.8 | 0.5 | 0.1 | 0.2 | 5.0 | — |
| | Max | 0.11 | 1.15 | 0.8 | 0.02 | 0.028 | 0.8 | 11.2 | 1.0 | 0.4 | 0.6 | 7.0 | 0.03 |
| (d) | S/SJV | C | Mr | Si | Cr | Ni | V | Mo | S | P | N | | |
| | | 0.08 | 0.5 | — | 11.0 | 2.0 | 0.25 | 1.5 | — | — | 0.02 | | |
| | | 0.15 | 0.9 | 0.35 | 12.5 | 3.0 | 0.40 | 2.0 | 0.03 | 0.03 | 0.045 | | |
| (e) | T/CP | 99.9Ti | | | | | | | | | | | |
| (f) | T/SZ | 11 Sn, 5 Zr, 2-2.5 Al, 1 Mo | | | | | | | | | | | |

HEAT TREATMENT OF THE ALLOYS

The followed heat treatment procedures are based on the procedures used by at least one well known aero-engine manufacturing company.

(a) Fully Heat Treated

S/SAV—Pre-heated at 650°C for 15 mins. Hardened at 1170°C for 15 mins. 1st Temper at 580°C for 5 hours air cooled. Deep freeze at — 70°C for 15 mins. 2nd Temper at 615°C for 5 hours air cooled.

N/901—Solution treated at 1090°C for 3 hours, water quenched. Stabilized at 775°C for 4 hours, air cooled. Aged at 705°C for 24 hours, air cooled.

N/PK31—Solution treated at 1130°C for 4 hours, air cooled. Stabilized at 650°C for 4 hours, air cooled. Aged at 770°C for 16 hours, air cooled. Aged at 700°C for 16 hours, air cooled.

S/SJV—Hardened at 1050°C for 15 mins. air cooled. Tempered at 560°C for 3 hours, air cooled.

T/SZ—Solution treated at 900°C for 1 hour, air cooled. Aged at 500°C for 24 hours, air cooled.

T/CP—Annealed at 675°C for 1 hour, air cooled.

(b) Annealed or Solution Treated.

S/SAV — Annealed at 680°C for 2 hours, air cooled.

S/SJV — Annealed at 690°C for 2 hours, air cooled.

N/901 — Solution treated at 1090°C for 1 hour, water quenched.

NPK/31—Solution treated at 1130°C for 1 hour, air cooled.

T/SZ — Solution treated at 900°C for 1 hour, air cooled.

T/CP — Annealed at 675°C for 1 hour, air cooled.

## EXPERIMENTAL DETAILS

THE BROACHING CONDITIONS

| | |
|---|---|
| Broaching speeds | — less than 5 m/min |
| Top rake angle | — 0° to +25° |
| Rise per tooth | — Roughing—up to 0.2 mm<br>Finishing—0.025 to 0.075 mm |
| Clearance angle | — 2° to 6° |
| Flank Wear land | — up to 0.375 mm |
| Cutting fluid | — ILOBLOACH 9 |
| Tool Material | — M42 High Speed Steel of hardness 850-950 Hv |

THE EXPERIMENT SIMULATING THE BROACHING CONDITIONS

A Heller vertical milling machine was modified to perform planing operations. The milling head was locked by means of a locking plate and a tool holding device was fitted on to the plate. The cutting tool used was "Eclipse M42" HSS tool (composition 1.1C, 3.75Cr, 1.15V, 1.5W, 9.5Mo, 8.0Co). In order to obtain a perfect indentation of the micro-hardness indenter, a surface finish of up to 4 microns was necessary. The specimens were first ground and then lapped. They were then numbered in pairs. Each pair was clamped onto the work holding fixture on the machine table. The top layers of the specimens were cut in pairs so that each pair was absolutely parrallel with the machine table. After pre-machining, the specimens were polished and heat treated in a controlled atmosphere furnace. The previously polished plates were clamped together and the cutting test was performed. The plates were separated and a micro-hardness survey was made of the region below the cut surface on the "inner" face of one of the plates; for this purpose a knoop diamond indentor was used. The hardness values were then plotted against the depth below the cut surface at which the hardness measurement was made and a smooth curve was drawn through the points. By extrapolation, the value of the hardness at the cut surface, Hm, and the depth, $\Delta_m$ below the surface at which the hardness becomes equal to that of the uncut specimen were obtained.

