Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 100 (2015) 1424 – 1433

Procedia Engineering

www.elsevier.com/locate/procedia

25th DAAAM International Symposium on Intelligent Manufacturing and Automation, DAAAM 2014

Increasing Cutting Tool Efficiency When Machining Regulatory Spindles Made from Ion Nitrided Nimonic 901 for Steam Turbine Valves

Radek Sykora*, Miroslav Zetek*

Faculty of Mechanical Engineering, University of West Bohemia Pilsen, Univerzitni 8, Pislen 306 14, Czech Republic

Abstract

This article deals with issues during production of nimonic spindles used for controlling the volume of steam in the valves of steam turbines. With more extreme operating conditions in the power plant block with ultra-super-critical parameters of steam, the production of a conventional steel spindle is not suitable. This article describes machining technology for nickel alloy Nimonic 901. Ceramic or carbide cutting tools were used for the machining process. The text deals with progress of tool wear of the cutting edge. It describes the machining process to reduce tool wear during cutting. The second part of the report describes the process of ion nitriding nimonic spindles. The main aim was to get the best sliding properties on the surface of the spindle. The experiments confirmed the correctness of the solution. After nitriding several tests were performed, for example progress of microhardness of the nitrided layer and analysis of track wear after pin on disc test.

Peer-review under responsibility of DAAAM International Vienna

Keywords: Nimonic 901; HRSA machining; plasma nitriding; Pin on disc

Introduction

This research report deals with issues of producing nitrided nimonic regular spindles used for controlling volume of steam in valves of industrial steam turbines. The modern trend and a key objective of the company Skoda Power

* Corresponding author. Tel.: +420 377 638 520; fax: +420 377 638 501.
E-mail address: radek.sykora@doosan.com

Peer-review under responsibility of DAAAM International Vienna
doi:10.1016/j.proeng.2015.01.512

Doosan is to increase the efficiency of the steam turbine cycle. This can be achieved by increasing the pressure or increasing the inlet temperature of the steam cycle. In the case of increasing inlet temperature steam at a power station which works with USC (ultra super critical) steam parameters, superheated steam temperatures over 540 ° C and pressures of 25-36 MPa are used. The use of steel spindles in valves for steam turbines which work with higher operating conditions at USC power plants, are not suitable due to their short life. Our solution is the use of more advanced materials for the production of spindles. Suitable candidates are nickel-based alloys, which are characterized by high strength and oxidation resistance at high temperatures and excellent creep properties. Our selected material for spindles is Nimonic 901.[9] Next information about machining Nimonic 901 is presented in [1,7]. Information about machining HRSA materials is presented in [13,15].

The valve is a pressure regulating device. Its function is to regulate and transmit the required amount of steam to the turbine. The steam passes between the cone of the spindle and the diffuser, which are mutually shape resurfaced. Contact surfaces of the control elements are materials based on cobalt alloys against nickel alloys.[11]

1. Turning spindles made of Nimonic 901

Machining of HRSA (heat resistant super alloy) materials is an important area for research into new technologies. The increasing application of these materials requires knowledge of machining technology with respect to the lowest cost of production. Inconel materials are poorly machinable materials for several reasons. They have a low coefficient of thermal conductivity (about 5 times smaller than carbon steel) because they are heat-resistant. Hence most of the heat comes into the tool and the surroundings in the form of chips (about 80%). A typical characteristic of nickel alloys is cold hardening. This causes surface hardening of the cutting tool, making removing layers more difficult, leading to reduction in tool life. For better machinability it is necessary to select appropriate cutting conditions for machining Nimonic so that machining is carried out in the heated state. This increases the thermal conductivity of the workpiece and better chip removal.[8,10,]

Machining HRSA materials is carried out usually in three phases according to the tool used, cutting conditions, durability and accuracy machining. [2,3,4]

