



<https://matplus.shop/produkt-kategorie/fosta-berichte>

Bestell-Nr. P 1373

ISBN 978-3-946885-41-2

Das Werk ist urheberrechtlich geschützt. Alle Rechte, auch die der Übersetzung in andere Sprachen, bleiben vorbehalten. Ohne schriftliche Genehmigung der Forschungsvereinigung Stahlanwendung e. V. sind Vervielfältigungen, Mikroverfilmungen und die Einspeicherung und Verarbeitung in elektronischen Systemen nicht gestattet.

Das IGF-Vorhaben der Forschungsvereinigung Stahlanwendung e. V., Düsseldorf, wurde über die AiF im Rahmen des Programms zur Förderung der industriellen Gemeinschaftsforschung (IGF) vom Bundesministerium für Wirtschaft und Klimaschutz aufgrund eines Beschlusses des Deutschen Bundestages gefördert.

Gefördert durch:



aufgrund eines Beschlusses
des Deutschen Bundestages



Optimierung von Werkzeugwerkstoffen für das Schneiden hochfester Materialien durch kryogene Behandlungen und Beschichtungen

Optimizing of cutting tools for high strength
materials by means of deep cryogenic
treatments and coatings

Forschung für die Praxis P 1373 / IGF-Nr. 240 EBG



Forschungsvereinigung
Stahlanwendung e. V.



Schlussbericht vom 31.03.2022

zu IGF-Vorhaben Nr. 240 EBG

Thema

Optimierung von Werkzeugwerkstoffen für das Schneiden hochfester Materialien durch kryogene Behandlungen und Beschichtungen

Optimizing of cutting tools for high strength materials by means of deep cryogenic treatments and coatings

Berichtszeitraum

01.01.2019 - 30.09.2021

Forschungsvereinigung

Forschungsvereinigung Stahlanwendung e. V.

Forschungseinrichtung(en)

Fraunhofer-Gesellschaft e.V. Fraunhofer-Institut für Werkzeugmaschinen und Umformtechnik IWU

Fraunhofer-Gesellschaft e.V. Fraunhofer-Institut für Schicht- und Oberflächentechnik IST

Gefördert durch:



Bundesministerium
für Wirtschaft
und Klimaschutz

aufgrund eines Beschlusses
des Deutschen Bundestages

**Common report of the
CORNET-project 240 EGB “DCT4Cut”**

Optimizing of cutting tools for high strength materials by means of deep cryogenic treatments and coatings

M. Demmler¹
M. Weber²
G. Claus³

¹ Fraunhofer Institute for Machine Tools and Forming Technology (IWU)

² Fraunhofer Institute for Surface Engineering and Thin Films (IST)

³ The Collective Center of the Belgian technological industry (SIRRIS)