## RESULTS AND DISCUSSION

### THE WORKHARDENABILITY OF VARIOUS THERMAL RESISTANCE ALLOYS

Fig. 1 shows that except for T/SZ, there is a hardness gradient near the edge of the machined workpiece. The gradient of workhardening is of hyperbolic form which agrees with most of the other investigations on machining of soft metals [4, 5, 6]. The degree of

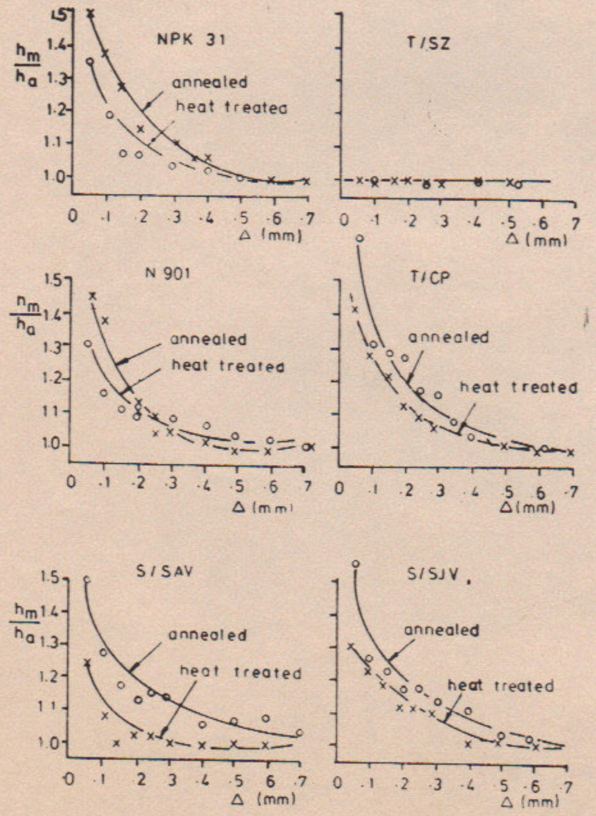


Fig. 1. Work hardenability of various thermal Resistance alloys. Cutting conditions : $V_c = 1{\cdot}5$ m/min, $\alpha = 20°$, $\beta = 5^0$

workhardening, defined as the ratio of maximum hardness to the bulk hardness, $h_m$, and the depth of workhardening $\Delta_m$, can be obtained from this figure.

The same figure shows the degree and depth of workhardening for various alloys with different types of heat treatment prior to the cut. For each case it can be seen that the annealed alloys possess a greater capacity for workhardening than the heattreated alloys.

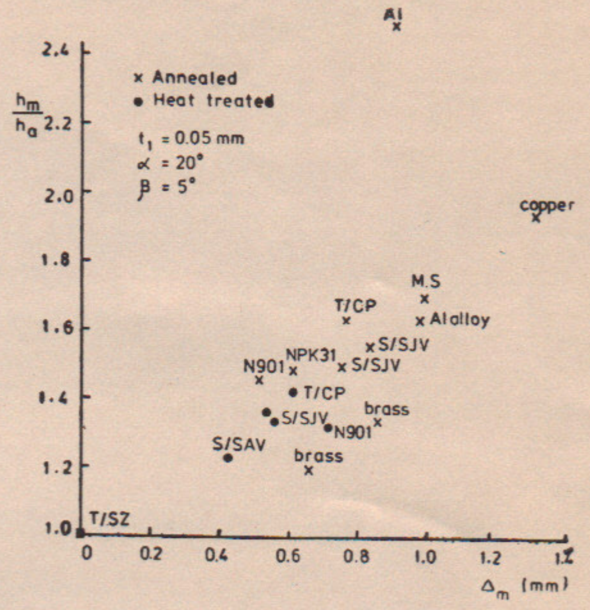


Fig. 2 $\frac{h_m}{h_a}$ vs. $\Delta_m$ Plot for various Thermal Resistance alloys and soft metals. Cutting Conditions : $V_c = 1.6$ m/min, $\alpha = 20°$ $\beta = 5°$

