JOURNAL OF MATERIALS SCIENCE 31 (1996) 3613–3616

Optimizing the performance of high speed steel circular saw blades machining cupro 107, Inconel 600L† and Nimonic PK31† nickel based alloys

M. SARWAR
Department of Mechanical Engineering and Manufacturing Systems, University of Northumbria at Newcastle, Newcastle upon Tyne, UK
S. R. BRADBURY*
Department of Mechanical and Process Engineering, University of Sheffield, Sheffield, UK
D. B. LEWIS
Materials Research Institute, Sheffield Hallam University, Sheffield, UK

Nickel based alloys are machined by methods similar to those used to cut ferrous materials, however there are additional process requirements due to the poor machinability of these alloys. The current paper reports on work undertaken to optimize the cutting conditions for high speed steel circular saw blades machining materials from three of the principal categories of nickel based alloy.

Techniques have been developed and verified that simulate the cutting characteristics of multi-point cutting tools by testing blade segments that contain representative teeth. The cutting behaviour of high speed steel circular saw blades have been simulated in this manner. Materials from three of the principal classifications of nickel based alloy; Cupro 107, Inconel 600L and Nimonic PK31, have been machined over a range of cutting feeds and speeds. Cutting and thrust forces were measured and the performance criteria, specific cutting energy (Esp) evaluated. Optimized cutting conditions for each material were determined from curves of Esp against feed rate at the selected cutting speeds.

In an area of high product and material costs, the information contained within this paper will be of interest to the manufacturing engineer and end user when appraising the suitability of high speed steel circular saw blades as a tool for machining these materials.

1. Introduction

By retaining mechanical, corrosion and oxidation resistant properties at high temperature, nickel and its alloys are widely used for product applications where the operating environment is chemically or thermally hostile. There are numerous nickel based alloys commercially available, each with its own distinctive set of properties. The work reported in the current paper optimizes the performance of high speed steel (HSS) circular saw blades machining representative alloys from three of the principal categories: Cupro 107, Inconel 600L and Nimonic PK31. Cutting tests have been undertaken using methods developed by the authors [1]. Circular saw blades were selected for the work since they are commonly used for industrial cut-off processes that involve machining nickel based alloys.

High temperatures and stresses are generated along both the tool/chip and the tool/workpiece interfaces when machining nickel based alloys. Normal stresses on the tool are often roughly double those developed machining mild steel at the same cutting speed [2]. Consequently, to avoid overloading the tool, nickel based alloys are machined at relatively slow cutting speeds. Under such conditions chip control and chip breaking characteristics are poor, since the chips are continuous, abrasive and have a high flow strength.

The thermal behaviour of single point tools machining nickel based alloys and steels have been compared [3]. It was shown that cutting temperatures were higher and the temperature gradient lower in the tools machining the nickel based alloys, also the hottest part of the tool was found to be along the cutting edge

*Author to whom all correspondence should be addressed.
†Inconel 600L and Nimonic PK31 are registered trademarks of the Inco Family of Companies.

rather than at the point of tool/chip separations, as when machining ferrous materials.

2. Practical difficulties machining nickel based alloys

The poor machinability of nickel based alloys make it essential to optimize cutting conditions. In an industrial application where large segmental circular saw blades were used to section forged bar and cast ingots (air cooled) of nickel based alloys prior to extrusion, a number of practical machining difficulties were identified:

(i) Cuts often produced curved, off-square surfaces with a poor surface finish.
(ii) High cutting temperatures accelerated tooth wear.
(iii) Chips adhered to both teeth and gullets. On occasions this debris evaded tooth cleaning mechanisms and lead to clogging and catastrophic tooth failure.
(iv) Sectioning cast ingots; tooth damage occurred when cutting through hard scale on the outside of the bar and the internal pipe.
(v) Excessive machine vibration.
(vi) Relief of internal stresses within the bar can cause the kerf to close and "jam" the blade.

When sectioning 250 mm diameter ingots of Nimonic PK31, it was expected that a 72 inch (182.88 cm) segmental blade would cut a maximum of two sections before the teeth needed regrinding.

3. Workpiece material selection

Workpiece materials were selected from the copper–nickel, nickel–chromium and nickel–chromium–cobalt categories of nickel based alloy. The characteristics of each alloy are briefly described. Material composition and hardness are listed in Table I.

3.1. Cupro 107 (Cu–Ni)

Not strictly a nickel, but a copper based alloy with 30% nickel content. Copper–nickel alloys combine the attributes of corrosion and oxidation resistance with strength and ductility. Applications tend to be in moderately corrosive environments which do not merit use of alloys with higher nickel content.

