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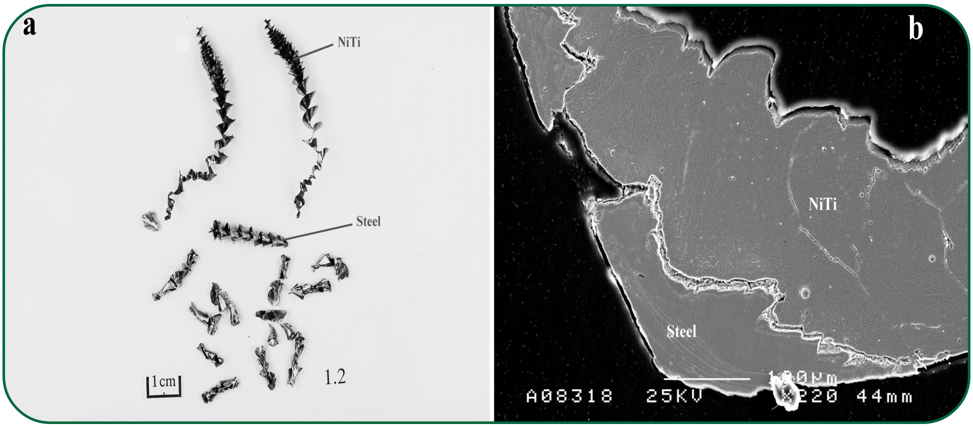

Jukka Paro

Machinability effects of stainless steels with a HIPed NiTi coating in high-efficiency machining operations

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Keywords stainless steels, machinability, machine tools, wear, surface coating, grinding, turning, drilling, nickel-titanium alloys

Abstract

The machinability effects of new high-strength stainless steels are researched due to specific properties arising from their structure. In grinding operations, HIPed (Hot Isostatically Pressed) austenitic 316L, duplex 2205 and super duplex 2507, and as-cast 304 stainless steel, in turning HIPed 316L, duplex stainless steel 2205 and X5 CrMnN 18 18 stainless steel, and in drilling HIPed PM (Powder Metallurgic) Duplok 27 and duplex stainless steel ASTM8190 1A and X2CrNi 1911 with HIPed NiTi coating were researched in revised machining testing environments using tool life testing, chip and workpiece surface morphology analysis. Chips, workpiece surfaces and cutting tools were analysed by SEM and EDS.

High toughness, workhardening and low heat conductivity have a synergistic effect in inducing machinability difficulties e.g. decreased product quality, shorter tool life, increased power consumption and decreased chip evacuation. An increased amount of alloying elements is found to decrease machinability in the form of increased cutting force and workhardening rate of the machined surface, and decreased tool life and surface roughness. Also, the machinability of PM-produced stainless steels is decreased because of the increased amount of hard oxide particles included in the microstructure of PM-produced stainless steel. The formation of BUE (Built-up Edge) is found, affecting the machinability and tool life of tested high-strength stainless steels.

In grinding operations HIPed austenitic 316L and duplex 2205 stainless steel are rated according to cutting force, workhardening rate and the amount of microvoids and microcracks in ground surfaces. In turning operations HIPed 316L, duplex stainless steel 2205 and X5 CrMnN 18 18 stainless steels are

assessed in machinability order. The machinability of conventional cast duplex stainless steel ASTM8910 and HIPed duplex stainless steel Duplok27 were sorted according to the PRE-value (Pitting Resistance Equivalent).

Finally in this study, the suitability of coated cemented carbide tools in the drilling of conventionally produced cast stainless steels with HIPed NiTi-coating was investigated. In drilling of difficult-to-cut X2CrNi 19 11 stainless steel with a pseudo-elastic coating, effective cutting parameters that maintain an adhesion layer between the NiTi coating and the stainless steel intact with an advantageous surface finish were generated.

Paro, Jukka. Machinability effects of stainless steels with a HIPed NiTi coating in high-efficiency machining operations [Isostaattisella kuumapuristusmenetelmällä NiTi-pinnoitetun ruostumattoman teräksen suurtehotyöstön lastuttavuusvaikutuksia]. Espoo 2006. VTT Publications 610. 51 s. + liitt. 82 s.

Avainsanat stainless steels, machinability, machine tools, wear, surface coating, grinding, turning, drilling, nickel-titanium alloys

Tiivistelmä

Uusien lujien ruostumattomien terästen ominaisuuksilla on suuri vaikutus niiden lastuttavuuteen. Tässä työssä tutkittiin isostaattisella kuumapuristuksella (HIP) valmistettujen austeniittisen 316L, duplex 2205 ja super duplex 2507 sekä valetun 304 ruostumattomien terästen hiontaa, HIP-menetelmällä valmistetun 316L ruostumattoman teräksen ja X5 CrMnN 1818 -typpiteräksen sorvausta sekä HIP-menetelmällä valmistetun Duplok 27 -teräksen ja ruostumattoman duplex-teräksen ASTM8190 1A porausta. Lisäksi tutkittiin HIP-menetelmällä valmistetun NiTi-pinnoitteella pinnoitetun X2CrNi 1911 ruostumattoman teräksen porausta. Lastuttavuutta selvitettiin sovelletuin testein tutkimalla terän kestoaikaa, analysoimalla lastujen ja työkappaleen pinnan morfologiaa. Lastuja, työkappaleiden pintoja sekä teriä tukittiin pyyhkäisyelektronimikroskoopilla (SEM) ja energiadispersiivisellä alkuaineanalyysillä (EDS).

Tutkittujen terästen ominaisuuksista suuri sitkeys, muokkauslujittuminen sekä matala lämmönjohtavuus aiheuttavat lastuttavuusongelmia. Runsaan seostuksen on todettu huonontavan lastuttavuutta, sillä lastuamisvoimat kasvavat, terien kestoajat lyhentyvät, koneistetut pinnat muokkauslujittuvat sekä työkappaleen pinnanlaatu huononee. Pulverimetallurgisesti valmistetuttujen ruostumattomien terästen mikrorakenteen kovat oksidit vaikeuttavat myös koneistettavuutta. Irtosärmän muodostumisen todettiin myös heikentävän testattujen terästen lastuttavuutta.

Tässä työssä havaittiin suurten lastuamisvoimien sekä hiotun pinnan muokkauslujittumisen ja mikrohalkeamien ja -säröjen muodostumisen vaikuttavan 316L sekä duplex 2205 ruostumattoman teräksen hiottavuuteen. Sorvaustutkimuksissa selvitettiin 316L:n, 2205:n sekä X5 CrMnN 1818:n lastuttavuuteen vaikuttavia

tekijöitä, terän kestoaikoja sekä kulumismekanismeja. Porauksessa arvioitiin myös perinteisen valetun duplex-teräksen sekä HIP-menetelmällä valmistetun duplex ruostumattoman teräksen lastuttavuutta PRE-arvon (Pitting Resistance Equivalent) avulla. Lopuksi selvitettiin pinnoitettujen kovametalliporien soveltuvuutta pseudoelastisella NiTi-pinnoitteella pinnoitettujen valettujen ruostumattomien terästen poraukseen. Työssä löydettiin menetelmät ja lastuamisarvot, joilla voidaan saavuttaa riittäviä terien kestoaikoja ja pitää NiTi-pinnoitteen ja ruostumattoman teräksen välinen adheesiokerros vaurioitumatta sekä reikien pinnanlaatu hyvänä.

Preface

This thesis is based on the work carried out mainly in the Laboratory of Production Engineering at the Helsinki University of Technology (HUT) from 1993–1999. Publications I and II were accomplished during the "Machining of New Strength Stainless Steels" project in close co-operation with the Laboratory of Engineering Materials funded by the Academy of Finland. Publications III and IV were produced during the author's work at the Graduate School of Concurrent Mechanical Engineering (GSCME). This work was financially supported by Tekniikan edistämissäätiö (TES). The appended Publications V, VI and VII were prepared during several machining projects at VTT.

I would like to express my gratitude to Professor Veijo Kauppinen and Professor Hannu Hänninen for their guidance and invaluable support. Laizhu Jiang Ph.D. is thanked for his close co-operation during the course of this work. The encouragement of Dr.Tech. Jyrki Kohopää is also especially appreciated. Professor Mauri Airila (GSCME) is also especially acknowledged. I am also grateful to my colleagues for their helpful collaboration over the years.

Finally, warm thanks are owed to my dear family, wife Marjut and daughters Emmi and Anni, for their patience and support.

Geneve, June 2006

Jukka Paro

Contents

Appendices

List of publications

This dissertation consists of an introductory report and seven appended publications (I–VII).

I Jiang, L., Paro, J., Hänninen, H., Kauppinen, V. & Oraskari, R. 1996. Comparison of grindability of HIPped austenitic 316L, duplex 2205 and super duplex 2507 and as-cast 304 stainless steels using alumina wheels. Journal of Materials Processing Technology 62(1996), pp. 1–9.

II Jiang, L., Hänninen, H., Paro, J. & Kauppinen, V. 1996. Active wear and failure mechanisms of TiN-coated high speed steel and TiN-coated cemented carbide tools when machining powder metallurgically made stainless steels. Metallurgical and Materials Transactions A, Vol. 27 A September 1996, pp. 2796–2808.

III Paro, J., Hänninen, H. & Kauppinen, V. 2001. Tool wear and machinability of X5 CrMnN 18 18 stainless steels. Journal of Materials Processing Technology, 119(2001), pp. 14–20.

IV Paro, J., Hänninen, H. & Kauppinen, V. 2001. Tool wear and machinability of HIPed P/M and conventional cast duplex stainless steels. Wear 249(2001), pp. 279–284.

V Paro, J.A., Gustafsson, T.E. & Koskinen, J. 2004. Drilling of conventional cast stainless steel with HIPed NiTi coating. Journal of Materials Processing Technology, 153–154(2004), pp. 622–629.