From Fig. 2, it can be seen that the workhardenability of thermal resistance alloys can be arranged in the following order:

T/CP Annealed, S/SJV Annealed, NPK31 Sol. Annealed, N901 Sol. Annealed, T/CP Heat treated, NPK31 Fully heat treated, N901 Heat treated, S/SJV Fully heat treated, T/SZ Sol. Annealed and T/SZ Sol. treated and aged.

### FACTORS INFLUENCING THE WORKHARDENING OF N901

#### Variation of Rake Angle

Fig. 3 shows that both the maximum workhardening $h_m$ and the total depth of workhardening $\Delta_m$ decrease as the rake angle is increased. This is attributed to the fact that the increase in rake angle reduces the wedge angle of the tool [7] and the material below the cutting edge is subjected to less compression and friction. Furthermore, the increase in angle reduces the chip thickness and according to [4, 5], reduces the tensile field of the tool which plays a significant role in workhardening.

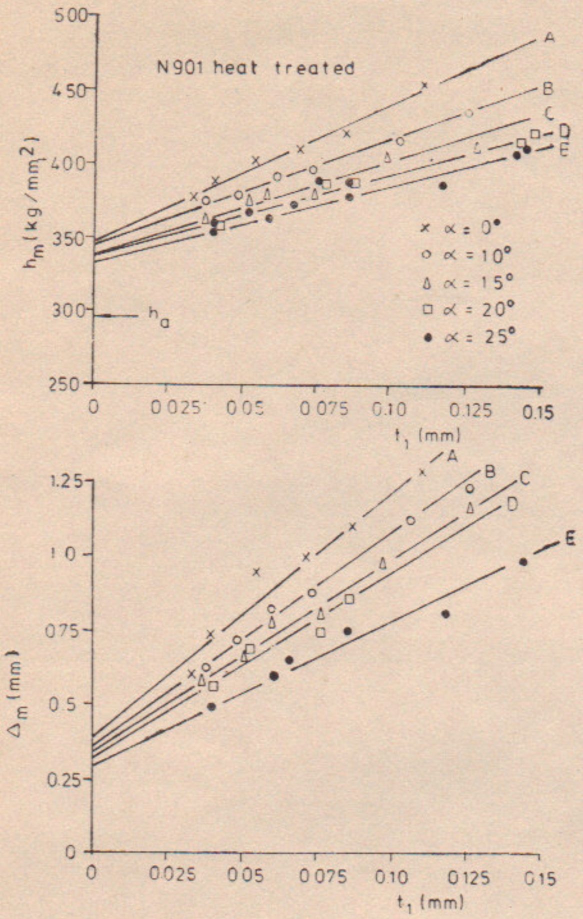


Fig. 3. Variation of rake angle. Cutting conditions, $V_c = 1{\cdot}9$ m/min, $\beta = 5°$

Variation of Clearance angle

Fig. 4 shows that both the maximum workhardening $h_m$ and the total depth $\Delta_m$ decrease as the clearance angle is increased. This is again due to the fact that the increase in clearance angle reduces the wedge angle of the tool, therefore, the cutting edge radius should also be reduced. Also, for a larger clearance angle, the area of contact between the workpiece and the flank face of the tool is smaller. This reduction in area of contact reduces the frictional drag and hence reduces the vertical nose force component which in turn reduces workhardening.

