World Academy of Science, Engineering and Technology
International Journal of Materials and Metallurgical Engineering
Vol:11, No:4, 2017

Process Optimisation for Internal Cylindrical Rough Turning of Nickel Alloy 625 Weld Overlay

Lydia Chan, Islam Shyha, Dale Dreyer, John Hamilton, Phil Hackney

Open Science Index, Materials and Metallurgical Engineering Vol:11, No:4, 2017 publications.waset.org/10006829.pdf

***Abstract*—**Nickel-based superalloys are generally known to be difficult to cut due to their strength, low thermal conductivity, and high work hardening tendency. Superalloy such as alloy 625 is often used in the oil and gas industry as a surfacing material to provide wear and corrosion resistance to components. The material is typically applied onto a metallic substrate through weld overlay cladding, an arc welding technique. Cladded surfaces are always rugged and carry a tough skin; this creates further difficulties to the machining process. The present work utilised design of experiment to optimise the internal cylindrical rough turning for weld overlay surfaces. An L27 orthogonal array was used to assess effects of the four selected key process variables: cutting insert, depth of cut, feed rate, and cutting speed. The optimal cutting conditions were determined based on productivity and the level of tool wear.

***Keywords*—**Cylindrical turning, nickel superalloy, turning of overlay, weld overlay.

I. INTRODUCTION

THERE has always been a growing demand in the oil and gas industry for components with longer life and ability to withstand more extreme servicing conditions. From material selection to manufacturing methods, each process has to be considered to achieve such goals.

Since not all surfaces of an oil and gas component, such as valve, end terminal, and pipe, need to endure high acidity and abrasive environment, it is more cost effective to manufacture those selected areas, internal bore in most cases, with superalloy and the rest with steel. Weld overlay cladding (WOC) is employed to perform such task. This is a surfacing technique, whereby multiple runs of superalloy are laid upon each other through arc welding to create a new surface layer [1]. Cladded surfaces require post-process machining in most cases; it is necessary for achieving dimensional, geometrical, and surface finish requirements.

There are major differences between machining clad surfaces and wrought or cast materials:

1) The cladding process introduces severe unevenness to the surface due to the solidification of material; this causes heavily interrupted cuts and varying depths of cut throughout machining.
2) Hardness of the top layer of the clad surface is high due to rapid cooling during the cladding process as it is directly exposed to ambient atmosphere.

References [2], [3] are two of the few publications that addressed the difficulties of turning externally clad surfaces. When it comes to turning internally cladding surfaces, further complications arise. The external turning tool is typically short, rigid, and firmly clamped. In contrast, internal turning requires a boring bar which is long and hence subject to deflection [4]. The resulting surface can be non-uniform because of boring bar vibration. There have been very few researchers investigating internal turning process or parameters optimisation experimentally; most would be focused on modelling or designing boring bars with the aim to minimise vibration.

Material selection is key to product design. Alloy 625, a nickel-based superalloy, is widely used on subsea components because of its excellent wear, corrosion and oxidation resistance, and its ability to service under high temperatures while maintaining strength and has low thermal conductivity. This type of superalloy is known to be difficult to machine as it is highly ductile and prone to work hardening. It also contains hard abrasive carbide particles which shorten tool life dramatically [5], [6]. Because of the above characteristics, Alloy 625 has very low machinability.

Despite being a fairly common superalloy, Alloy 625 research is not as widely publicised in comparison with the more well-known Alloy 718, an aerospace material. Some comparison can be drawn between the two alloys in terms of machinability, but it is hard to apply conditions directly without further investigation [7].

Further difficulties arise when Alloy 625 is used as a clad material in comparison to non-superalloy clads. Dilution with the substrate during the cladding process causes a change in chemical composition which produces a higher surface hardness. Moreover, Alloy 625 work hardens very easily. Therefore, it is important to select tool with tough coating and suitable cutting conditions to achieve the desired surface finish [8].

Some recent literatures are available with regards to machining wrought Alloy 625, for example in [9]-[11], but there is very little published research on Alloy 625 clad. Though the findings can only be applied to finish machining clad surfaces, the similar methodology and techniques can be used for optimising the roughing process. The present work demonstrates a systematic approach of employing design of experiments to identify the optimal rough turning conditions for Alloy 625 cladded internal bore to maximise productivity

L. Chan was with the Department of Mechanical and Construction Engineering, Northumbria University, Newcastle upon Tyne, UK. She is now with the Renown Group, UK.

I. Shyha is with the Department of Mechanical and Construction Engineering, Northumbria University, Newcastle upon Tyne, NE1 1ST, UK (corresponding author; e-mail: islam.shyha@northumbria.ac.uk).