VI Paro, J.A., Gustafsson, T.E. & Koskinen, J. 2003. Chip morphology in drilling of conventional cast stainless steel with HIPed NiTi coating. Proceedings of the 3rd International Conference on Research and Development in Mechanical Industry, RaDMI 2003, Hotel Plaža, 19–23 September, Herceg Novi, Serbia and Montenegro. 8 p.

VII Paro, J.A., Gustafsson, T.E. & Koskinen, J. 2005. Deformation effects on the interface between X2CrNi 19 11 stainless steel and HIPed NiTi coating in machining. Proceedings of the 18th International Conference on Production Research, 31st July – 4th August 2005, Salerno, Italy. 5 p.

Original findings

The experimental data and analyses of this thesis report are directed towards evaluating the high-efficiency machining and machinability of new high-strength stainless steels, especially in modern machine tools and with modern tool materials. The following features of this thesis are believed to be original:

- The machinability effects of high-strength stainless steels with modern machine tools and cutting tools were studied over a wide range of machining parameters in grinding, turning and drilling operations.

- When using alumina wheels, the workhardening of the workpiece surface and the formation of microcracks decreases the grindability of HIPed austenitic 316L, duplex 2205 and super duplex 2507 and as-cast 304 stainless steels.

- When turning HIPed austenitic 316L, duplex 2205 using TiN-coated cemented carbide tools, the dominant tool wear mechanisms are fatigue-induced failure and diffusion wear.

- When the machining of PM-produced stainless steel is compared to that of conventionally produced stainless steel, the tool life is found to decrease. PM-produced stainless steel shows a higher workhardening rate, thus decreasing the tool life. On the other hand, the formation of BUE is increased when conventionally produced stainless steel is used.

- The presence of BUE decreases the machinability of X5CrMnN 18 18 stainless steels by causing decreased surface roughness and evidence of microcracks at the worked surface. The increase of nitrogen content was found to decrease the workhardening rate of the workpiece surface.

- The macroscopic geometry of stainless steel chip with a HIPed NiTi coating differs from conventional stainless steel chip and a combined chip structure is built. On the other hand, when effective cutting speeds and feed rates were utilized, optimal drill performance is achieved without a deterioration in coating properties.

List of symbols and abbreviations

a	Depth of cut
BUE	Built-Up Edge
CBN	Cubic Boron Nitride
CVD	Chemical Vapour Deposition
d	The diameter of the rotating tool or workpiece
f	Feed rate
EDS	Energy Dispersive Spectroscopy
EDM	Electric Discharge Machining
F_n	Normal force component
F_t	Tangential force component
F_x	Cutting force component in the direction of the x-axis
F_y	Cutting force component in the direction of the y-axis
F_z	Cutting force component in the direction of the z-axis
G	Grinding ratio
HEM	High Efficiency Machining
HIP	Hot Isostatically Pressed
HSC	High-Speed Cutting

HSM	High-Speed Machining
HSS	High-Speed Steel
k_v	Factor
K_v	Workability co-efficient
n	Rotation speed
OM	Optical Microscope
PCD	Polycrystalline Diamond
PM	Powder Metallurgy
PRE	Pitting Resistance Equivalent PRE = wt% Cr+ 3.3 x wt% Mo + 13x wt% N
R_a	Surface roughness (Mean Arithmetic Deviation)
SEM	Scanning Electron Microscopy
SMA	Shape Memory Alloy
T	Tool life
VB	Flank wear value
v, v_c	Cutting speed
v_f	Feed speed
V	Cutting volume
z	The number of cutting edges

1. Introduction

There is a tendency in the field of machined materials towards stainless steels with higher strength and higher corrosion resistance. Duplex stainless steels are often applied (Schintlmeister & Wallgram 1999). High-efficiency machining and the machinability of high-strength stainless steels are considered to be the most important future trends affecting machining operations. Duplex stainless steels have a lower nickel content than austenitic stainless steels, and an austenite plus ferrite structure. Increased strength with enhanced properties for service in a corrosive environment provides difficulties from a machinability point of view.

The characteristics of stainless steels raised from the austenitic structure are high toughness, low thermal conductivity and high workhardening co-efficient (Peckner & Bernstein 1977). From a machinability point of view the most important characteristic is the workhardening. Because of the low thermal conductivity, the chips are formed on the basis of catastrophic failure in narrow shear surfaces (Dolinšek 2003). When carbide tools are used these characteristics cause the formation of BUE and low values of tool life. Cutting forces are also increased and the unfavourable formation of tough chips appears (Dolinšek 2003).

Tool materials, such as CVD-coated (Chemical Vapour Deposition) with hard Al_20_3 coatings, are often preferred (Belejchak 1997). The need for a hard tool surface coating is especially required when HIPed stainless steels containing hard inclusions are to be machined.

Near-equiatomic nickel-titanium alloys (NiTi) have many attractive properties for engineering applications, such as pseudo-elasticity and good cavitation resistivity, in addition to their more well-known shape memory properties (Li & Sun 2002, Starosvetsky & Gotman 2001). In drilling stainless steel with a pseudo-elastic coating material, machinability difficulties are involved with the pseudo-elastic properties of the coating material. Nevertheless, both technical and commercial limitations arise when NiTi is considered as a material for large engineering components. Consequently, interest in NiTi-coating technologies, for example for stainless steels, is on the rise. The cutting process of NiTi-based shape memory alloys is influenced by their high ductility and high degree of workhardening, and the unconventional strain-stress behaviour (Weinert & Petzoldt 2004).

The investigation of machining austenitic stainless steels in different cutting processes has been initiated by industry, where the need for effective tools and demands for reliable data on cutting parameters extends far beyond the experiences or recommendations given by tool producers (Dolinšek 2003). The machinability studies are often carried out by vT-tests in turning, milling and drilling operations. Tool wear is studied by using optical microscopy to define the amount of flank and crater wear. The interaction between tool and chip can be effectively studied using SEM.

There are several tendencies affecting the technology and methods used in the metalworking industry. Highly efficient machining strategies are used, and HEM (High Efficiency Machining) is used as a machining method. In HEM machine tools, modern tools are used with sufficient cutting parameters. HEM focuses on optimising cutting efficiency to maximise material removal rate. Compared to HSM (High Speed Milling), lower spindle speeds and increased chip thicknesses are used. The modern tools and tool materials available for this research were specifically designed cutting tools for HEM machine tools. The machine tool reliability and productivity is controlled by optimising machining parameter selection and acceptable and adequate sufficient parameters are used. Also, nowadays modern machine tools are very complex mechatronical systems and their capability and efficiency are mainly determined by their kinematics, structural dynamics, computer numerical control system and the machining process (Altintas et al. 2005 and Weck et al. 2003).

The hypothesis of this work is that tool wear mechanisms and workhardening of the chip and workpiece surface also affect machinability behaviour in the drilling of stainless steels with a HIPed NiTi coating. The aim of the present research was to provide information about the effects, e.g. tool life, cutting forces and surface roughness, arising in the machining of new high-strength stainless steels in high-efficiency machining operations with respect to machining method, the amount of alloying elements and workpiece coating. The machinability tests of these materials were carried out with the machine tools installed in the Laboratory of Production Engineering at HUT.

The new high-strength stainless steels HIPed austenitic 316L, duplex 2205, super duplex 2507 and as-cast 304 were tested firstly in conventional grinding and turning operations (Publications I and II). The effect of nitrogen content in turning operation of high nitrogen X5 CrMnN 18 18 stainless steels is presented in Publication III.

The machining operations with a high-performance machine tool were carried out when a machining centre equipped with modern drilling tools was applied (Publications IV–VII). The machinability of HIPed stainless steel Duplok27 and the conventionally produced cast stainless steel ASTM A890 1A was compared in Publication IV. The machinability effects of stainless steel with HIPed NiTi coating are presented in Publications V, VI and VII.

The machine tools and cutting tools used in the present study are widely commercially available without any special laboratory-oriented features, and also SEM is mainly used for sample visualisation in drilling tests with modern cutting tools. The results gained in the laboratory are also applicable in real machining operations of high-strength stainless steel components.

2. Experimental materials and procedure

2.1 Materials

Several duplex stainless steels and new high-strength stainless steels typically used in process industry applications were included in this study. The workpiece materials for the grinding tests were HIPed austenitic stainless steel PM 316L, duplex stainless steel PM 2205, super duplex 207 and as-cast 304. The workpiece materials for the turning tests were HIPed austenitic stainless steel PM 316L, HIPed duplex stainless steel PM 2205 and X5CrMnN 18 18 high nitrogen stainless steels. The test materials for the drilling tests were HIPed duplex stainless steel Duplok 27, cast duplex stainless steel A 890 1A, and cast stainless steel X2CrNi 1911 with a HIPed NiTi coating, the composition of which in wt-% is 55/45. The chemical compositions of the tested steels are given in Table 1.

Duplex stainless steels are increasingly used as an alternative to conventional stainless steels. The main advantages of the duplex grades are good resistance to stress corrosion cracking and also to corrosion fatigue in environments containing chlorides (Nyström 1995). Powder metallurgy (PM) materials are considered to have poor machinability, a behaviour explained by three contradictory theories, namely interrupted cutting, hard inclusions and reduced thermal conductivity (Agapiou et al. 1988). For austenitic stainless steels, it is difficult to combine the improvement of corrosion resistance with good machinability.

Improvements in machinability are often obtained by an increase in sulphur content. In order to combine high corrosion resistance properties with improved machinability, a Cu-enriched alloy has been developed (Coudreuse et al. 1997). Stainless steels containing malleable oxides form the latest generation of steels with improved machinability (Bletton et al. 1990). By modifying the composition of the non-metallic inclusions and controlling the shape, size and distribution of the inclusions, considerable improvements in the machinability of 2205 duplex stainless steel are obtained (Arnvig et al. 1994).