3.2. Inconel 600L (Ni–Cr).

Nickel–chrome alloys combine excellent resistance to oxidation with good resistance to corrosion at elevated temperatures and are used for components that require a long service life when operating under such conditions. In general, mechanical properties are also maintained at high temperatures.

3.3. Nimonic PK31 (Ni–Cr–Co)

This alloy is used for applications where high strength and durability are required under severe thermal conditions. Resistance to creep, fatigue, oxidation and thermal shock have made this range of material important in the development of jet engines.

4. HSS circular saw blades

Circular saw blades are used for cut-off operations that generally require dimensional accuracy and a good surface finish. In the current investigation, M2 high speed steel circular saw blades, 250 mm diameter, 2.5 mm thickness, 160 teeth were used. The teeth were ground to the Heller profile, a "triple-chip" design that features an alternate rougher-finisher tooth configuration, as shown in Fig. 1.

Techniques developed and validated [1] were used to simulate the cutting behaviour of the tools through testing blade segments that contain a single rougher and finisher tooth. This approach allows:

(i) Isolation and analysis of the cutting characteristics of individual teeth.
(ii) Multiple segments to be obtained from a single blade: reduced tool costs.
(iii) Lower material removal requirements: reduced testing time and workpiece demand.
(iv) Compact: size better suited for the application of advanced surface treatments and coatings.

5. Performance test results and discussion

Performance tests were undertaken to determine the "as new" ability of the tool to cut the materials over a range of cutting speed and feed rates. The performance was quantified by evaluating the specific cutting energy (Esp), a measure of the energy required to remove a unit volume of workpiece material [4]. Full detail of techniques and procedures are given elsewhere [1]. Results relating to the cutting of mild steel (En 3b) are given as a benchmark from which the machinability of the other materials can be compared.

5.1. Ideal performance curve

For multi-point cutting tools a performance curve of the type shown in Fig. 2 would be expected. It features three distinct regions:

TABLE I Material specification (%) and Vickers hardness (H_V)

Material	Ni	Cr	Mn	Al	Ti	Cu	Co	Mo	Nb	H_v
Cupro 107	30.0	–	1.1	–	–	68.0	–	–	–	126
Inconel 600L	76.0	15.5	–	–	–	–	–	–	–	146
Nimonic PK31	53.0	20.0	–	0.4	2.4	–	14.0	4.5	5.0	340

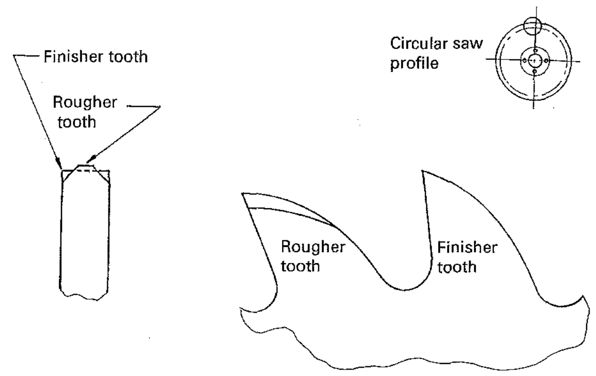

Figure 1. Circular saw geometry and tooth profile.

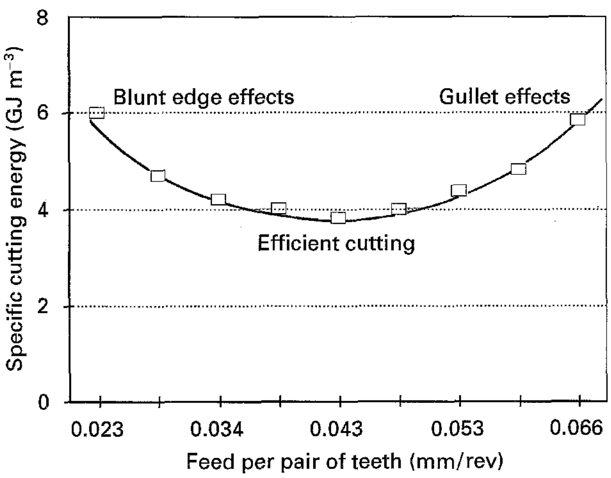

Figure 2 Idealized performance curve.

Towards the left-hand side where the depth of cut is low, cutting efficiency is also low (reflected by high Esp values). Inefficient cutting conditions are attributed to the relatively large cutting edge radius compared to the depth of cut. This effectively gives the tool a negative rake angle.