D. Dreyer and J. Hamilton are from the Renown Group, 23-24 Brindley Road, Washington, NE37 2SF, UK.

P. Hackney is with the Department of Mechanical and Construction Engineering, Northumbria University, Newcastle upon Tyne, UK.

whilst producing an acceptable surface integrity for subsequent finishing cut.

Note: Due to confidentiality agreement, limited data of the research is disclosed.

II. Experimentation

A. Material Preparation

A total of 27 low alloy Cr-Mo steel pipe sections with wall thickness of 25 mm were acquired. Four extra test pieces were prepared later on in the same way for additional tests. All of them were of length, l, and inner diameter, ϕ.

Previous research was carried out by the authors to optimise the cladding procedure [12]. The as-clad surface was significantly improved in terms of reducing the unevenness of the surface. The same procedure was used, and a cladding sequence was designed to ensure that the same amount of Alloy 625 was applied internally within each test piece and that all cladded surfaces were as similar as possible. This was carried out using an automatic tungsten insert gas cladding system.

Once cladded the test pieces were sent for post weld heat treatment. Liquid penetrant inspection was performed afterwards to examine the surface integrity in terms of cracks and porosity. All dimensions including bore diameter, circularity, and cylindricity, and clad thickness were recorded for reference.

B. Process Variables

Four factors were selected as critical process variables which are listed in Table I below.

TABLE I
Process Variables

Variable	Symbol	Unit
Turning insert	I	--
Depth of cut	d	mm
Feed rate	f	mm/rev
Cutting speed	v	m/min

Three levels of each factor were tested. The levels were chosen based on the following criteria:

- Turning inserts from different manufacturers were selected based on cost, quality, and reputation.
- Depths of cut were in the region that would be deep enough to remove the tough uneven layer on the cladded surface and would leave sufficient material for the subsequent finishing machining process, as illustrated in Fig. 1.
- Feed rate and cutting speed were set according to the insert manufacturers' guide.

The main features such as shape, nose radius, and size of the three turning inserts were kept constant. The focus was pointed towards testing the chip breaker and coating performances of each chosen insert at various sets of cutting parameters. The benchmark was established by existing machining settings.

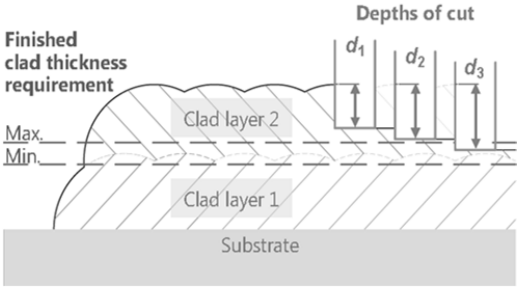

Fig. 1 Determining the levels for depth of cut

C. Experiment Design

For a four-factor three-level experimentation plan, an L27 Taguchi orthogonal array was used. The coded array can be found in Table II.

TABLE II
L27 Orthogonal Array (Coded Levels)

Test	Turning insert	Depth of cut	Feed rate	Speed
M1	$I1$	$d1$	$f1$	$v1$
M2	$I1$	$d1$	$f2$	$v2$
M3	$I1$	$d1$	$f3$	$v3$
M4	$I1$	$d2$	$f1$	$v2$
M5	$I1$	$d2$	$f2$	$v3$
M6	$I1$	$d2$	$f3$	$v1$
M7	$I1$	$d3$	$f1$	$v3$
M8	$I1$	$d3$	$f2$	$v1$
M9	$I1$	$d3$	$f3$	$v2$
M10	$I2$	$d1$	$f1$	$v1$
M11	$I2$	$d1$	$f2$	$v2$
M12	$I2$	$d1$	$f3$	$v3$
M13	$I2$	$d2$	$f1$	$v2$
M14	$I2$	$d2$	$f2$	$v3$
M15	$I2$	$d2$	$f3$	$v1$
M16	$I2$	$d3$	$f1$	$v3$
M17	$I2$	$d3$	$f2$	$v1$
M18	$I2$	$d3$	$f3$	$v2$
M19	$I3$	$d1$	$f1$	$v1$
M20	$I3$	$d1$	$f2$	$v2$
M21	$I3$	$d1$	$f3$	$v3$
M22	$I3$	$d2$	$f1$	$v2$
M23	$I3$	$d2$	$f2$	$v3$
M24	$I3$	$d2$	$f3$	$v1$
M25	$I3$	$d3$	$f1$	$v3$
M26	$I3$	$d3$	$f2$	$v1$
M27	$I3$	$d3$	$f3$	$v2$

D. Key Responses

Two main performance characteristics were selected to be the key responses from the tests:

- Flank wear on turning insert (VB)
- Cutting time (T)

To measure the flank wear on each turning insert, firstly images of the working edge were captured against a scale using a digit microscope. Then, they were analysed using Fiji, an image processing package. Cutting time was calculated using (1) with the corresponding feed rate and speed against the longitudinal length of clad.

$$T = \frac{\pi\phi \times l}{1000 \times f \times v} \tag{1}$$

Other desirable responses include dimensional accuracy, bore uniformity, and surface integrity. These were not critical as they would be addressed at the latter machining stage where the final requirements are achieved.