Duplex stainless steels show different technological behaviour when compared to other classes of stainless steel. Therefore, new geometry and cutting parameters are defined for duplex stainless steels (Pellegrini et al. 1997). Duplex stainless steels have a machinability profile that differs somewhat from that of austenitic steels with a similar corrosion resistance, and they are not as difficult to machine with high-speed steel tools as with cemented carbide tools (Arnvig et al. 1994).

Table 1. Chemical composition (wt%) of the test materials.

Material	Test performed	C wt%	Si wt%	Mn wt%	P wt%	S wt%	Cu wt%	Cr wt%	Ni wt%	Mo wt%	V wt%	Al wt%	N wt%	O wt%
PM 316L	grinding, turning	0.05	0.68	1.44	0.022	0.009	0.19	16.7	11.0	2.7	0.11	0.021	0.12	0.12
PM2205	grinding, turning	0.03	0.07	1.42	0.022	0.008	0.013	22.1	5.3	3.0	0.07	0.016	0.21	0.014
PM2507	grinding	0.03	0.30	0.30	0.035	0.009	0.16	25.0	7.0	4.0	0.08	0.020	0.30	0.015
AC304	grinding	0.03	0.40	1.20	0.040	0.015	0.176	18.4	9.2		0.06	0.025	0.10	0.001
X5CrMnN18 8 (G88216)	turning	0.05	0.29	18.89				18.13	0.43	0.11	0.08		0.57	
X5CrMnN18 8 (DDT63)	turning	0.05	0.49	19.8				18.6	0.61	0.08	0.13		0.91	
Duplok 27	drilling	0.03	0.02	0.7	0.02	0.001	2.3	26.5	7.0	3.0			0.3	
A890 1A	drilling	0.03	0.74	0.63	0.026	0.006	3.01	25.0	5.54	2.03				
X2CrNi 1911	drilling	0.03	0.4	1.20	0.04	0.015		18.4	9.2		0.06			

According to Charles (1994) the most interesting characteristics of duplex stainless steels include:

- A low thermal expansion coefficient that makes these materials suitable for use in thermal cycling conditions.
- Higher thermal conductivity than in austenitic grades makes the duplex grades good candidates for heat exchanger applications.
- Strongly magnetic behaviour due to the presence of about 50 per cent ferrite, enabling the use of magnetic clamping during machining.

Chemical compositions of some duplex stainless steels are presented in Table 2.

Table 2. Chemical composition of duplex stainless steels designed for new applications (Charles 1994).

	Chemical Composition [wt%]					**Applications**
	Cr	**Ni**	**Mo**	**N**	**Others**	
CLI UR 35 N Cu	23	5	0.1	0.1	2 Cu	Improved machinability
AVESTA 2205 NRG	22	5.6	3	0.13	0.02 S	-”-
CLI UR 52 NRS	25	6.5	3	0.2	0.02S-1.6Cu	
SUMI-TOMO	22.5	10	–	0.1	3 Si	Nitric acid
AVESTA 2308 PM	22.5	9	2.4	0.02	0.04 Ti-0.06Al-2Si	Bars/ forgings
NIPPON S.S.	17.5	4	–	0.05	1Cu-3Si-3Mn	Railway car
COREA 3W-1Mo	22	5.5	1	0.16	3W	General purpose

Recent industrial applications in raw material handling, food processing and environmental management show the considerable advantages of high nitrogen steels compared to regular wear-resistant materials (Rennhard 1998). Choosing high nitrogen steels for jewellery is motivated by nickel allergy prevention, and a unique combination of corrosion resistance and strength is achieved in specific medical applications by new grade high nitrogen steels (Rennhard 1998 and Ilola 1999). According to Sundvall et al. (1998) nitrogen alloyed stainless steel grades are commonly used in modern process industry applications.

2.2 Test methods

The main testing methods showing the machinability behaviour used in this study were drilling, grinding and turning tests. The machinability of the test materials was determined by means of tool wear testing, cutting force measurements and analysis of the tool surfaces and chips with SEM. Tool wear was measured with optical microscopy, the tools and chips were analysed by SEM, and the workpiece surfaces using microhardness measurements.

The machinability tests were carried out using the existing machine tools of the laboratory of Production Technology, which are also conventional machine tools applicable to the Finnish metalworking industry. The machining experiments for new high-strength stainless steels were selected to clarify the machinability of recently developed steels. Machining tests were also carried out using commercially available appropriate tooling and fixtures. The test methods are described in Appendix I.

The most common machining operations were selected, and machining tests were carried out using turning, grinding and drilling operations. Conventional machine tools and cutting tools were selected. After machining, the cutting tools and chips were analysed using optical microscopy and SEM to determine tool wear and tool wear mechanisms.

Test methods were selected to find the effects of new high-strength stainless steels during machining operations. For conventional machining operations there are standardised tool wear tests. In this research, the machinability behaviour of new high-strength stainless steels with modern material analysing equipment is shown, and the revised machinability tests were carried out using tool life testing in turning, grinding and drilling operations. Tool wear was studied to define the amount of flank and groove wear.

2.2.1 Grinding experiments

The grinding experiments presented in Publication I were carried out using an Okamoto horizontal-grinding machine with Norton 43A6 GVX Al_2O_3 wheels of 200 mm diameter. A cutting speed of 30 m/s and a 0.25 m/min table speed were applied. The materials presented in Table 1 were cut into test pieces of 8 mm wide and 200 mm long. During grinding the radial wheel wear was measured using a Micro-HITE height gauging instrument. Grinding force components were measured with a Kistler piezo-electric dynamometer and the surface roughness was measured after grinding with a Taylor surface roughness instrument. After the grinding tests, metallographic examinations and analyses of the ground surfaces were performed by SEM together with energy dispersive spectroscopy (EDS). Workhardening of the specimen surface was investigated with an MHT-4 microhardness tester with a load of 20 g. The methods are described in Appendix I.

2.2.2 Turning experiments

The results of the turning tests using a VDF lathe with a 100 kW spindle motor are presented in Publication II. TiN-coated high-speed steel (HSS) T42, P30 cemented carbide inserts and SPUN 120308 inserts are applied in the turning of samples. The samples were 70 mm in diameter and 350 mm in length. A lathe with a quick-stop device at Imatra Steel works was applied for chip root samples. The turning experiments on X5CrMn 18 18 presented in Publication III were carried out using TiN- and Al_2O_3-coated cemented carbide inserts of type SNMG 120408-PM P15/K15. HSS tools were applied with cutting speeds of 15–55 m/min, and solid carbide tools were applied with cutting speeds of 100–250 m/min. A feed rate of 0.15 mm/r and a depth of cut of 1 mm were utilised.

The flank wear (VB) of the cutting tools was measured with a toolmaker’s microscope. The criterion for tool life was either VB = 0.3 mm or catastrophic failure of the tool edge. Cutting forces were measured with a three-component piezo-electric force dynamometer. The possible bonding interface between the tool materials and chips was analysed using SEM and EDS analysis. Solid carbide inserts and chips were also analysed using SEM and EDS after the turning tests on X5CrMn 18 18 stainless steels. The measurement of the hardness value of the machined surface was also performed. The methods are described in Appendix I.

2.2.3 Drilling experiments

The drilling experiments on HIPed and conventionally produced stainless steels are presented in Publication IV. These were carried out by using a modern horizontal machining centre, a Mazatech FH480 equipped with a 12 000 rpm spindle and conventional precision tool holders, allowing a cooling trough spindle with solid carbide drills of Titex Alpha4+ DX45 ∅8.5 mm, P40. Cutting speeds between 40–69 m/min with a feed rate of 0.2 mm/r were used. The methods are described in Appendix I.

The drilling experiments on conventional cast stainless steels with a HIPed NiTi coating are presented in Publications V, VI and VII. The same machining centre was equipped with TiCN- and TiN-coated Mitsubishi MZS850L with a diameter of Ø8.5 mm. A cutting speed of 50 m/min and feed rates of 0.1, 0.15, and 0.2 mm/rev were used. The drilling tests were done both with and without through-spindle cooling.

The flank wear (VB) of the solid carbide drills was measured with a toolmaker's microscope. The criterion for tool life was either VB = 0.3 mm or catastrophic failure of the drill. SEM was used to analyse tool wear from cemented carbide drills and chip morphology. Chips were investigated with a MHT-4 microhardness tester using a load of 20 g.

3. Summary of main results

3.1 Comparison of test methods

Machinability is often defined as the quality or state of being machinable by different machining methods such as turning, milling, grinding, etc. In machining it is generally desirable to produce a satisfactory part at the lowest possible cost (Cook 1975). Lindgren (1980) divides machinability tests into authentic and simulated tests. Machinability is often characterised by the following three aspects:

- easy metal removal; such as power requirement and chip forming characteristics (curl or break down)
- tool life (crater wear, flank wear and chipping)
- workpiece quality (surface roughness, dimensional accuracy).

In Publications I and II preliminary tests are shown applying grinding and turning operations in the machining of high-strength stainless steel. Tool wear rate and phenomena are studied.

Tool wear plays a vital role in influencing both the ease of cutting and the resultant machined surface (Liew et al. 2003). The high strength, low thermal conductivity, high ductility and high workhardening tendency of austenitic stainless steels are the main factors that make their machinability low. In machining, segmental chips are formed and the formation of BUE is present when carbide tools are used (Dolinšek 2003). In many cases, machining problems with austenitic stainless steels are associated with BUE formation, bad surface, burr formation and unfavourable chip size. In Publication I, grindability and ground stainless steel surfaces are studied.