Variation of flank wear land

Fig. 5 shows that both the maximum workhardening $h_m$ and the depth of workhardening $\Delta_m$ increase as

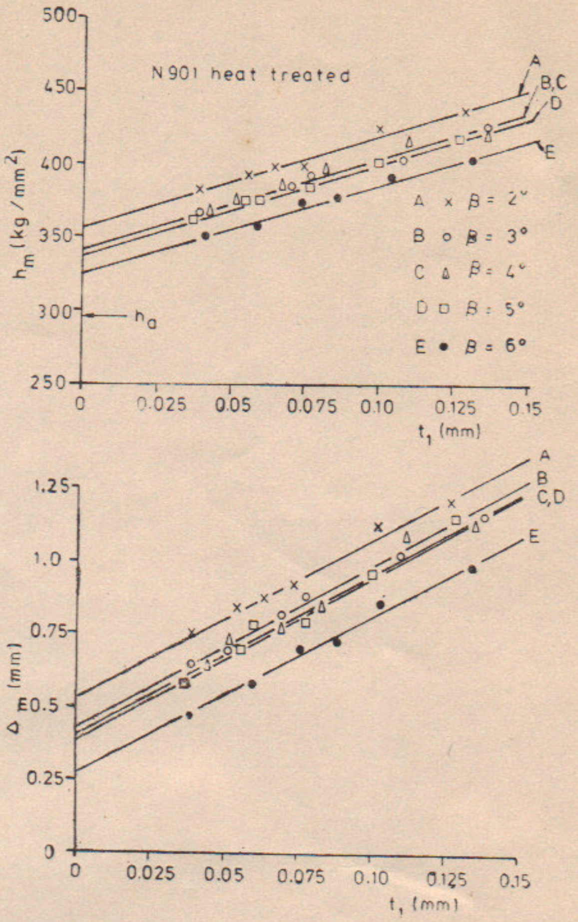


Fig. 4. Variation of clearance angle. Cutting conditions: $V_c = 1{\cdot}9$ m/min, $\alpha = 15°$

the flank wear land is increased. In this case, in addition to the hardness induced by the tensile stress ahead of the cutting tool, which is constant for all flank wear lands, there is an additional workhardening caused by the material being ploughed at the rounded portion of the cutting edge radius and hence compressed under the flank wear land $l_f$ creating additional frictional drag.

Application of ILOBROACH Cutting Fluid

Fig. 6 shows that both $h_m$ and $\Delta_m$ increase linearly with the uncut chip thickness, but decrease when Ilobroach cutting fluid is applied.

Fig. 8 shows the variation of cutting component of the machining force with uncut chip thickness $t_1$. The solid lines show the data when cutting dry whereas the broken lines show the same when cutting fluid is used. The main effect of the cutting fluid is seen to be the reduction in the nose force component ($F_c'$). Thus $F_{c\ air}' > F_{c\ cutting\ fluid}'$

In [5] a similar observation was made with aluminium alloy. This was attributed to the fact that the shear

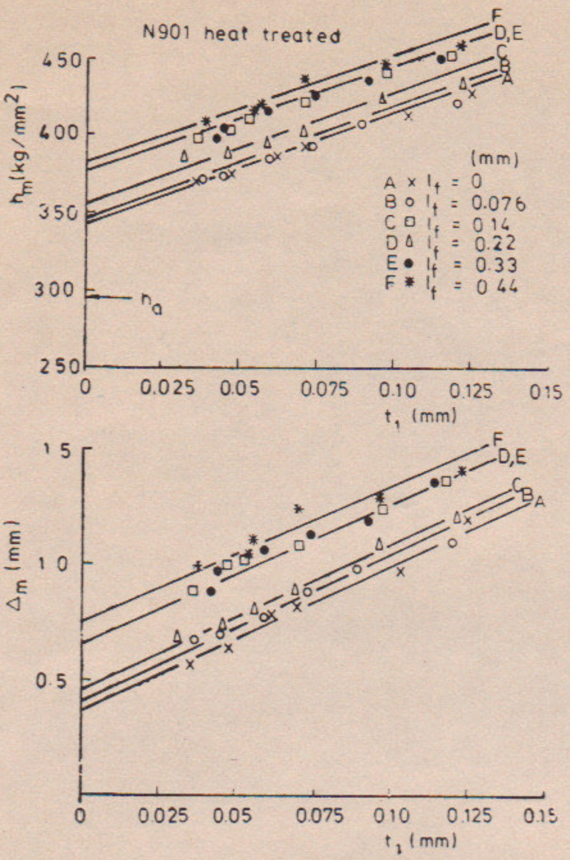


Fig. 5. Variation of flank, wear land, Cutting conditions. $V_c = 1.9$ m/min, $\alpha = 10°$, $\beta = 5°$.