E. Equipment and Experiment Setup

All experiments were carried out on a Mazak Integrex CNC lathe. A 200 mm long boring bar was used with external coolant. Test piece was aligned and secured in a three-jaw chuck prior to machining as illustrated in Fig. 2. One insert was used per test which made a single continuous cut to the end of the piece. No interruption was permitted unless a catastrophic event happened (e.g. insert breakage).

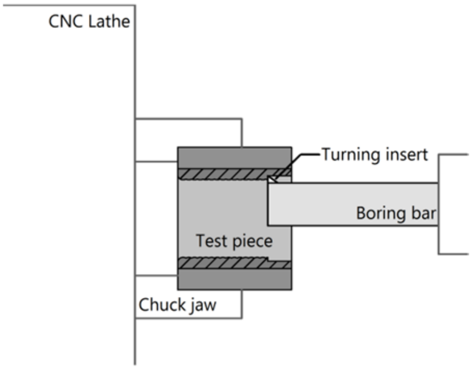

Fig. 2 Schematic diagram of experiment setup

III. RESULTS

Cutting times were calculated for each test and were compared against the existing machining settings. The results were also ranked from fastest to slowest as shown in Table III.

All inserts were then collected afterwards for inspection. An image of each insert was captured, which was shown in Fig. 3. The flank wear was measured digitally using a portable microscope, and comparison was drawn between all tests. All tests were ranked according to the level of wear as shown in Table III.

TABLE III
RANKING OF TEST RESPONSES

Flank Wear	Cutting Time
M1	M3
M10	M12
M8	M21
M19	M5
M22	M14
M13	M23
M4	M9
M17	M18
M2	M27
M15	M2
M21	M11
M3	M20
M5	M7
M12	M16
M14	M25
M23	M4
M9	M6
M18	M13
M11	M15
M20	M22
M25	M24
M6	M8
M27	M17
M7	M26
M16	M1
M24	M10
M26	M19

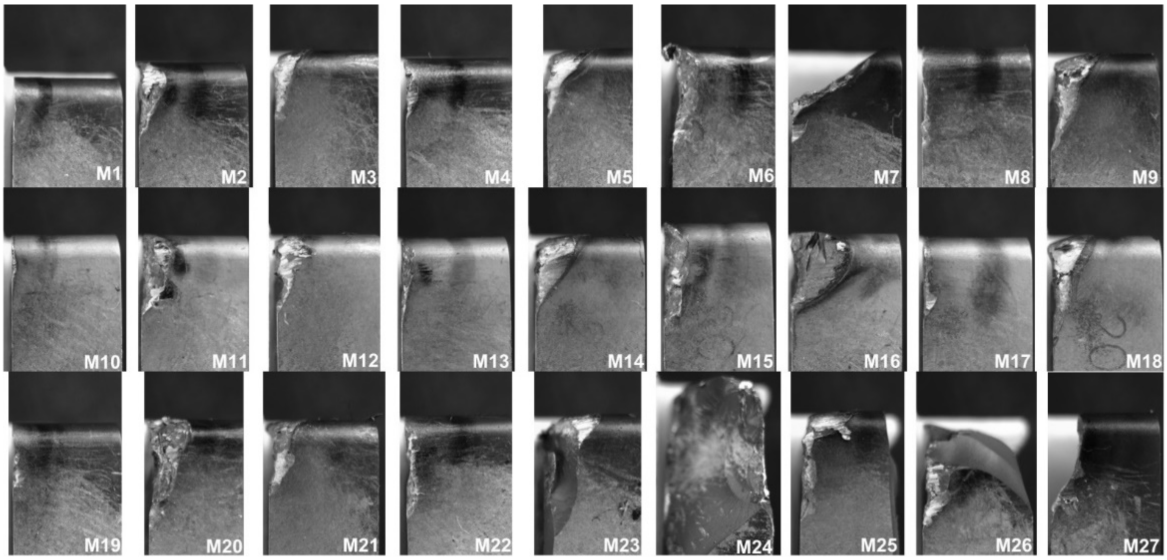

Fig. 3 Flank wear on inserts from test M1 to M27

IV. Discussion

A. Flank Wear

Not all 27 tests were completed successfully due to the limited integrity of the turning inserts which led to fracture or severe edge chipping during some experiments. Among all, five sets (M7, M16, M24, M26, and M27) experienced total failure during the test. The depths of cut from all failed tests were at the highest level, *d*3, apart from M24 which was at *d*2.