Komanduri and Brown (1981) compiled a detailed classification of chips produced by non-homogenous cutting, named as wavy chip, discontinuous chip, segmental chip and catastrophic shear chip. According to von Turkovich (1981) the properties of materials manifest themselves in cutting forces, chip form (curl, segmentation, BUE, strain and strain rates (including fracture), chip-tool contact length, temperatures in the shear zone and along the chip-tool interface and the mechanical and metallurgical state of the new surface. In this study cutting forces, chip forms and workhardening of chips and workpiece surfaces were found to be sufficient indicators of the machinability of the tested stainless steels. The macroscopic morphology of the chips and the workhardening are studied against the cutting parameters in Publications II and III.

The cutting force is one of the most important physical variables embodying relevant process information in machining. Such information can be used to assist in understanding critical machining attributes such as machinability, cutter wear or fracture, machine tool chatter, machining accuracy and surface finish (Tlusty & MacNeil 1975, Budak & Altintas 1994, Budak & Altintas 1995). The effects of thermal conductivity and shear strength where considered in tool life prediction with a modified Taylor equation is presented by Schäpermeier (1999). In the most commonly used tool condition monitoring systems, sensors measure cutting force components or quantities related to cutting force (power torque, distance/displacement and strain (Jemelniak 1999). The machinability of new high-strength stainless steels is verified by the means of cutting force measurements in Publications I to IV.

Many models and attempts have been made to analyse the mechanics of the orthogonal machining process (Stevenson & Stephenson 1998, Beno 1996). In analytical studies of the mechanics of the machining process, attention is usually restricted to the simplified orthogonal case where a layer of material is removed by a single, straight cutting edge set normal to the cutting velocity (Arsecularatne et al. 1998). In this study, the machinability of the new high-strength stainless steels was presented by vT-curves in Publications III to VI. A quantitative evaluation system of machinability, grindability and other workabilities based on specific cost productions is proposed by Taniguchi (1971), Yeo (1989) and Yeo (1995).

It is suggested by Höglund (1976) and Šalak et al. (2005) that plastic deformation is the main phenomenon in the cutting process, and that this deformation takes place at a microscopic scale under extreme conditions. It has also been suggested by Recht (1964), that thermally-aided adiabatic instabilities from the interaction of strain rate, flow stress and temperature could be responsible for the serrated or discontinuous chip behaviour during the machining of titanium or steel. Iwata and Kanji (1976) show the significance of dynamic crack behaviour during the metal cutting process. As shown in Publications I and III, cracks were found in the worked surfaces.

Research work into the physics of machinability theory is as yet unable to completely define the metal cutting processes (Mackerle 1999, Mackerle 2003, Shaw 1985, Oxley 1988, Özel 2006). Machinability data simply recommend "reasonable" sets of tool materials, feeds, speeds, fluids, etc., for given machining requirements, or a list of specific tool-life values for a set of machining conditions (Cook 1975). Beno (1996) lists modern methods describing material behaviour during a cutting operation near the shear zone. Chick and Mendel (1998) have expressed a model using wear curves to predict the cost of changes in cutting conditions. The effect of cutting fluid on workpiece surface quality is studied in Publications V and VI, where the effect of using through-spindle cooling is tested.

The commonly used basis for tool life criteria according to Tipnis and Joseph (1975) is presented in Table 3.

Table 3. Commonly used basis for tool life criteria (Tipnis & Joseph 1975).

Basis	**Criteria**
State of Machined Surface	Dimensional Tolerance, Surface Finish, Surface and Functional Integrity, in terms of residual stresses, surface damage and affected functional properties
Rate of Material Removal	Rate of Material Removal Under Fixed Force
Ease of Chip Disposal	Chip Length, Breakability
Duration of Tool Life	Location of Tool Wear, Distortion, Deflection, Loss of Edge Geometry

The machinability of stainless steels is often compared to the pitting resistance equivalent value representing the alloying content of the steel. The Pitting Resistance Equivalent (PRE) index, PRE= wt%Cr+3.3x wt%Mo+30x wt% N is presented in Figure 1.

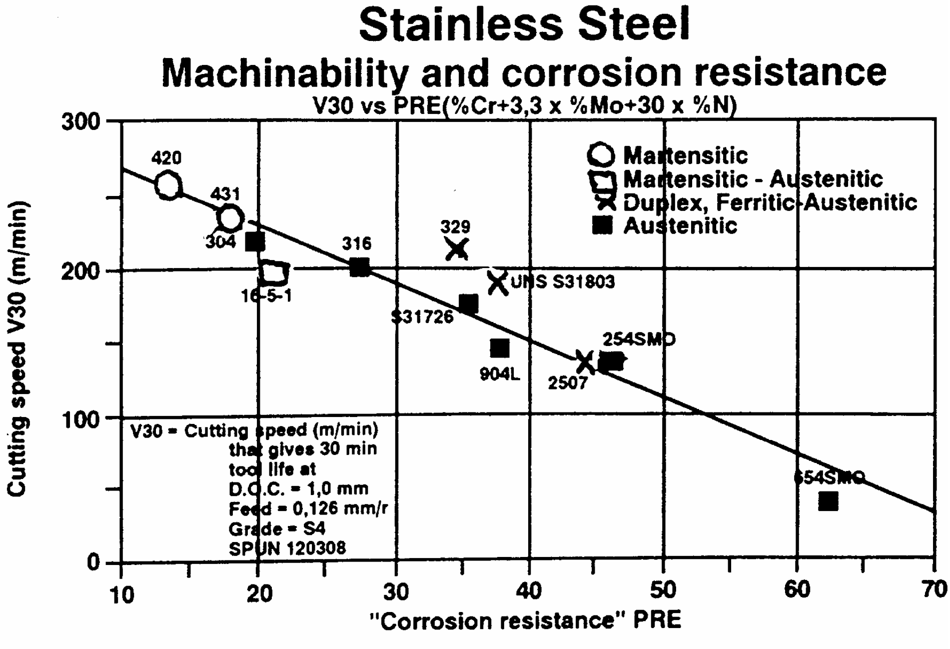

Figure 1. Machinability and corrosion resistance of stainless steels. V30 vs. PRE (Östlund 1994).

The machinability can be also expressed by the machinability by workability coefficient, K_v,which estimates material resistance to a cutting process. Tensile strength has been found to be the most useful attribute for determining the workability of stainless steels through this relationship (Hallum 1995).

$$K_v = -1.74 + {}^{200}\!/_{\sigma} \qquad (1)$$

3.2 Turning of new high-strength stainless steels

Stainless steels have always been considered difficult to machine. In the stainless steel family, duplex steels are particularly difficult to machine, generating more BUE and irregular wear than single-phase stainless steels (Roos 1997). The composition that provides high tensile strength and high corrosion resistance in stainless steels usually results in lower machinability than carbon steels, for example (Belejchak 1997).

It is suggested (Leffler et al. 1996) that the lower alloyed duplex grades, such as S32304, are comparatively easy to machine. In general, modern duplex grades tend to be more difficult to machine than the older grades, by virtue of higher austenite and nitrogen contents (Gunn 1997).

The machinability of PM 316L and PM 2205 was studied in this work. In turning operations, TiN-coated cemented carbide tools have a longer tool life when machining PM 316L than PM 2205 stainless steel. Selecting rapid and reliable manufacturing parameters and optimising these with respect to the machining task involved is a constant challenge for production planners and programmers. It is known that cutting tool material selection can be based on PRE-index classification (Jonsson 1994). The tested steels were ordered against the PRE-index in Publications I and II.

The shear instability in the cutting operation of stainless steel is often reflected in the formation of serrated chips. The mechanism of serrated chip formation has been explained in terms of the varying strength of the work material at the rake face (Sullivan et al. 1978). The chip formation process is studied in Publications II and III.

Workhardening has been recognised as an important feature in the poor machinability of austenitic stainless steel. According to Jiang et al. (1996), Sullivan et al. (1978) and Wright and Trent (1954), workhardening, together with low thermal conductivity, is believed to result in segmental chip formation. Workhardening of chips and machined surface was studied in Publications I–IV.

According to Chandrasekaran and Johansson (1994), notch wear at the depth of the cut is a serious problem during the machining of high alloyed austenitic stainless steels. Thick workhardened zones, stringy chips, harsh harmonics and high machining temperatures all take a toll on material removal rates, reducing insert life and increasing downtime (Belejchak 1997). Stainless steel producers currently often improve the machinability of austenitic stainless steels. Both austenitic and duplex stainless steels are supplied by stainless steel producers (Roos 1997).

3.3 The effect on grindability

When the grindability of PM 316L, PM 2205, PM 2507 and AC 304 were examined in terms of grinding ratio, grinding force and surface roughness using alumina wheels, the ratio decreased in the order AC 304, PM 316L, PM 2205 and PM 2507 steel; the grinding force increased in the following order: AC 304, PM 2205, PM 316L and PM 2507 steels; and surface roughness increased in the following order: PM 316L, PM 2205, PM 2507 and AC 304 steel.

Grinding methods utilise undefined cutting tool geometry in the form of grinding wheels or grinding paste. The cutting operations proceed via the interaction between the workpiece and hard grinding particle. According to Malkin (1984), material removal in grinding occurs via the interaction of abrasive grains in the grinding wheel with the workpiece at extremely high speeds and shallow penetration depths. The interaction between the grains on the grinding wheel and the workpiece can be placed into three categories: rubbing, blowing and cutting (Hahn 1962). Wear and the deformation of the grinding wheel are analysed using geometrical data (Tso & Yang 1998).

The workhardening behaviour of stainless steels during grinding increased in the following order: AC 304, PM 316L, PM 2205 and PM 2507. Also, a considerable number of microvoids were detected on the ground surfaces, increasing in the following order: PM 316L, PM 2205, PM 2507 and AC 304 steels.

Of the alloying elements in stainless steels, Ni and Mo promote diffusion wear of TiN-coated cemented carbide tools because of the replacing diffusion of Ni from the workpiece to the tool. It also causes diffusion of Co from the cemented carbide substrate to the workpiece, and diffusion of Mo from the workpiece to the substrate, partially replacing W. (König 1981.)