1.1. Phase 1 - Machining rough reinforced surface of forging

After delivery of forging to production the reinforced and hard surface must be removed. A rough surface causes crust shocks during machining. It is undesirable to use a ceramic cutting edge. A ceramic cutting edge is brittle. Vibrations during machining cause the destruction of the cutting edge. A preferable option is to use a sintered carbide cutting edge. This is a better solution for machining due to its higher toughness. The sintered carbide edge is more resistant to impact during machining rough surfaces. From experience, it is better, if possible, to limit the number of input cuts into a hard crust. Vibrations and shocks cause formation of a notch on the tool. This is undesirable. Other input cuts should be chosen for already machined surfaces. [4]

1.2. Phase 2 - Roughing material

Roughing is necessary to remove the greatest amount of material to approach most closely the final shape of the part. Due to the removal of a large amount of material it is economically and time suitable to use a circular ceramic cutting edge. Because of its hardness and heat resistance up to 4x faster cutting speed (up to 200 m/min) should be selected, making the cutting process faster and more productive. The circular shape and a negative geometry increase cutting resistance, which means the workpiece is heated and better machined. Furthermore, its strength is increased, ensuring economy due to the number of cutting edges. A disadvantage is the increased hardening of the machined material at the tool cutting edge. Therefore roughing is recommended with different cutting depths. There is a decrease of notch wear influencing the changing point of contact between the cutting edge and workpiece material. The change of the contact point can be limited by roughing with different depths of cut or roughing under a cone (ramping). [4]

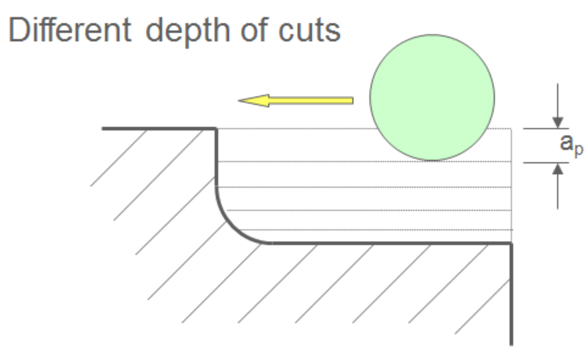

Fig. 1. Roughing with different depth of cuts [4].

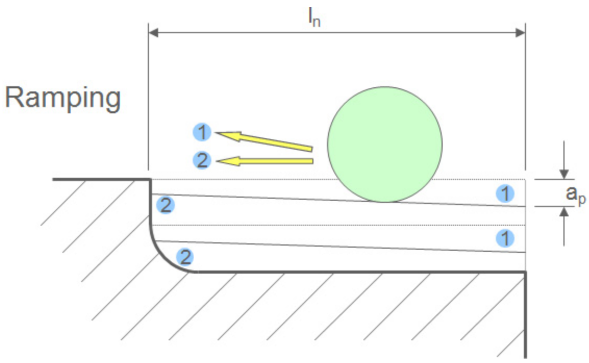

Fig. 2. Roughing with ramping [4].

Optimal difference in depths of cut or ramping should be between 15-25% of the circular cutting edge, or the depth of the chips kept at a cutting angle of 45-60 °. Tool life can be increased with radius entrances and exits of the cut, which also changes the point of contact between the cutting edge and workpiece. [4]

1.3. Phase 3 - Finish Machining

This is the last and technologically most demanding machining phase. The desired surface integrity and accuracy of the part is achieved here. Carbide cutting edges with positive geometry are used for the finishing operations. They are more reliable in terms of surface integrity. The sharp edge reduces the introduction of residual stresses on the final surface. Faster, but cost-expensive option for finishing is to use the cutting edge of CBN (cubic boron nitride). Cutting speed is chosen to 7 times higher than that of the sintered carbide edge. It is used a low feed. The achieved roughness parameters Ra, are about 0.4µm. [4]