There were 11 other tests that were not able to achieve uniformity on the machined surface (from M3 to M6 on Table III). They showed signs of chatter and deflection of the boring bar. Such unevenness could be rectified in the subsequent finish machining process if the clad thickness difference is less than the depth of the finish cut. However, this might add difficulties in achieving final surface roughness as it is not desirable for finish machining inserts to experience varying depths of cut. Most of them exhibited excessive flank wear where the insert significantly exceeded the maximum acceptable level of 1mm during the tests.

The results were imported to Minitab for statistical analysis. A main effect plot was produced to assess the effect of each factor on flank wear. Fig. 3 shows that the depth of cut had the largest effect; feed rate and cutting speed had moderate effect. It also shows that even though features on inserts *I*2 and *I*3 were the same their performance varied dramatically.

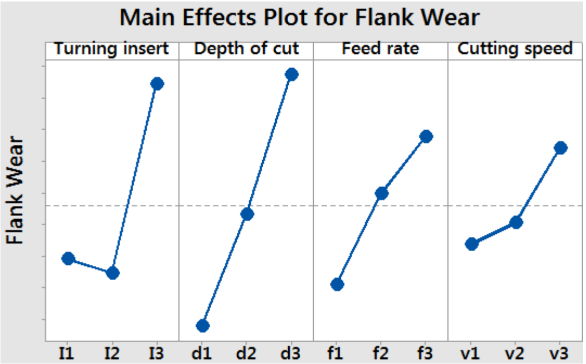

Fig. 3 Main effects plot for flank wear

The optimal machining conditions for the least flank wear were *I*2-*d*1-*f*1-*v*1 according to the above analysis. However, this combination was not ideal for improving productivity as it had one of the slowest cutting times as shown in Table III – around 150% slower than the company's existing settings. Therefore, a compromise had to be made to achieve the best results for both responses.

B. Process Optimisation

The tests that were incomplete or had a poorly machined surface were omitted. The results for flank wear and cutting time from the remaining tests were combined and ranked from the fastest cut with least wear to the slowest with most wear. Results are shown in Table IV.

M21, M2, and M22 resulted in the best cutting time with the least flank wear. Depth of cut, feed rate, and cutting speed used for these three tests were selected for additional tests (A1-A3) using turning insert from the existing settings.

TABLE IV
RANKING OF COMBINED TEST RESPONSES

Flank Wear & Cutting Time
M21
M2
M22
M13
M4
M15
M8
M17
M1
M10
M19

A benchmark test (A4) was also carried out using parameters from the company's existing machining settings. The flank wear on the insert used for this test was measured and compared with inserts used for tests M21, M2, M22, and the respective additional tests A1-A3. A visual contrast can be seen in Fig. 4.

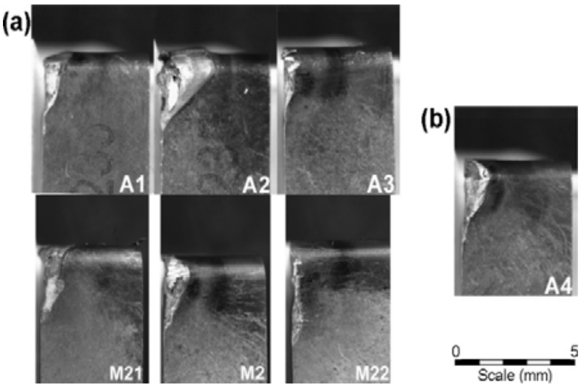

Fig. 4 (a) Flank wear comparison of M21, M2, and M22 against respective additional tests; (b) Flank wear of benchmark test

It was clear that A1 and A3 exhibited better performance than the others and the benchmark on flank wear. Despite having nose wear in addition of flank wear, A1 was still in the acceptable level of 1 mm. The cutting times of tests A1 and A3 were then compared against the benchmark value, and the percentage differences are shown in Table V.

Further examinations were carried out to assess the quality of the machined surfaces. The surface roughness on both A1 and A3 was similar to the benchmark test result. Neither test showed any signs of chatter; the machined surfaces were uniform. Since A1 had the fastest cutting time, it was deemed to be the overall optimal rough turning condition.