Difficult to cut, various high-strength stainless steels are produced by combinations of the following: Grain refinement by thermomechanical treatment, solid solution strengthening by lattice distortion through the addition of an alloying element, transformation strengthening by martensite transformation, workhardening by the formation of strain-induced martensite through rolling, strain ageing hardening by tempering or ageing of martensite, and precipitation strengthening of inter-metallic compounds which are coherent with the matrix (Murata et al. 1993).

3.4 Turning of high-nitrogen stainless steels

The effect of nitrogen on the machinability of high-nitrogen stainless steels was studied in turning tests, as shown in Publication III. According to Ilola (1999), the strength of austenitic stainless steels at room temperature can be markedly increased with nitrogen alloying, without a significant reduction in toughness. By utilising alloying, small grain size, cold working and ageing strengthening methods, a yield strength of 3400 MPa can be achieved for austenitic stainless steels.

According to Ilola (1999), nitrogen-alloyed stainless steels have excellent fracture toughness over a wide temperature range. Although an increase in nitrogen content increases the yield strength, the fracture toughness is only slightly affected at room temperature (Speidel 1989).

Nitrogen alloying increases the fatigue strength of austenitic steels at room temperature in both high cycle and low cycle fatigue (Ilola 1999). The beneficial effects of nitrogen in low cycle fatigue can reach a limit at a relatively low nitrogen content, as happens with AISI 316LN with a nitrogen content of 0.12 wt% (Degaillaix et al. 1989). The creep resistance of austenitic steels is improved by nitrogen alloying (Ilola 1999), and nitrogen increases the creep rupture strength without decreasing the rupture ductility (Nakazawa et al. 1989).

Austenitic stainless steels are considered to be high-nitrogen stainless steels if they contain more than 0.4% nitrogen in solid solution (Speidel 1989). According to Wallén et al. (1992) and Romu (2000), the main reasons for the interest in nitrogen as an alloying element in austenitic stainless steels are to save on other expensive alloying elements such as nickel, and at the same time to introduce good property combinations to steels.

High-nitrogen steel with a higher nitrogen content is supposed to have lower machinability. According to Tervo (1998), the general trend appears to be that an increase in nitrogen content decreases the strain-hardening exponent, and increases the strength factor. Nitrogen makes cutting forces greater due to dynamic strain ageing, whereas carbon and phosphorous make it smaller because of the formation of voids and cracks in the primary and secondary shear zones (Katayama & Hashimura 1990). In Publication III, a difference in cutting forces is shown between X5 CrMnN 18 18-trial materials. Instead of a tangential force of F_y = 2.2–2.5 kN in turning X5 CrMnN 18 18-trial material with 0.91% N, a lower tangential force of F_y = 2.2 kN is achieved when applying X5 CrMnN 18 18-trial materials with 0.57% N.

In the turning of high-nitrogen steels, presented in Publication III, the main failure mechanisms were catastrophic failure by tool nose breaking due to high cutting forces, and sharp edge chipping. Rapid tool wear and a tendency towards chipping have been studied on the major cutting edge. In turning tests of X5 CrMnN 18 18-trial material with a nitrogen level of N 0.91% using a cutting speed of v_c = 60 m/min, a tool life of about T = 31 min is achieved. Tool life decreases to T = 25 min at a cutting speed of 65 m/min. When increased cutting speeds are used, chip formation difficulties cause the chipping of tool material and catastrophic failure of the tool often occurs.

It has also been observed in turning tests that the machinability of high-nitrogen stainless steels is affected by BUE formation. The presence of BUE decreases the machinability of X5 CrMnN 18 18-trial materials. The formation of BUE worsens surface roughness and workpiece surfaces are strongly deformed. The workhardening of a workpiece surface decreases when nitrogen content is increased. According to Kubota et al. (1998), both yield strength and workhardening rate increase with increasing values of nitrogen concentration. The maximum microhardness value measured from X5 CrMnN 18 18-trial material with a nitrogen level of N 0.57% was approximately 600 HV, and with a nitrogen level of 0.91%, hardness values were just below 400 HV.

3.5 Drilling of HIPed and conventionally produced stainless steel

In Publication IV the difference between the machinability of HIPed PM and conventional stainless steel was studied in drilling experiments in the machining centre using solid carbide drills with an internal coolant supply. It is supposed by

Ezugwu et al. (1999) that in drilling operations there are complex sets of demands for the operation of tool and coolant. Coolant reduces the wear of the main flute. Spur and Stöferle (1979) have stated that chip form and dimensions have to be taken into account in those machining operations that have a small amount of chip room, such as drilling, broaching and milling.

When machining a number of alloys, a BUE may form on the tool and have a considerable influence on the tool wear rate, surface finish, and dimensional tolerances (Wallbank 1979). The study of the cutting angles of drills is of importance in the design and analysis of drills. Many models and analyses, such as calculation of force, temperature, wear, and chip ejection, are based on cutting angle analysis (Kaichun & Jun 1999).

According to Fujiwara et al. (1977), during drilling operations free-machining additives such as, S, Pb, Se and Te increase the machinability of austenitic stainless steels.

As observed in drilling tests using cutting speeds of 40–60 m/min and a feed rate of 0.2 mm/r, HIPed PM stainless steels show a shorter tool life than conventional cast stainless steels. When using solid carbide drills with an internal coolant supply, tool wear proceeded continuously and the tool life is between 5–12 min in machining of Duplok 27 stainless steel, and between 7–20 min in machining of A890 1A stainless steel.

According to Klocke et al. (1999), Klocke and Krieg (1999) and Gunn (1997), frittering and flaking of the coating takes place during the drilling of austenitic stainless steels.

It is also observed in drilling tests that the machinability of HIPed PM and conventional cast duplex stainless steels are affected by the formation of BUE. The formation of BUE causing adhesion wear is supposed to be the dominant failure mechanism of solid carbide drills. There is a higher tendency to form BUE in A890 1A than in Duplok 27 steel. Compared to that, at fast cutting speeds plastic deformation of the tool takes place, and in combination with flaking of the insert coating and frittering (Gunn 1997), the tool wear is also affected by the formation of BUE and flaking of the coating. Duplok 27 chips are more strongly deformed than A890 1A chips; the chip bottom of austenite in

Duplok 27 605 HV(20g) (original microhardness 370 HV(20g)) vs. austenite phase of A890 1A steel 505 HV(20g).

In many cases, machining problems with austenitic stainless steels are associated with BUE formation, bad surface, burr formation and unfavourable chip shape (Dolinšek 2003). In the drilling test of conventional cast stainless steels with a HIPed NiTi coating presented in Publications IV–VII, bad surface qualities from drilled holes were also found. Also, the drilling operation was affected by BUE formation.

4. Discussion

4.1 Comparison of test methods

In the reported tests and in the available literature, which is presented in Chapter 3 of this thesis, there is a lot of variation in how well different measuring methods and analysis techniques have worked. This is due to various factors affecting the results and because the result of the machining process depends on the properties of the machine tool, cutting tool, cutting tool material, workpiece dimensions features and workpiece material conditions, and also the peripheral equipment and human factors.

When machinability tests are carried out instead of standardised vT-testing, revised machinability test is often utilised, as in this research. The dynamic behaviour of machine tools and cutting tools is not considered in this research, though it has a remarkable effect on cutting results. Of course the machining parameters used in this research were selected to be sufficient and adaptable for the group of machine tools available in the laboratory of Production Technology at HUT. Tooling microscopes, length measuring devices are also presented widely in industry.

In the drilling tests, high-quality solid carbide drills fixed with high rotational accuracy tool adapters were used to decrease the effect of the dynamical behaviour of the rotating tools affecting the cutting tool wear. Tool holder rotational inaccuracy has been reported to decrease behaviour of rotating cutting in demanding machining conditions (Ranta et al. 1999).

4.2 The effect on grindability

Detailed studies of the grindability behaviour of PM 316L, PM 2205, PM 2504 and AC304 stainless steels with alumina wheels were carried out, and the results are presented in Publication I. Surface workhardening of ground stainless steels and the chemical interaction between them and alumina wheels was found. Attrition, abrasive and adhesive wear mechanisms were found affecting wear mechanisms. Grinding is particularly characterised by high friction between the abrasive grits and the ground surface, and a high risk of thermal damage to the generated surfaces and to loading and wear of the grinding wheel could appear in the forms of thermal micro-cracks (Snoeys et al. 1978).

The effect of hard carbides of Cr and Mo on grinding wheel wear and the stainless steels used in this grinding research have a low content of C, and therefore the amount of carbides should be low.

A number of alumina particles were also found on the steels studied. The grinding forces were dependent not only on the workhardening of the workpiece, but also on the density of microcracks and microvoids forming during grinding. Grinding wheel wear has also an effect on the measured grinding force. Another factor which affects grinding force measurement is the sharpening of the grinding wheel. The balance of the grinding wheel and the vibrations of the grinding spindle have an effect on grinding wheel wear.

The grinding experiments were conducted on a surface grinding machine under reciprocating plunge grinding conditions. During grinding, radial wheel wear was measured using a Micro-HITE height measuring instrument. Based on these results, the grinding ratio (G) in the ready stage of wheel wear could be obtained as could the ratio of volumetric workpiece removal to volumetric wheel wear.

Grinding ratio, grinding force and surface roughness values were measured from the selected number of workpieces, and there is a possibility that the results could vary slightly as the amount of specimen increases, taking into account the uncertainty of the force measurement device, the surface roughness measurement device and the length measurement device. The grinding process related workpiece fixing, grinding wheel fixing and grinding strategy and grinding parameter controlling effects may inhibit fluctuations in the results.

The workhardening of stainless steels during grinding in this research was also researched from the selected amount of test pieces, based on microhardness values of distance from the ground surfaces and austenite and ferrite phases existing on the ground surfaces. The accuracy of microhardness tester depth measurement technology gives a level of displacement measuring accuracy resulting in measured microhardness values and plotted curves. Also, the surface being tested generally requires a metallographic finish, the smaller the load used the higher the surface finish required.