2. Cutting tools used for nimonic machining

Tools for machining nickel alloys are mainly sintered carbide classes M and S, and ceramics. Due to the low thermal conductivity of nimonic (approximately 5 times less than for carbon steels), more heat is transferred to the tool which can cause plastic and abrasive degradation of the cutting edge. Therefore, in the case of edges of sintered carbide, positive geometry and lower cutting speeds (around 40 - 50 m / min) are used for machining the spindle. Ceramics are thermally and chemically resistant. Cutting speed is selected 4 times higher than for SK (in our case about 160 - 200 m / min). Due to higher cutting speeds, the workpiece is heated and it is more easily machined. For increased durability of the ceramic cutting edge, cooling is used. This can be used but only with constant cutting during turning.

3. Experiment - the ability to machine the required accuracy

The experiment was conducted in Doosan Skoda Power, based in Pilsen (Czech Republic). The aim was to determine the appropriate cutting conditions for machining a spindle from the alloy Nimonic 901. Due to time conditions it was not necessary to achieve optimal cutting conditions, but to find a workable and reliable machining technology to fulfil the technical and economic requirements. The optimal cutting condition is the subject of further research.

3.1. Cutting tools

For turning spindles (larger areas), these cutting edges were used.
Rough sintered carbide plate CNMG

Rough ceramic plate RNGN
Rough sintered carbide plate DNMG
Finish sintered carbide plate DNMG

3.2. Workpiece

The experiment was conducted on the heat treatment of the forging Ø 52-1015 mm, made of alloy Nimonic 901. Cutting tools were programmed with circular entry. Cutting conditions were set in terms of time and accuracy for one tool track (approximately 24 minutes).

3.3. Cutting conditions

Initial cutting conditions were chosen according to the tool manufacturer with respect to the workpiece. For carbide edge vc = 40-50m/min. For ceramic edge vc = 160-200m/min.

3.4. Results

Important output values were radial runout of spindles, roughness and dimensional accuracy. Values of radial runout on the test spindle ranged from 0.01 to 0.05 mm / 1000 mm before grinding. After grinding the value of 0.01 mm / 1000 mm was achieved. Roughness measured after machining was from Ra 1.63 µm to 1.83 µm. After grinding roughness was Ra 0.11 µm. Machined part after the capillary test was evaluated without defects. Table 1 shows average values achieved in the radial runout during active production of the first series of spindles. The values may be distorted by less precise spindles, and must be recalculated to average values.

Table. 1 Average value of radian eccentric running.

Radial runout [mm]							
forging	1st roughing	annealing	2nd roughing	annealing	finishing	grinding	ion nitriding
0.37	0.5	0.53	0.35	0.51	0.15	0.02	0.03

Figures 3,4,5 show wear of cutting edge after machining. Although for roughing nimonic the preferred option is a circular ceramic cutting edge, in our case, a long piece with small diameter, we could not dampen the vibration of the M-T-W system (machine-tool-workpiece). The resulting vibration led to the destruction of the ceramic. Therefore, we used sintered carbide edges for roughing. Figure 3 shows wear of rake and flank face of carbide cutting tools after roughing. Figure 4 shows wear of rake and flank face of carbide cutting tools after semi-finishing. Wear of sintered carbide edge after finishing is shown in Figure 5.

Fig. 3. Wear on rake face and flank face of carbide cutting tools after roughing.

Fig. 4. Wear on rake face and flank face of carbide cutting tools after semi finishing.

Fig. 5. Wear on rake face and flank face of carbide cutting tools after finishing.