TABLE V
CODED LEVELS OF TESTS A1 & A3 AND CUTTING TIME COMPARISON AGAINST BENCHMARK VALUE

Test	Depth of cut	Feed rate	Cutting speed	Percentage difference against benchmark cutting time
A1	*d*1	*f*3	*v*3	-58.33%
A3	*d*2	*f*1	*v*2	+25.92%

Open Science Index, Materials and Metallurgical Engineering Vol:11, No:4, 2017 publications.waset.org/10006829.pdf

V. CONCLUSION

An experiment of 27 tests (M1-M27) was carried out with the aim to optimise the rough turning process of Nickel Alloy 625 weld overlay. L27 Taguchi orthogonal array was employed to seek an improvement in productivity while maintaining machined surface quality. Three levels of depth of cut, feed rate, and cutting speed were tested on three turning inserts from different manufacturers. Flank wear and cutting time were measured and calculated, respectively. Tests were then ranked accordingly. A main effects plot was produced and indicated that the least flank wear was achieved by the lowest level of parameters. However, the cutting time was significantly longer than the original settings.

To achieve a balance between flank wear and cutting time, the two responses were combined and tests were ranked. Parameters from the top three were later tested (A1-A3) with the turning insert used currently at the company. A benchmark test (A4) was also carried out to set as comparison. Even though the flank wear on A1 ($d1$-$f3$-$v3$) was marginally acceptable, the cutting time was reduced by 58%, and there were no major defects on the machined surface. It was therefore considered as the overall optimal rough machining condition.

VI. FUTURE WORK

Further experimentation will be carried out to test the repeatability of the new optimised parameters. As the test pieces were smaller than a typical production part, additional tests will be carried out to assess the scalability of the parameters on a larger bore.

The next step in the investigation will be to optimise the finish machining conditions and also to examine the interactions between the two machining processes.

ACKNOWLEDGMENT

The authors gratefully acknowledge Renown Group for facilitating this project, and funding it along with Innovate UK through the Knowledge Transfer Partnership Scheme. Gratitude also goes to the Department of Mechanical and Construction Engineering at Northumbria University for providing resources.

REFERENCES

[1] J. Davis, “Hardfacing, Weld Cladding, and Dissimilar Metal Joining,” in ASM Handbook Volume 6 - Welding, Brazing, and Soldering, ASM International, 1993, pp. 789-829.

[2] M. Brožek, “Cutting conditions optimization when turning overlays,” Journal of Materials Processing Technology, vol. 168, pp. 488-495, 2005.

[3] M. Brožek, “The turning of overlays using sintered carbide tools,” International Journal of Advanced Manufacturing Technology, vol. 40, pp. 438-446, 2009.

[4] M. Munawar, J. Chen and N. Mufti, “Investifation of cutting parameters effect for minimization of surface roughness in internal turning,” International Journal of Prevision Engineering Manufacturing, vol. 12, no. 1, pp. 121-127, 2011.

[5] E. Ezugwu, Z. Wang and A. Machado, “The machinability of nickel-based alloys: a review,” Journal of Materials Processing Technology, vol. 86, pp. 1-16, 1999.

[6] Nickel Development Institute, Machining Nickel Alloys, 1992.

[7] S. Turner, M. Taylor, A. Etxeberria and P. Arrazola, “Machinability of the Nickel Alloys Inconel 625 and 718,” in 23rd AeroMat Conference and Exposition, Charlotte, NC, 2012.

[8] J. Petrů, T. Zlámal, R. Čep, M. Pagáč and M. Grepl, “Influence of strengthening effect on machinability of the welded Inconel 625 and of the wrought Inconel 625,” in 6th International Multi-Conference on Engineering and Technological Innovation, Orlando, FL, 2013.

[9] P. Matimuthu and R. Baskaran, “Optimal setting of machining parameters for turning Inconel 625 using coated tool,” Applied Mechanics and Materials, vol. 573, pp. 632-637, 2014.

[10] A. Altin, “Machining of Nickel based super alloy based on the Taguchi Method,” in 24th International Conference on Metallurgy and Materials, Brno, 2015.

[11] H. Jain, J. Tripathi, R. Bharilya, S. Jain and A. Kumar, “Optimisation and evaluation of machining parameters for turning operation of Inconel 625,” Materials Today: Proceedings 2, pp. 2306-2313, 2015.

[12] L. Chan, S. Shyha, D. Dreyer and J. Hamilton, “Optimisation of weld overlay cladding parameters using full-factorial design of experiment,” Materials Science Forum, vol. 880, pp. 54-58, 2017.