Detailed metallographic examination and EDS analysis of ground surfaces gave results of scratches and grooves and transferred Al_2O_3 particles on the ground surfaces. Also, metallographic examination and EDS analysis of ground surface profiles showed the existence of Al_2O_3.

The formation of microcracks and microvoids affecting surface roughness, grinding forces and the ground surface morphology can be widely researched by means of SEM and EDS. Fluctuations in cutting fluid distribution during the grinding operation may also affect the grindability results.

4.3 Turning of new high-strength stainless steels

The turning tests of PM316 L and PM 2005 stainless steel, presented in Publication II, and X5CrMnN 18 18 stainless steel, presented in Publication III, of this research were carried out with a lathe powered with a 100 kW spindle motor and the tested HSS and solid carbide inserts were fixed with a tool holder of 25 mm. The setting of cutting depth was manual and feed rate values were set manually according to values provided by the machine tool. Rotational speed was checked by means of a rotameter. The flank wear (VB) of the cutting tools was measured with a toolmaker's microscope. During turning, the principal cutting force was measured with a piezoelectric turning dynamometer. Chip root samples were obtained by means of a quick stop device. Inserts and chip root samples were analysed by means of SEM and EDS. Chip root samples were also taken using the microhardness device presented in Appendix I.

During tool life testing of these researched difficult-to-machine materials, high cutting forces occurred, resulting in rapid tool wear. Increasing the amount of experiments, the vT-curve presentation may orientate slightly because of microscope interpretation of worn and damaged inserts. Also, the dynamic behaviour of the lathe head is supposed to cause fluctuations in the results of tool wear and tool life measurements.

Cutting force measurements were firstly used for showing serrated chip formation resulting in cutting force fluctuations, and secondly in turning experiments to point to the effect of nitrogen alloying on cutting force level. Various factors affect the results achieved with the force measurement device.

The wear topography and wear mechanisms of TiN-coated HSS and cemented carbide tools were researched with SEM and EDS methods from chip root samples, and the macroscopic morphology of chips showed the behaviour of stainless steel chip formation and BUE formation. According to Chang (2003), the formation of BUE is dynamically unstable and quite hard, causing rapid wear of the tool and gouging the face.

4.4 Drilling experiments

The drilling experiments presented in Publications IV–VII were carried out using the machining centre presented in Appendix I. A high-accuracy tool holder was used for fixing the tested drills. The tested machining parameters were controlled by numerical control of the machining centre. The tool wear of the drills was presented as a vT curve with selected cutting speeds. For the drilling tests of Duplok 27 and A890 1A, cutting speeds of 20–100 m/min were used with feed rates of 0.15–0.25 mm/revolution, and solid carbide drills with a diameter of Ø8.6 mm were used.

Drills and chips were analysed using SEM and EDS. Microhardness measurements of the chips were also performed. In the drilling experiments on stainless steels with a HIPed NiTi coating, HIP treatment was used to sinter coatings from NiTi powder onto a stainless steel block. The HIPing parameters were 900ºC, 100 MPa, and 3 h. The cooling rate was 4.6 K/min.

These tests used TiCN- and TiN-coated cemented carbide drills with a diameter of Ø8.5 mm, at a cutting speed of 50 m/min and feed rates of 0.1, 0.15, and 0.2 mm/rev. The chips and drilled holes were researched with SEM and EDS mapping. Several analyses from the NiTi coating and stainless steel samples showed the behaviour of this interface during the drilling operation. Weinert and Petzoldt (2004) examined the machinability of shape memory alloys by varying different process parameters and the cooling lubricant concept, and evaluated the hardening of the machined subsurface zone.

To analyse the correlation of the measured parameters on the behaviour of the researched materials in the drilling tests, as was used by Belluco and Chiffre (2004), an analysis of variance was performed to investigate the effect of different cutting fluids on all measured parameters.

5. Summary of the thesis

The main objective of this thesis was to investigate the machinability effects of new high-strength stainless steels. The machinability of these new stainless steels is often poor. By selecting solid carbide cutting tools and machining parameters selected based on the revised machining presented in this research, sufficient tool lives and wear rates are achieved. The machinability effects arising when new high-strength stainless steels are machined with modern machine tools and cutting tools are researched in this thesis.

The test methods that were employed (drilling, grinding and turning tests) gave corresponding results for the machinability of new high-strength stainless steels. The results of the tests complement each other, and give a wider view of the workhardening of chips and machined surfaces with the mechanism of wear with applied machining parameters. Increasing the amount of alloying elements of stainless steels shows decreased machinability in grinding and turning operations. The formation of BUE was present in chip forming operations. Relevant machinability information of studied stainless steels is achieved. Machinability data and information affecting tool wear can be found in these tests, with electron microscopy investigations on chips and machined surfaces.

The grindability of HIPed austenitic 316L, duplex 2205 and super duplex 2507 and as-cast 304 were investigated. The grinding ratios, grinding forces and surface roughness were measured during grinding with alumina wheels. The effects on the grindability of workhardening, chemical interactions between the alumina wheel and the workpiece, and microcracks and microvoids were investigated. The workhardening behaviour of stainless steels was found to increase in following order, according to the amount of alloying elements and the production method of the steel: PM 316L, PM 2205, PM 2507 and AC 304.

The active wear and failure mechanisms of TiN-coated HSS and cemented carbide tools when machining powder metallurgically made 316L and 2205 stainless steels was examined by the turning test. In the cutting speed range of 100 to 250 m/min, fatigue-induced failure and diffusion wear was found to affect the tool life of TiN-coated cemented carbide tools.

In the turning and drilling operations tested, the presence of both BUE and workhardening were found to decrease the machinability of new high-strength stainless steels. HIPed and conventional cast stainless steel were compared in drilling operations, where PM-produced stainless steel Duplok 27 was found to be more difficult to machine than ASTM A 8910 stainless steel. Chips of Duplok 27 were found to be more strongly deformed than A890 1A chips. The formation of BUE causing adhesion wear was supposed to be the dominant failure mechanism of tools.

The effect of nitrogen was studied in the turning tests of high-nitrogen X5 CrMnN 18 18 stainless steels. The workhardening of a workpiece surface is decreased when the nitrogen content decreases from a nitrogen level of 0.91% to a level of 0.57%. Catastrophic failure of the tool nose was found. The machinability was also decreased by the presence of BUE.

Finally, in the drilling operations of conventionally cast stainless steel X2CrNi 19 11 with HIPed NiTi, effective cutting speeds were found of 50 m/min and feed rates of 0.1–0.2 mm/r without a deterioration in coating properties. The deformation effects of NiTi-coating and as well as stainless steels were found from chips and workpiece. An intact interface layer between the stainless steel and the NiTi-coating was also found on the deformed chips.

The first paper (Publication I) about the grindability of HIPed stainless steels was carried out in co-operation with the laboratories of Production Engineering and Engineering Materials at HUT. Lic.Tech. Risto Oraskari has been studying grinding technology and is currently working at the Helsinki Institute of Technology. The grinding experiments were carried out with the author and Dr.Tech. L. Jiang. The SEM analyses and metallography were done by Dr.Tech. L. Jiang. The author finished the paper during a research period financed by the Academy of Finland.

Publication II was also written in co-operation with the laboratories of Production Engineering and Engineering Materials at HUT. The turning experiments were carried out by the author and Dr.Tech. L. Jiang. The SEM analyses and metallography were mainly done by Dr.Tech. L. Jiang. The paper was finished and figures produced by the author during a research period financed by the Academy of Finland.

The research work presented in Publications III and IV was carried out during a period financed by the Graduate School of Concurrent Mechanical Engineering, supervised by Prof. Mauri Airila at HUT.

Publications V, VI and VII were written by the author. The presented research work was carried out at VTT Industrial Systems. The SEM and EDS analyses were carried out in co-operation with Tom E. Gustafsson M.Sc.

6. Summary of the appended papers

Publication I presents a comparison of the grindability of HIPed austenitic 316L, duplex 2205, super duplex 2507 and as-cast 04 stainless steels, using alumina wheels. Machinability was studied by grinding ratio, grinding force and surface roughness measurements. The ground surfaces were analysed by SEM and workhardening rates were measured.

Publication II compares the active wear and the failure mechanism of TiN-coated High-Speed Steel and Cemented Carbide tools when machining PM stainless steels. The machinability was studied by the turning of PM 316L and PM 2205 stainless steels. Chip samples were provided by a quick-stop device. Wear topography and the wear or failure mechanisms of tools were studied by SEM and EDS analyses.

Publication III compares the machinability of X5CrMnN 18 18 stainless steel with two different nitrogen levels. Solid carbide tools and chips were analysed by SEM. Machinability was studied by analysing chip morphology and the workhardening rate of the machined surface.

Publication IV compares the tool wear and machinability of HIPed PM with conventional cast stainless steel. The machinability testing was carried out in a machining centre using solid carbide drills with internal cooling. VT-curves are presented and machinability is compared to the Pitting Resistance Equivalent (PRE) index. The chips and drills are examined by SEM.

Publication V investigates the suitability of TiN and TiCN-coated cemented carbide tools in the drilling of conventionally cast stainless steel with a HIPed NiTi-coating. The machinability testing was carried out in a machining centre using solid carbide drills with internal cooling. The deformation of the stainless steel and NiTi chip is studied with SEM and EDS.

Publications VI and VII investigate chip morphology in the drilling of conventional cast stainless steel with a HIPed NiTi-coating. The machinability testing was carried out in a machining centre using solid carbide drills with external and internal cooling. The chip formation and surface quality is studied with SEM and EDS.