In the central region, efficient cutting occurs since the depth of cut is greater than the cutting edge radius.

Towards the right-hand end of the curve, at large depths of cut, cutting efficiency decreases due to the gullet becoming unable to accommodate the relatively large volume of material removed. Energy is used to deform the chip within the gullet and difficulties are experienced when trying to eject the chip debris.

Improvements in cutting performance are implied by a reduction in specific cutting energy per unit volume of material removed.

5.2. Analysis of results

Performance tests that related specific cutting energy (Esp) to feed per pair of teeth were established over a range of cutting speeds. Summary performance graphs were formulated to allow direct comparisons between cutting speeds per material.

Cutting tests machining Cupro 107 workpieces were carried out at speeds between 10 and 20 $m\,min^{-1}$ in 5 $m\,min^{-1}$ increments. For each speed the feed rate was varied between 0.023 and 0.066 mm/rev.

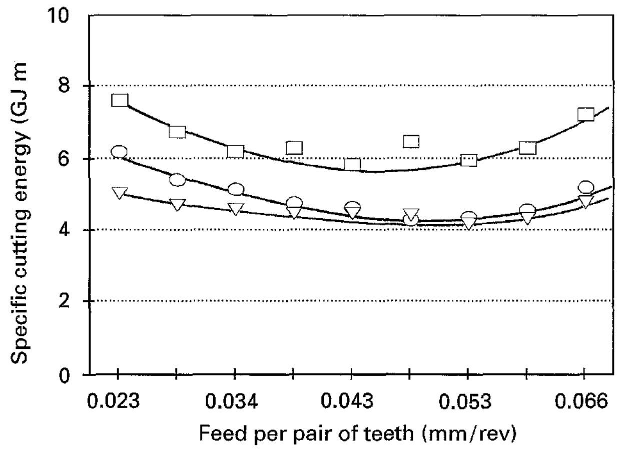

Figure 3 Performance curve summary: Cupro 107 tests. □ 10 $m\,min^{-1}$; ○ 15 $m\,min^{-1}$; ▽ 20 $m\,min^{-1}$.

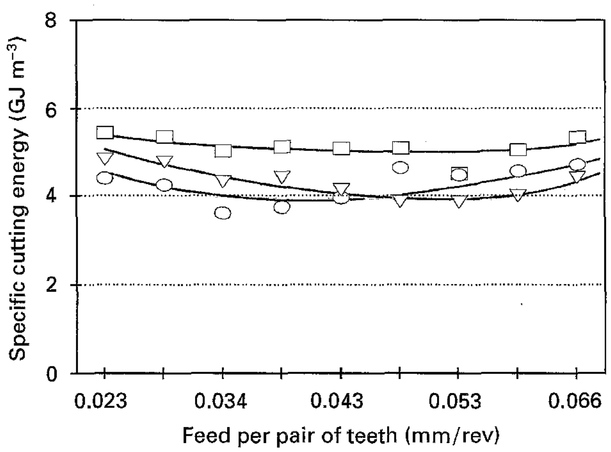

Figure 4 Performance curve summary: Inconel 600L tests. □ 10 $m\,min^{-1}$; ○ 15 $m\,min^{-1}$; ▽ 20 $m\,min^{-1}$.

A summary of the performance curves are given in Fig. 3. Optimized cutting conditions correspond to a feed rate of 0.048 mm/rev at a cutting speed of 15 $m\,min^{-1}$.

Cutting tests machining Inconel 600L workpieces were undertaken over the same range of cutting speeds and feeds. A summary of the performance curves are given in Fig. 4. Optimized cutting conditions correspond to a feed rate of 0.052 mm/rev at a cutting speed of 20 $m\,min^{-1}$.

Cutting tests machining Nimonic PK31 workpieces were undertaken at cutting speeds of 4.5, 6 and 8 $m\,min^{-1}$. At each speed the feed rate varied between 0.023 and 0.059 mm/rev. A summary of the performance curves are given in Fig. 5. Optimized cutting conditions correspond to a feed rate of 0.054 mm/rev at a cutting speed of 6 $m\,min^{-1}$.

Each performance curve resembles the general shape of the ideal performance curve at low and moderate depths of cut. At large depths of cut there is evidence of the onset of detrimental gullet effects at some cutting speeds.