4. Ion nitriding spindles made of Nimonic 901

Component life is related directly to wear on the surface, with corrosive effects and the occurrence of fatigue cracks. These affect the surface of the part and therefore it is necessary to influence the properties only in this area. Diffusion processes consist of saturating the surface with other substances. The result is a change in the structure, mechanical properties and chemical composition of the surface layer. The advantage is the homogeneity of the resulting layers and good adhesion to the basic material. [5] The spindles are moving parts functioning as regulators of steam flow or as fast-closing spindles in valves. Due to seizure and sticking of spindles in the valves there are high demands made on the accuracy and production requirements of the spindle surface. For higher friction properties, nitriding is carried out on parts of the spindle guides. This is a chemical-thermal treatment of the surface, enrichment by nitride-creating alloying elements such as chromium, nickel, vanadium, molybdenum or aluminium, which produce hard nitrides. Nitriding consists in saturating the surface with atomic nitrogen, at temperatures of about 400-600 ° C for up to 100 hours of nitriding. The process is very long with large energy consumption and is relatively expensive. After nitriding there is no need for further heat treatment. Due to low iron content in Nimonic 901 nitriding penetrates only several hundredths of mms.

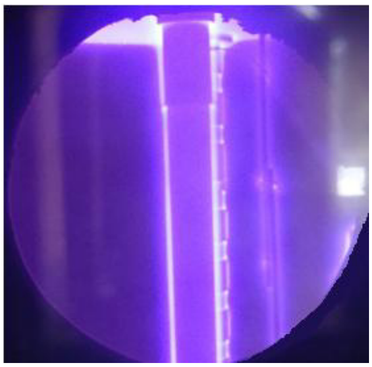

Fig. 6. Shining corona surrounding the spindle during ion nitriding.

5. Principle of nitriding

Nitriding in glow discharge, or plasma or ion nitriding, as with other nitriding depends on the presence of atomic nitrogen at the surface of the metal. At elevated temperatures nitriding is able to penetrate into the lattice of the base metal through the absorption layer of nitride and further diffuse into the material.
The nitrided components are placed in isolation in a vacuum vessel (the recipient) and connected as a cathode. The recipient is connected as the anode. In the recipient, there is maintained at low pressure a mix of diluted gases, mostly (N2 + H2), which is required for the nitriding process.
By connecting a direct current (voltage of 400 to 1,000 V), an electric field arises between the walls of the recipient (anode) and the surface of the part (the cathode). The values of voltage, current and pressure must be adjusted to fit the area of anomalous discharge. Current action will start a bluish-purple luminous discharge with high ionization (plasma) that uniformly covers the nitrided surface of the component. Atomic nitrogen is released on the surface by bombardment with ions, which is necessary for diffusion into the surface of the part. In the electric field there is a strong migration of molecules of diluted gas due to impacts from cleavage and ionization, when positive ions are accelerated towards the cathode, i.e. to the surface of the nitrided components. When ions move to the cathode kinetic energy is not linear. The speed sharply increases only in the immediate vicinity of the surface part of the cathode. ~~It occurs in a voltage drop~~. This results in the greatest intensity of anomalous phenomena of glow discharge taking place in a narrow band around the surface of the component, regardless of the shape or distance from the wall of the recipient - anode. Especially in this band there is a breakdown of molecules and ionization of atoms and therefore the anomalous discharge has a surface character and the glowing corona follows the surface of the part [5,6]. More information about nitriding kinetics of Inconel is presented in [14].