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Appendix I: Test devices

Grinding experiments (Publication I)

1. Materials

Workpiece materials

- PM316L, PM2205, PM2507 and AC304
- chemical compositions are presented in Table 1
- workpiece size
    - width x length: 8 x 200 mm^2
    - number of work pieces: 3 per material

Table 1. Chemical compositions of the stainless steels studied.

Code	%C	%Si	%Mn	%P	%S	%Cu	%Cr	%Ni	%Mo	%V	%Al	%N	%O
PM 316L	0.015	0.68	1.44	0.022	0.009	0.19	16.7	11.0	2.7	0.11	0.021	0.12	0.012
PM 2205	0.03	0.68	1.42	0.022	0.008	0.13	22.1	5.3	3.0	0.07	0.016	0.21	0.014
PM 2507	0.03	0.30	0.30	0.035	0.009	0.16	25.0	7.0	4.0	0.08	0.020	0.30	0.015
AC 304	0.03	0.40	1.20	0.040	0.015	0.17	18.4	9.2	-	0.06	0.025	0.10	0.001

Grinding wheel

- Norton 43A46 GVX
- diameter: Ø200 mm
- width: 12 mm
- grinding material: alumina Al_2O_3
- number of grinding wheels: 4

Grinding fluid

- 5% Castrol no. 7
- flow rate: 2 l/min

2. Machine tools

Surface grinding machine Okamoto PSG-5UAN

- grinding width and length: 200 x 500 mm^2
- distance between table and spindle: 500 mm
- hydraulic feed speed: 0.3–25 m/min
- automatic down feed: 0.004–0.03 mm
- grinding wheel dimensions
    - maximum diameter: Ø205 mm
    - wheel width: 19 mm
    - boring diameter: Ø50.8 mm
- power of the spindle motor: 1.5 kW

3. Measuring and analysing devices

Tesa Micro Hite I Height measuring device

- measuring area: 515 mm
- resolution: 0.001 mm
- accuracy: (3+6*L) µm, where L = meters

Kistler piezoelectric grinding dynamometer

Taylor Hobson surface roughness measurement device

Zeiss DSM 962 scanning electron microscope

- equipped with EDS link ISIS-system for qualitative chemical analysis

Microhardness measuring device MHT-4

- load: 20 g

Micrometer

4. Procedure

The microstructures of the test materials were characterised and photographed using a Nikon Epiphot optical microscope. Samples were polished mechanically and then etched with a mixture of HNO_3 (1 part), HCl (3 parts) and H_20 (4 parts).

The work pieces were held by a magnetic chuck. In the steady stage of wheel wear during grinding, the volumetric workpiece removal was calculated and radial wheel wear was measured using a Micro Hite device as a volumetric wheel wear for grinding ratio measurements. Wheel radius measurements were performed three times. Each material had its own grinding wheel.

The speed of the wheel was 30 m/s, the table speed was 0.25 m/s and the down feed was 0.015 mm/pass.

During grinding, F_n and F_c were recorded using a Kistler piezoelectric dynamometer and surface roughness was measured. After the grinding tests, metallographic examination and analyses of ground surfaces and profiles were performed using SEM and EDS.

5. Estimation of uncertainty of grinding ratio measurements

- test piece width and length measured with micrometer
- uncertainty: 0.005 mm
- material removal according to half of down feed value: 0.008 mm
- work piece material removal: V_w ±0.018 mm^3

- grinding wheel wear

$$\Delta V = 2*3.14*\Delta r*\Delta w$$
$$\Delta r = (3+6*0.2)\ \mu m$$
$$\Delta w = 0.005\ mm$$
$$\Delta V = \pm 0.03\ mm^3$$
$$\Delta G = \pm 0.018\ mm^3/\pm 0.03\ mm^3 = \pm 0.6$$

Turning experiments of PM316L and PM2205 (Publication II)

1. Materials

- bars with diameter of Ø70 mm and length of 350 mm
- bars of PM316L and PM 2205 with analyses according to Table 2
- heat treatment 3 hours at 1100 ºC

Table 2. Chemical compositions (wt. %) of HIP Stainless Steels: PM 316L and PM 2205.

Code	%C	%Si	%Mn	%P	%S	%Cr	%Ni	%Mo	%V	%Al	%Cu	%N	%O
PM 316L	0.05	0.68	1.44	0.022	0.009	16.7	11.0	2.7	0.11	0.021	0.19	0.12	0.012
PM 2205	0.03	0.66	1.42	0.022	0.008	22.1	5.3	3.0	0.07	0.016	0.13	0.21	0.014

2. Machine tool

Lathe VDF Heidenreich&Harbeck

- spindle power: 100 kW
- turning length: 750 mm
- max diameter: Ø300 mm
- rotation speed: max. 5000 1/min

Tools SPUN 120308

- HSS TiN Coeted Edgar Allen
- cutting speed: 15–55 m/min
- feed rate: 0.15 mm/r
- depth of cut: 1.0 mm

P30 cemented Carbide TiN coated

- cutting speed: 100–250 m/min
- feed rate: 0.15 mm/r
- depth of cut: 1.0 mm

Cutting fluid was not used

A quick stop device (Chip root experiments at Imatra Steel)

3. Measuring and analysing devices

Kistler piezoelectric turning dynamometer

Mitutoyo tool maker's microscope

Zeiss DSM 962 scanning electron microscope

- equipped with EDS link ISIS-system

Microhardness measuring device

MHT-4, load 20 g

4. Procedure

The test pieces were fixed using a chuck and tailstock. After turning, tool wear was measured from the insert until the criteria of 0.3 mm was reached. During machining cutting force components were recorded. Chip root samples were produced using a quick stop device.

The microstructures of the test materials were characterised and photographed using a Nikon Epiphot optical microscope. Samples were polished mechanically, and then etched with a mixture of HNO_3 (1 part), HCl (3 parts) and H_20 (4 parts).

Inserts and chips and chip root samples were analysed with SEM and EDS. Work piece samples were measured with a microhardness tester.

5. Estimation of uncertainty of tool wear measurements

- cutting parameters were set manually
- tool wear measurements were carried out using a tool maker's microscope
- accuracy 0.005 mm
- revised tests

Turning experiments of X5CrMnN18 18
(Publication III)

1. Materials with analysis according to Table 3

- one bar with a diameter of Ø125 mm and length of 620 mm, of high nitrogen steel 0.91%N
- one bar with a diameter of Ø130 mm and length of length 400 mm of high nitrogen steel 0.57%N

Table 3. Chemical compositions (wt.%) of X5 CrMnN 18 18 trial materials.

Melt	%C	%Si	%Mn	%Cr	%Mo	%Ni	%V	%N
G88216	0.05	0.29	18.89	18.13	0.11	0.43	0.08	0.57
DDt63	0.05	0.49	19.8	18.6	0.08	0.61	0.13	0.91

2. Machine tool

Lathe VDF Heidenreich&Harbeck

- spindle power: 100 kW
- turning length: 750 mm
- max diameter: Ø300 mm
- rotation speed: max. 5000 1/min

3. Cutting tools

Tools SNMG120408-PM

- P15/K15 cemented Carbide TiN- and Al_2O_3-coated
- cutting speed: 60, 65, 70 and 100 m/min
- feed rate: 0.24 mm/r
- depth of cut: 1.6 mm
- cutting fluid was not used

4. Measuring and analysing devices

Mitutoyo tool maker’s microscope

Kistler piezoelectric turning dynamometer

Zeiss DSM 962 scanning electron microscope

- equipped with EDS link ISIS-system

The Zeiss DSM 962 scanning electron microscope used was equipped with an EDS link ISIS-system for qualitative chemical analysis in the microstructure of chips and work piece surface profiles.

Microhardness measuring device

MHT-4, load 20 g

5. Procedure

The test pieces were fixed using a chuck and tailstock. After turning the tool wear was measured from the insert until the criteria 0.3 mm was reached. During machining cutting force components were recorded.

The microstructures of the test materials were characterised and photographed using a Nikon Epiphot optical microscope. Samples were polished mechanically, and then etched with a mixture of HNO_3 (1 part), HCl (3 parts) and H_20 (4 parts).

SEM and EDS were used for qualitative chemical analysis in the microstructure of chips and work piece surface profiles. Workpiece samples were measured with a microhardness tester.

6. Estimation of uncertainty of tool wear measurements

- cutting parameters were set manually
- tool wear measurements were carried out using a tool maker’s microscope
- accuracy: 0.005 mm
- revised tests

Drilling tests (Publication IV)

1. Materials

Materials with analysis according to Table 4 presented below.

- 4 plates of Duplok 27 (200 x 300 x 40 mm^3)
- 4 plates A8910 1A (200 x 300 x 40 mm^3)

Table 4. Chemical composition of the studied stainless steels (wt.%).

Code	%C	%Si	%Mn	%P	%S	%Cu	%Cr	%Ni	%Mo	%V	%Al	%N	%O
Duplok 27	0.03	0.2	0.7	0.02	0.001	2.3	26.5	7.0	3.0	-	-	0.3	-
A890 1A	0.03	0.74	0.63	0.026	0.006	3.01	25.0	5.54	2.03	-	-	-	-

2. Machine tool

Horizontal machining centre Mazatech FH480 with Mazatroll M Plus Control

- spindle revolution speed: 35–12000 1/min with spindle power of 22 kW
- spindle taper CAT 40
- feedrate: 32 m/min
- maximum workpiece size: diameter Ø610 mm, height 670 mm, weight 400 kg

3. Cutting tool

Solid carbide drills

- Titex Alpha4 + DX45

Tool adapter

- MST HiArt CT40-ART32-85S91

Cutting fluid

- Blaser BlasoCut –7%
- through spindle

4. Measuring and analysing devices

Mitutoyo tool maker's microscope

Zeiss DSM 962 scanning electron microscope
- equipped with EDS link ISIS-system

Microhardness measuring device
- MHT-4, load 20 g

5. Procedure

The work piece was fixed on a vice into the pallet of a machining centre. Drills were fixed using a high accuracy drilling tool holder. After drilling the drill wear was measured from the insert until the wear criteria of 0.3 mm was reached. During drilling cutting force components were recorded.