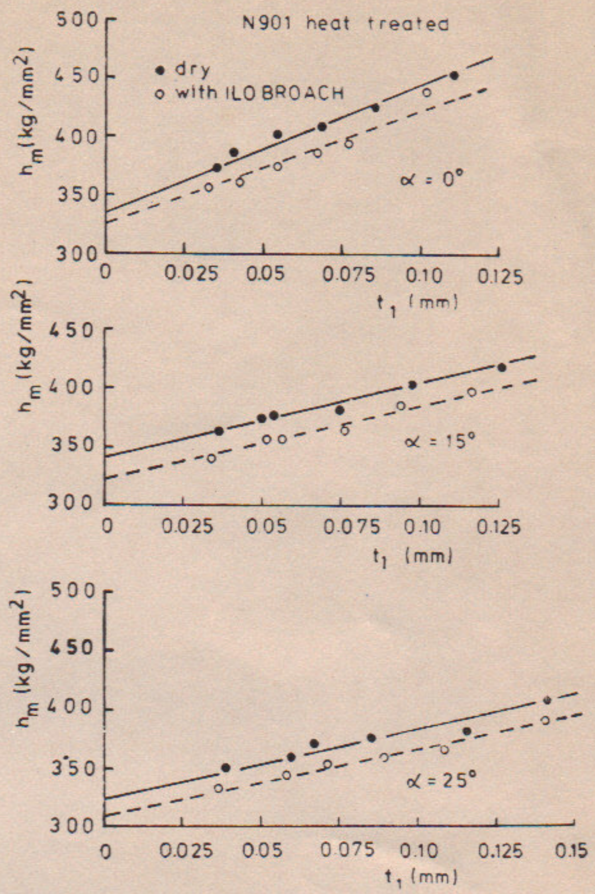


Fig. 6. Application of ILOBROACH cutting fluid. Cutting conditions : $V_c = 1.9$ m/min, $\beta = 5°$.

angle $\varphi_{air} < \varphi_{cutting\ fluid}$. As a result, the effect of the application of cutting fluid on the surface hardening of Incoloy alloy N901 will be :

(i) a reduction in the hardness and the depth of hardness due to the reduction in the length of flank face-workpiece contact (which in turn, is determined, for a given tool geometry, by the depth of workpiece material extruded below the tool) causing a reduction in $F_c'$ and thus, resulting in a reduction in the surface hardness and the depth of workhardening,

(ii) a further reduction in the hardness and the depth of hardness due to the increase in the shear angle, which would affect the state of stress ahead of the cutting tool which in turn determines the degree and depth of workhardening.

Relative workhardening tendencies

Figs. 8a, b and c show the plots of $h_m/h_a$ versus uncut chip thickness for annealed Incoloy N901 material under dry cutting in a wide range of tool parameters (rake angle: 0 to 25°, clearance angle: 2° to 6° and flank wear land: 0 to 0.44 mm). It is seen that the variation follows a straight line with constant slope of $K = 0.4$ mm$^{-1}$. A similar constant was obtained when ILOBROACH was used. As discussed in [4] the constant K may be taken as a material constant and is useful in relating the degree to depth of workhardening during finish machining. Table 1 compares the values of the constant K for different materials including the conventional and the thermal resistance alloys. It is seen that generally the constant K is large for annealed materials.

Fig. 2 shows $h_m/h_a$ versus $\Delta_m$ plot for different alloys machined under identical conditions. This plot is useful in comparing the relative workhardening tendencies of various materials. For instance T/SZ alloy, associated with tear types of chips, shows hardly any workhardening tendency. Gummy materials like aluminium, copper and mild steel exhibit a great tendency for workhardening. Thermal resistance alloys show an intermediate tendency.