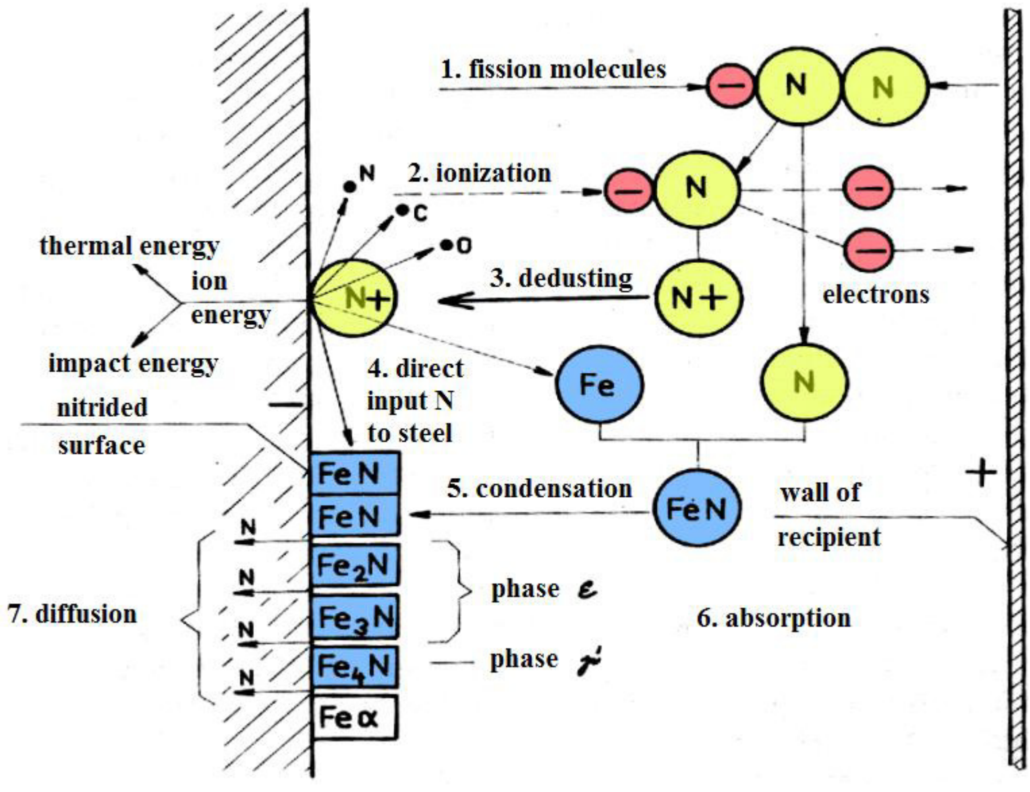

Fig. 7. Diagram of processes during ion nitriding [6].

6. Experiment - microhardness of the nitrided layer

Comtes FHT received samples to determine the microhardness and measure the depth of nitriding. From previous experience, a load of HV 0.05 was selected for measure microhardness.

6.1. Material of samples

For the experiment samples of the residual material previously machined Nimonic 901 were used. Samples were nitrided together with the charge spindles.

6.2. Results

Two samples were collected which were subjected to investigation of the microhardness of the nitrided layer. Microscopic measurement of thickness was determined as 26.9 µm and 35.1 µm. A nitrided layer was observed across the entire section. The measured hardness values with regard to the depth of the nitrided surface of the sample are shown in Fig. 8. The red line shows measured thickness of the nitrided layer.

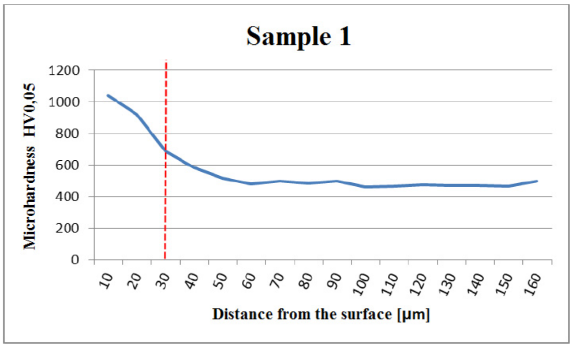

Fig. 8. Microhardness HV 0.05 on sample 1.

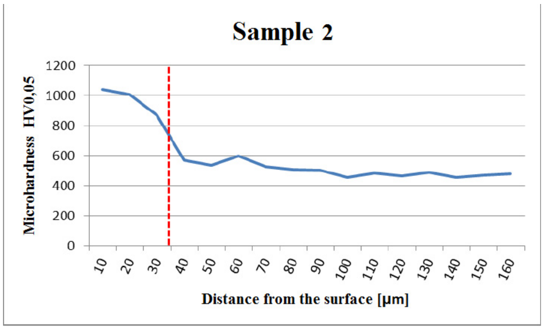

Fig. 9. Microhardness HV 0.05 on the sample 2.