The microstructures of the test materials were characterised and photographed using a Nikon Epiphot optical microscope. Samples were polished mechanically, and then etched with a mixture of HNO_3 (1 part), HCl (3 parts) and H_20 (4 parts).

Drills and chips and chip root samples were analysed with SEM and EDS. Workpiece samples were measured with a microhardness tester.

6. Estimation of uncertainty of drill wear measurements

- cutting parameters were set manually
- tool wear measurements were carried out using tool maker's microscope
- accuracy: 0.005 mm
- revised tests

Drilling tests (Publications V–VII)

1. Materials

NiTi coated sample and capsule presented in Publication V

- X2CrNNi 1911 stainless steel block according the table below
- NiTi coating 55/45 wt.% of average thickness 5 mm

Table 5. The nominal composition of the steel used in the drilling experiment.

% C	% Mn	% S	% P	% Cr	% Ni	% Si	% V
0.03	1.20	0.015	0.04	18.4	9.2	0.4	0.06

2. Machine tool

Horizontal machining centre Mazatech FH480 with Mazatroll M Plus Control

- spindle revolution speed: 35–12000 1/min
- spindle power of 22 kW
- spindle taper: CAT 40
- feedrate: 32 m/min
- maximum workpiece size:
    - diameter Ø610 mm
    - height 670 mm
    - weight 400 kg

3. Cutting tool

Solid carbide drills

- Dijet DDS 850M with TiCN/TiN-coating, 8 pcs

Tool adapter

- MST HiArt CT40-ART32-85S91

Cutting fluid

- Blaser BlasoCut –7%
- through spindle

4. Measuring and analysing devices

Mitutoyo tool maker's microscope

JSM 6400 scanning electron microscope

- equipped with X-ray microanalysis system PGT PRISM with thin window

Microhardness measuring device

- MHT-4, load: 20 g

5. Procedure

The work piece was fixed on a vice into the pallet of a machining centre. Drills were fixed using a high accuracy drill holder. After drilling the drill wear was measured from the edges of the drill until the wear criteria of 0.3 mm was reached. Drills and chips and chip root samples were analysed with SEM and EDS. Workpiece samples were measured with a microhardness tester.

6. Estimation of uncertainty of tool wear measurements

- cutting parameters were set manually
- tool wear measurements were carried out using tool maker's microscope
- accuracy: 0.005 mm
- revised tests

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Machinability effects of stainless steels with a HIPed NiTi coating in high-efficiency machining operations

Abstract

The machinability effects of new high-strength stainless steels are studied due to specific properties arising from their structure. In the grinding operations HIPed austenitic 316L, duplex 2205 and super duplex 2507 and as-cast 304 stainless steel; in turning HIPed 316L, duplex stainless steel 2205 and X5 CrMnN 18 18 stainless steel; and in drilling HIPed PM Duplok 27 and duplex stainless steel ASTM8190 1A and X2CrNi 1911 with a HIPed NiTi coating were studied in revised machining testing environments by tool life testing, and chip and work piece surface morphology analysis. Chips, work piece surfaces and cutting tools were analysed by scanning electron microscopy (SEM) and EDS.

High toughness, work hardening and low heat conductivity have a synergistic effect in inducing machinability difficulties. An increased amount of alloying elements is found to decrease machinability in the forms of increased cutting force and work hardening rate of machined surface, and decreased tool life and surface roughness. Powder metallurgically produced stainless steels introduce increased machinability difficulties caused by more hard oxide particles included in PM-produced stainless steels. The formation of built-up edge is found to affect the machinability and tools of the tested high-strength stainless steels.

In grinding operations, HIPed austenictic 316L and duplex 2205 stainless steel are rated according to cutting force, work hardening rate and the amount of microvoids and microcracks in the ground surfaces. In turning operations, HIPed 316L, duplex stainless steel 2205 and X5 CrMnN 18 18 stainless steels are assessed in machinability order. The machinability of conventional cast duplex stainless steel ASTM8910 and HIPed duplex stainless steel Duplok27 were sorted according to their PRE-value.

Finally, in this study the suitability of coated cemented carbide tools in the drilling of conventionally produced cast stainless steels with a HIPed NiTi coating was investigated. In the drilling of difficult-to-cut X2CrNi 19 11 stainless steel with a pseudo-elastic coating, effective cutting parameters that maintain the adhesion layer between the NiTi coating and the stainless steel with advantageous surface finish were generated.

Keywords
stainless steels, machinability, machine tools, wear, surface coating, grinding, turning, drilling, nickel-titanium alloys

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Isostaattisella kuumapuristusmenetelmällä NiTi-pinnoitetun ruostumattoman teräksen suurtehotyöstön lastuttavuusvaikutuksia

Tiivistelmä

Uusien lujien ruostumattomien terästen ominaisuuksilla on suuri vaikutus niiden lastuttavuuteen. Tässä työssä tutkittiin isostaattisella kuumapuristuksella (HIP) valmistettujen austeniittisen 316L, duplex 2205 ja super duplex 2507 sekä valetun 304 ruostumattomien terästen hiontaa, HIP-menetelmällä valmistetun 316L ruostumattoman teräksen ja X5 CrMnN 1818 -tyyppiteräksen sorvausta sekä HIP-menetelmällä valmistetun Duplok 27 -teräksen ja ruostumattoman duplex-teräksen ASTM8190 1A porausta. Lisäksi tutkittiin HIP-menetelmällä valmistetun NiTi-pinnoitteella pinnoitetun X2CrNi 1911 ruostumattoman teräksen porausta. Lastuttavuutta selvitettiin sovelletuin testein tutkimalla terän kestoaikaa, analysoimalla lastujen ja työkappaleen pinnan morfologiaa. Lastuja, työkappaleiden pintoja sekä teriä tukittiin pyyhkäisyelektronimikroskoopilla (SEM) ja energiadispersiivisellä alkuaineanalyysillä (EDS).

Tutkittujen terästen ominaisuuksista suuri sitkeys, muokkauslujittuminen sekä matala lämmönjohtavuus aiheuttavat lastuttavuusongelmia. Runsaan seostuksen on todettu huonontavan lastuttavuutta, sillä lastuamisvoimat kasvavat, terien kestoajat lyhentyvät, koneistetut pinnat muokkauslujittuvat sekä työkappaleen pinnanlaatu huononee. Pulverimetallurgisesti valmistetuttujen ruostumattomien terästen mikrorakenteen kovat oksidit vaikeuttavat myös koneistettavuutta. Irtosärmän muodostumisen todettiin myös heikentävän testattujen terästen lastuttavuutta.

Tässä työssä havaittiin suurten lastuamisvoimien sekä hiotun pinnan muokkauslujittumisen ja mikrohalkeamien ja -säröjen muodostumisen vaikuttavan 316L sekä duplex 2205 ruostumattoman teräksen hiottavuuteen. Sorvaustutkimuksissa selvitettiin 316L:n, 2205:n sekä X5 CrMnN 1818:n lastuttavuuteen vaikuttavia tekijöitä, terän kestoaikoja sekä kulumismekanismeja. Porauksessa arvioitiin myös perinteisen valetun duplex-teräksen sekä HIP-menetelmällä valmistetun duplex ruostumattoman teräksen lastuttavuutta PRE-arvon (Pitting Resistance Equivalent) avulla. Lopuksi selvitettiin pinnoitettujen kovametalliporien soveltuvuutta pseudoelastisella NiTi-pinnoitteella pinnoitettujen valettujen ruostumattomien terästen poraukseen. Työssä löydettiin menetelmät ja lastuamisarvot, joilla voidaan saavuttaa riittäviä terien kestoaikoja ja pitää NiTi-pinnoitteen ja ruostumattoman teräksen välinen adheesiokerros vaurioitumatta sekä reikien pinnanlaatu hyvänä.

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The machinability effects of new high-strength stainless steels are studied due to specific properties arising from their structure. In the grinding operations HIPed austenitic 316L, duplex 2205 and super duplex 2507 and as-cast 304 stainless steel; in turning HIPed 316L, duplex stainless steel 2205 and X5 CrMnN 18 18 stainless steel; and in drilling HIPed PM Duplok 27 and duplex stainless steel ASTM8190 1A and X2CrNi 1911 with a HIPed NiTi coating were studied in revised machining testing environments by tool life testing, and chip and work piece surface morphology analysis. Chips, work piece surfaces and cutting tools were analysed by scanning electron microscopy (SEM) and EDS.

High toughness, work hardening and low heat conductivity have a synergistic effect in inducing machinability difficulties. An increased amount of alloying elements is found to decrease machinability in the forms of increased cutting force and work hardening rate of machined surface, and decreased tool life and surface roughness. Powder metallurgically produced stainless steels introduce increased machinability difficulties caused by more hard oxide particles included in PM-produced stainless steels. The formation of built-up edge is found to affect the machinability and tools of the tested high-strength stainless steels.

In grinding operations, HIPed austenictic 316L and duplex 2205 stainless steel are rated according to cutting force, work hardening rate and the amount of microvoids and microcracks in the ground surfaces. In turning operations, HIPed 316L, duplex stainless steel 2205 and X5 CrMnN 18 18 stainless steels are assessed in machinability order. The machinability of conventional cast duplex stainless steel ASTM8910 and HIPed duplex stainless steel Duplok27 were sorted according to their PRE-value.

Finally, in this study the suitability of coated cemented carbide tools in the drilling of conventionally produced cast stainless steels with a HIPed NiTi coating was investigated. In the drilling of difficult-to-cut X2CrNi 19 11 stainless steel with a pseudo-elastic coating, effective cutting parameters that maintain the adhesion layer between the NiTi coating and the stainless steel with advantageous surface finish were generated.

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