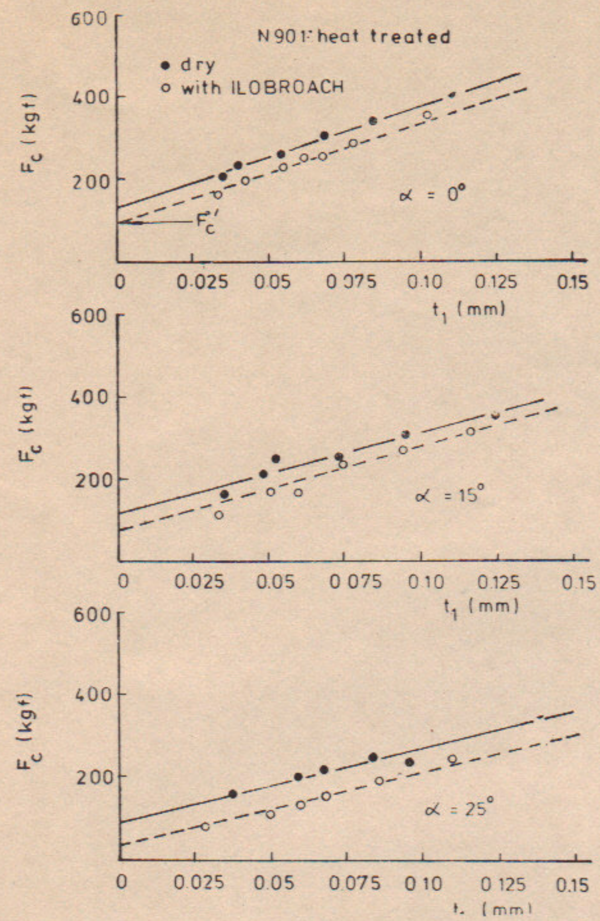


Fig. 7. Variation of cutting forces when ILOBROACH is applied. Cutting conditions : $V_c = 1.9$ m/min, $\beta = 5°$.

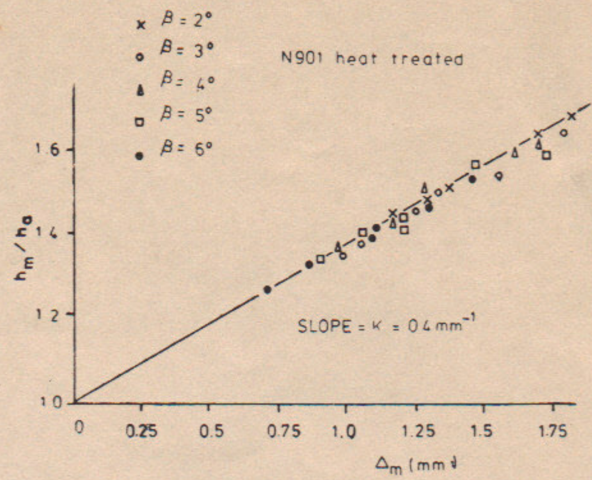


Fig. 8 (b).

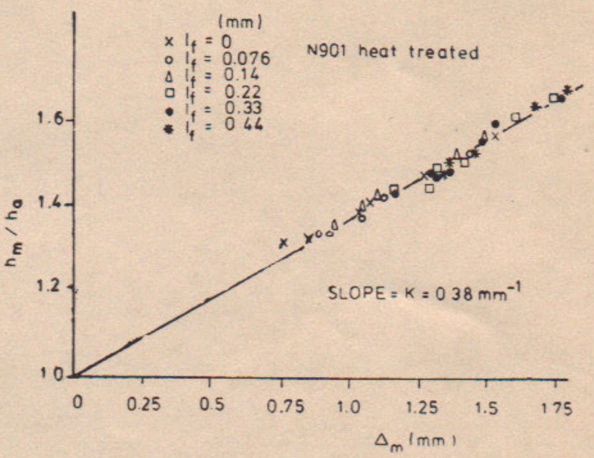


Fig. 8 (c).

Fig. 8. $h_m/h_a$ Vs. $\Delta_m$ Plots for (a) various rake angles (b) various clearance angles, (c) various flank wear lands.