7. Experiment - Analysis of wear after pin-on-disc test

A series of samples with different surface finishes was delivered to Comtes FHT. Pin-on-disc tests were performed to analyse wear. The aim of the tests was to obtain a suitable surface treatment for our case, the material of the disc (spindle) - tip material (case).

7.1. Measuring Equipment

Traces of wear were documented using an optical microscope NIKON EPIPHOT 200. The detailed images were taken on a Jeol 6280 scanning electron microscope.

7.2. Samples

Table 2. Samples.

Disc material A1 vs. Pin material A	Disc material B1 vs. Pin material C
Disc material B1 vs. Pin material A	Disc material D vs. Pin material A
Disc material A1 vs. Pin material C	Disc material C vs. Pin material A

7.3. Results

Pin-on-disk test was carried out on the samples with different surface treatment. Traces of wear after the test were subjected to analysis on an optical microscope and a scanning electron microscope. Summary of results in the wear volume × 10^6 μm3 shows all tested variants samples for load 3N. Values are indicated in column values in Fig. 13. Hardness values of individual samples were recorded during analysis. These hardness values HV of individual materials are shown to the right of the column values. Comparison of results of frictional properties with contact force 3N are shown in Fig. 14. Images of the optical and scanning electron microscopy variants (Disc material C vs. Pin material A) are shown in Figures ,10 and 11. There is significant wear and material transfer from tip to the base material. Significant amounts of cobalt were detected on the base material.

7.4. Analysis of variant (Disk material C vs. Pin material A)

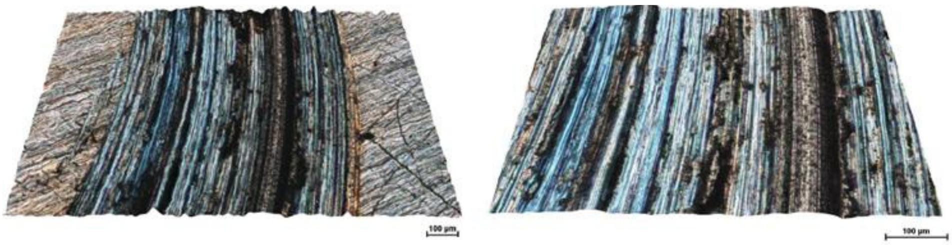

Fig. 10. Optical microscope, scar 10 mm, 50x and 100x.

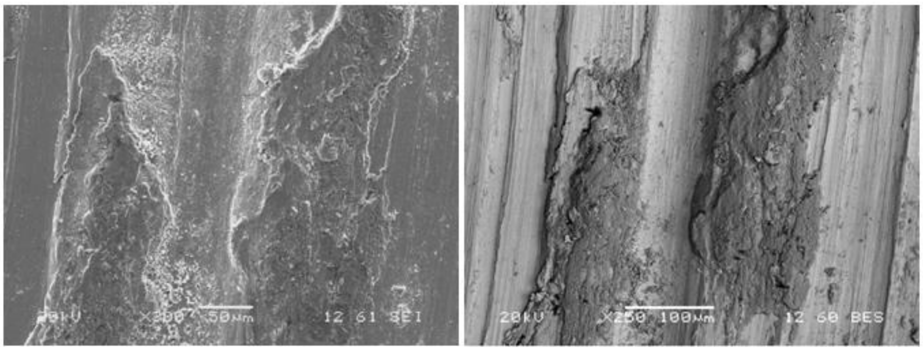

Fig. 11. Scanning electron microscope, scar 10 mm, 300x, SEM in mode SEI and 250x, SEM in mode BES.