A summary of the optimized performance curve for each nickel based alloy and mild steel are given in Fig. 6. The graph shows a large variation between the position of the curves, indicating the relatively poor machinability of nickel based alloys, particularly

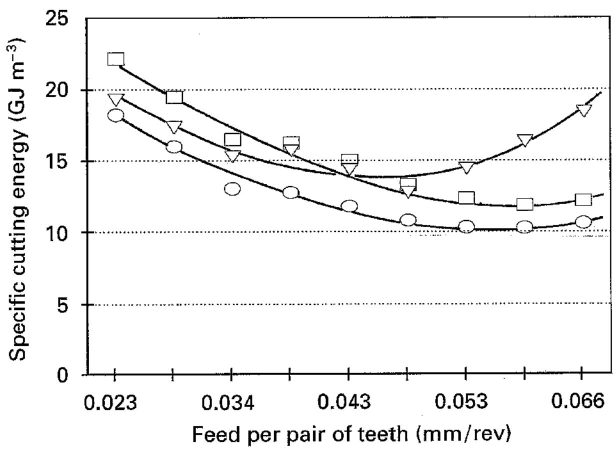

Figure 5 Performance curve summary: Nimonic PK31 tests. □ 4.5 m min^{-1}; ○ 6 m min^{-1}; ▽ 8 m min^{-1}.

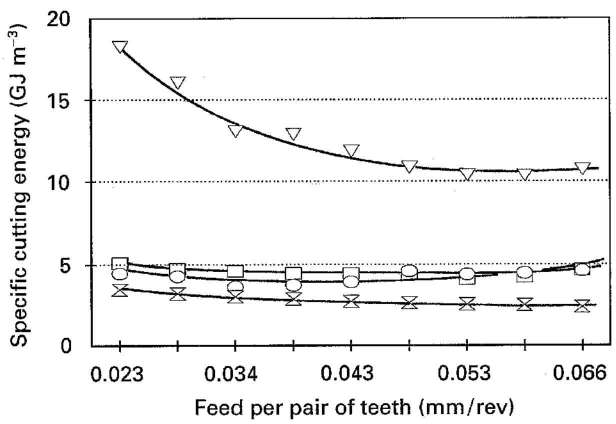

Figure 6 Summary of optimized performance curves. □ Cupro 107 (20 m min^{-1}); ○ Inconel 600L (15 m min^{-1}); ▽ Nimonic PK31 (6 m min^{-1}); ⧗ mild steel En3b (33 m min^{-1}).

Nimonic PK31. The poor machinability of these alloys is reflected when considering the wear mechanisms [5].

6. Conclusions

Tests developed by the authors have been shown to be successful in replicating the performance and wear characteristics of multi-point cutting tools [1] and useful in assessing the suitability of a cutting off process for a given application. From the current investigation, the following conclusions can be drawn:

1. As a test material, nickel based alloys are suitable for investigation using the developed simulation techniques.
2. Optimum cutting speeds and feeds derived from the tests are consistent to those recommended for machining nickel based alloys [2].
3. The machinability bases of nickel based alloys are both variable and relatively poor.
4. Optimized feed and speed values are consistent with those available from general engineering data.
5. High speed steel circular saw blades are not suitable for machining certain types of nimonic nickel based alloys due to the high temperatures generated and rapid rates of wear.
6. Diffusion wear and plastic deformation of the tool result from the extremely high localized temperatures generated [5].

Acknowledgements

The authors wish to express their thanks to members of the following organizations for their financial support and providing samples and materials: Material Research Institute, Sheffield Hallam University; Department of Mechanical and Process Engineering, University of Sheffield; Department of Mechanical Engineering and Manufacturing Systems, University of Northumbria at Newcastle; EPSRC; James Neill plc, Sheffield; Inco Alloys International Ltd, Hereford.

References

1. M. SARWAR, M. P. KEENAN and S. R. BRADBURY, in Proceedings of the International Conference on Advanced Materials Processing Technology, Dublin, (Aug 1993) p. 1939.
2. P. W. BREITZIG, " Materials handbook", 9th Edition, Vol 16 (ASM Int) (Metals Park, Ohio, March 1989) p. 835.
3. N. RICHARDS and D. ASPINWALL, *Int. J. Mach. Tool Manuf.* **29** (1989) 575.
4. G. BOOTHROYD, "Fundamentals of metal machining" (Edward Arnold, London, 1965) p. 18.
5. S. R. BRADBURY, D. B. LEWIS and M. SARWAR, in 10th Irish Materials Forum, Coleraine (Sept. 1994).

Received 8 December 1995
and accepted 13 February 1996