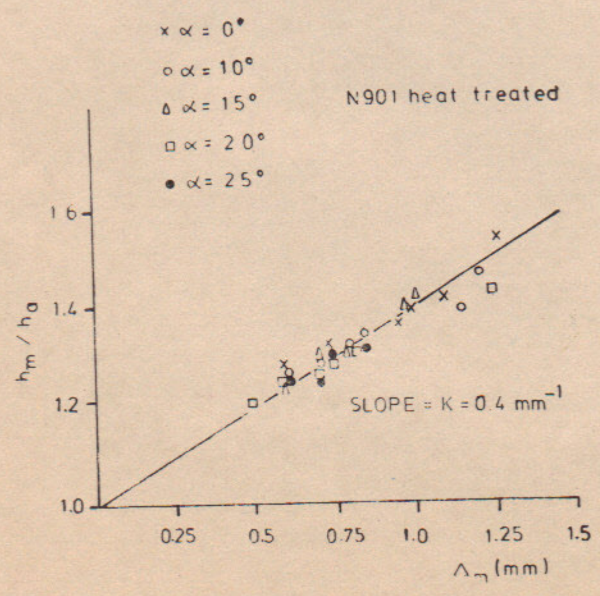


Fig. 8 (a).

## CONCLUSION

From the investigation, it can be seen that the thermal resistance alloys workharden in the same manner as soft metals and that the annealed alloys possess higher workhardenability than the heat treated alloys. The workhardening tendency of thermal alloys is generally lower than that of the conventional ductile alloys like mild steel, copper and aluminium, with the exception of T/SZ alloys which showed no workhardening tendency.

The relative work hardening tendencies of thermal resistance alloys are as indicated in Fig. 2. Work on Incoloy alloys indicates that the following factors cause an increase in the degree and depth of surface workhardening:

(i) an increase in uncut chip thickness
(ii) a decrease in rake angle
(iii) a decrease in clearance angle
(iv) an increase in flank wear land
(v) when no cutting fluid is applied.

The ratio of the degree and the depth of work hardening in finish machining is constant for a given material and heat treatment.


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Table 1

Constant K for various metals

| *Material* | $K(mm^{-1})$ | *Condition* |
|---|---|---|
| Aluminium | 1.75 | Annealed |
| N901 | 0.91 | Annealed |
| T/CP | 0.81 | Annealed |
| NPK31 | 0.80 | Annealed |
| Copper | 0.73 | Annealed |
| Aluminium Alloy | 0.70 | Annealed |
| Mild Steel | 0.70 | Annealed |
| S/SJV | 0.68 | Annealed |
| S/SAV | 0.66 | Annealed |
| T/CP | 0.66 | Heat Treated |
| S/SAV | 0.58 | Heat Treated |
| S/SJV | 0.57 | Heat Treated |
| NPK31 | 0.53 | Heat Treated |
| N901 | 0.40 | Heat Treated |
| Brass | 0.36 | As Received |

## REFERENCES


1. *Zlatin, N. and Merchant, M. E., "Cutter life, Hardness Distribution and Honing", Trans. ASME 69, 5, 1947.*
2. *Thomson, E. G., Lapsley, J. T. and Grassi, R. C., "Deformation Work Absorbed by the Workpiece During Metal Cutting", Trans. ASME 75, 1953.*
3. *Basuray, P. K., Misra, B. K. and Lal, G. K., "Transition from Ploughing to Cutting during Machining with Blunt Tools", Wear, 43, 1977.*
4. *Haslam, D. and Rubenstein, C., "Surface and Sub-surface Work-hardening Produced by the Planing Operation", Annals of the CIRP, Vol. 18, 1970.*
5. *Lau, W. S. and Rubenstein, C., "The Influence of Flank Wear, Cutting Speed and Cutting Fluid on the Surface and Sub-surface Work-hardening Produced in an Orthogonal Planing Operation", Int. J. MTDR, Vol. 12, 1972.*
6. *Camatina, E., "A Systematic Research on the Cold Work Produced on Carbon Steel by Machining with Lathe", The 8th Int. MTDR Conference, University of Manchester, 1967.*
7. *Albrecht, P., "The Ploughing Process in Metal Cutting", Trans. ASME 82, p 348, B, 1960.*