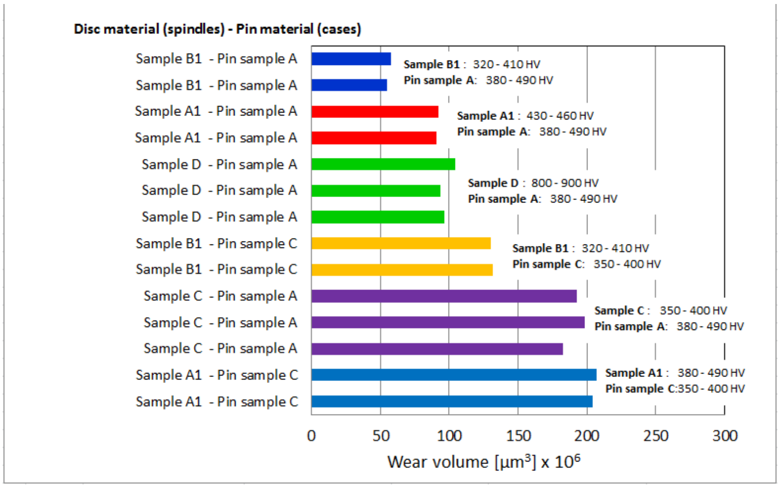

Fig. 12. Comparison of results of wear volume with load 3N.[12]

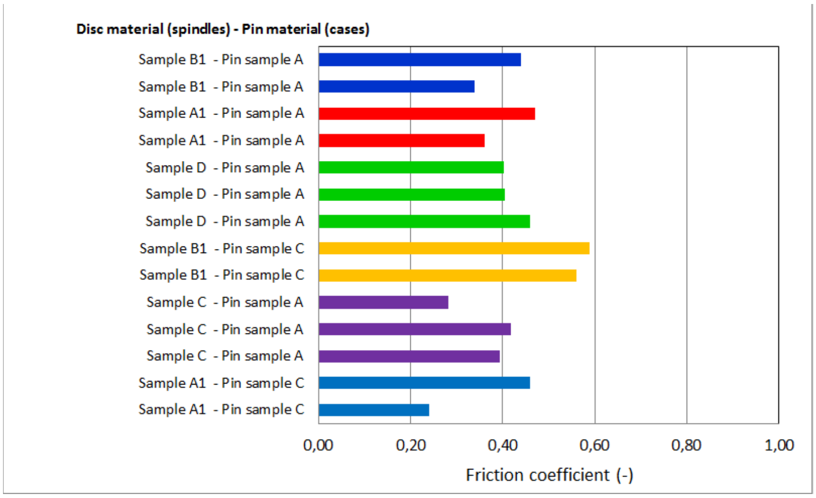

Fig. 13. Comparison of results of friction coefficient with load 3N.[12]

Conclusion and recommendations

The experimental results show that machining a spindle with the required quality is reliably possible, as shown by the values of radial runout after each operation. After nitriding an average radial runout of 0.03 mm is achieved. The permissible value after consultation with designers is 0.05 mm. The achieved roughness values are satisfactory. If the M-T-W system is able to dampen vibration, it is possible to deploy a more productive ceramic cutting edge. Sintered carbide is suitable for machining Nimonic 901 to the required criteria. However, VBD consumption is quite high. The results of the pin-on-disc text confirmed the increased useful properties of nitrided NIMONIC. Comparison with other alternative variants of surface treatment shows that our preferred variant is one of the best options. From the microhardness of the nitrided layer it is apparent that the depth of the nitrided layer is in the range of 25-35 μm. The relatively thin nitrided layer is caused by a smaller number of nitride-creative elements. The nitrided layer is relatively thicker for steel. Microhardness of the nitriding layer varies from 700 to 1050 HV. Prerequisite increase frictional properties of the surface of the spindle in place of the cases were confirmed by experiments. This should have a major impact on increasing durability in the future that will prevent galling mainly fast-closing spindles, thus increasing durability.

Acknowledgments

The authors would like to express their gratitude to University of West Bohemia and to the company Doosan Skoda Power for providing the machines and laboratory facilities. The research was supported by Project SGS-2013-031.

References

[1] Davim, J. Paulo. Machining of Hard Materials. Berlin, Germany, 2011. Springer. ISBN 978-1-84996-449-4.
[2] Special Metals Corporation. Machining [Online]. [Citation: 3. 12 2013]. Available from http://www.specialmetals.com/documents/machining.pdf
[3] Davis, J. R. Heat-resistant Materials, ASM Specialty Handbook, 1997, USA, ASM International, ISBN 0-87170-596-6
[4] AB Sandvik Coromant. Application Guide HRSA, Sandviken, 2010, Sweden. Printed Sandvikens Tryckeri.
[5] Alois Homelar, Vojtech Hruby. Ion nitriding in practice. Praha, 1989. Publishing SNTL. ISBN 80-03-00001-7.
[6] Karel Danourek, Selected technologies of surface modification – Prezentation Anomalous glow discharge, [Online] 2006 [Citation: 5.12.2013]. Available from http://www.kmt.tul.cz/edu/podklady_kmt_magistri/VTM/vtm%20Dad/10doutvyb.pdf
[7] Geddes Blaine, Leon Hugo, Huang Xiao. Superalloys: Alloying and Performance. Ohio, USA, 2010. ASM International. ISBN 978-1-61503-040-8.
[8] Narovec, Josef. Influence of the cutting tool geometry on power stress when machining superalloy Nimonic 80A. Pilsen, 2012. Diploma Thesis. University of Wet Bohemia in Pilsen, Faculty of Mechanical Engineering, Department Machining Technology.
[9] Glusa, Tomas. Research of structure and properties of welded joints for turbines with ultra super critical steam parameters. Pilsen 2012. Diploma Thesis. University of Wet Bohemia in Pilsen, Faculty of Mechanical Engineering, Department Materials and Materials Engineering.
[10] Trepka, Vaclav. Rationalization turning the rotary parts of hardmachining materials. Pilsen, 2010. Diploma Thesis. University of Wet Bohemia in Pilsen, Faculty of Mechanical Engineering, Department Machining Technology.
[11] Google books. Nickel, Cobalt, and Their Alloys – Joseph R. Davis. [Online] 2014. [Citation: 10.12.2013]. Available from http://books.google.cz/books?id=IePhmnbmRWkC&pg=PA71&dq=inconel+263&hl= cs&sa=X&ei=wOTcUfGFI4PetAbV2oGoBA&ved=0CDoQ6AEwAA#v=onepage&q=inconel%20263&f=false
[12] Internal documents of company Doosan Skoda Power
[13] K. Kadirgama, K.A. Abou-El-Hossein, M.M. Noor, K.V. Sharma, B. Mohammad, Tool life and wear mechanism when machining Hastelloy C-22HS, Wear, Volume 270, Issues 3–4, 12 January 2011, Pages 258-268, ISSN 0043-1648
[14] C. Sudha, R. Anand, V. Thomas Paul, S. Saroja, M. Vijayalakshmi, Nitriding Kinetics of Inconel 600, Surface and Coatings Technology, Volume 226, 15 July 2013, Pages 92-99, ISSN 0257-8972, http://dx.doi.org/10.1016/j.surfcoat.2013.03.040. (http://www.sciencedirect.com/science/article/pii/S0257897213003034) Keywords: Inconel 600; Nitriding; Internal nitridation; Diffusion coefficient
[15] C. Ezilarasan, V.S. Senthil kumar, A. Velayudham, An experimental analysis and measurement of process performances in machining of nimonic C-263 super alloy, Measurement, Volume 46, Issue 1, January 2013, Pages 185-199, ISSN 0263-2241, http://dx.doi.org/10.1016/j.measurement.2012.06.006. (http://www.sciencedirect.com/science/article/pii/S0263224112002473)Keywords: C-263 alloy; Response surface methodology (RSM); Cutting force (Fz); Flank wear (Vb); Surface roughness (Ra); Desirability; Whisker reinforced ceramics