Members of the User Committee

ADZ LüTec LEIPZIG GmbH, Markkleeberg

Albert Schmutzler GbR, Aue

Andreas Junghans GmbH & Co. KG, Frankenberg

Bond-Laminates GmbH, Brilon

CoolTech -180°C GmbH, Stanzach

IDEEMA GmbH, Kamenz

Ingenieurbüro Paatz, Chemnitz

IT Ingenieurtechnik GmbH, Augustusburg

KraussMaffei Technologies GmbH, München

KWD Automotive GmbH, Radeberg

Leibniz-Institut für Werkstofforientierte Technologien (IWT), Bremen

Mieruch & Hoffmann GmbH, Limbach-Oberfrohna

MSA Maschinenbau GmbH, Chemnitz

MSC Metall-Service-Center GmbH, Chemnitz

Parker Hannifin GmbH, Kaarst

SCHERDEL Marienberg GmbH, Marienberg

Sirris, Zwijnaarde

SYNTEKS Umformtechnik GmbH, Zwönitz

VOM, Leuven

Werkzeugbau Hartmann GmbH, Chemnitz

Werkzeugbau Ullmann, Bockau

WESOBÄ Werkzeug- und Sondermaschinen GmbH, Schwarzenberg

WESTFALIA Presstechnik GmbH & Co. KG, Crimmitschau

WVG Chemnitz Werkzeuge und Maschinen, Chemnitz

Table of Content

Summary	3
Zusammenfassung	4
List of Figures	5
List of Tables	8
List of Abbreviations and Symbols	9
1 State of the Art and Research	11
1.1 Cutting of sheet materials	11
1.2 DCT	12
1.3 Tool Materials and Coatings	13
1.4 Status of work and results of the previous project "Infiblack"	14
2 Scientific-and technical approach	15
2.1 The scientific and Economic Problem	15
2.2 Research Objectives	19
2.3 Innovation Target	19
2.4 Work Outline	20
3 Project Consortium	22
3.1 Overview	22
3.2 Contact data	24
3.3 User committee	26
4 Results in Detail	28
4.1 Selection and characterization of cutting processes	28
4.1.1 Definition of materials and geometries for lab scale tests and industrial demonstrators	28
4.1.2 Definition of wear characterisation tests / component quality determination	32
4.2 Optimization of the Tool Material (Sirris)	35
4.2.1 Material selection and acquisition	35
4.2.2 Heat treatment and deep cryogenic treatment of tool steels	37
4.2.3 Hardness and determination of retained austenite	38
4.3 Coating development and optimization (IST)	44
4.3.1 Optimization of the plasma diffusion treatment	44
4.3.2 Cryogenic treatment of coatings	50
4.3.3 PDT and coating of test and production tools	54
4.4 Tool manufacturing with different fabrication strategies (IWU)	55
4.5 Laboratory scale cutting tests & characterization of produced parts (IWU + IST)	55

4.5.1	Conventional cutting of different high strength materials (IWU)	55
4.5.2	High speed impact cutting (IWU)	60
4.5.3	Optical analysis of wear mechanisms (IST)	62
4.5.4	Cross-sectional investigation of the wear mechanisms (IST).....	71
4.5.5	Additional wear tests (IWU).....	74
4.6	Cutting tests under production conditions.....	76
4.6.1	Cutting of steel and high strength steel.....	76
4.6.2	High speed cutting	79
4.7	Systematization, Evaluation, Guidelines, Final report.....	80
5	Use of the grant	82
6	Explanation of the necessity and appropriateness of the work done	83
7	Presentation of the scientific-technical and economic benefits for SME	84
8	Adjusted plan for transfer of the results	85
9	Assessment of the feasibility of the proposed and updated transfer concept	88
10	Funding information	89

Summary

Cutting is an essential part in the production of parts and components in most industrial sectors. Nearly every part made from sheet material runs through several cutting steps. Especially shear cutting is very common for mass production in the industry due to its very high efficiency compared to other methods like laser cutting or water jet cutting. However, the increasing requirements concerning cutting of high strength sheet materials (e.g. high strength steel or fiber-reinforced materials) are pushing the shear cutting method to their limits. The main problem is insufficient lifetime of the blanking tools for cutting of high demanding materials. An increase in hardness and compression strength of the tool materials comes along with a decreasing fracture toughness. Early tool breakage or break out of the cutting edges are the limiting factor for cutting high strength materials. New highly efficient shear cutting methods like high-speed impact cutting (HSIC) cannot be used in the industry due to the limitations of the common tool materials.

There is a huge demand to overcome the problem of early tool breakage in demanding cutting operations by strengthening the tool materials.

In the CORNET-Project InFiBlank (14th Call) the lifetime of a highly loaded fine blanking tools made from high alloyed tool steels could be more than doubled by deep cryogenic treatment (DCT) of the tool material. Especially the break out of the cutting edges was significantly reduced. This approach was combined in this project with adepthed diffusion treatments and coatings. Main target of the project was a significant increase of tool life for cutting high strength materials (high strength steels, fiber-reinforced composites) and for HSIC.

Objectives in detail have been:

- Optimization and integration of DCT treatment in the production process of the tools
- Combination of DCT with plasma nitriding treatments and coatings
- Proof of concept for blanking of high-strength materials (steel, fiber-reinforced composites)
- Proof of suitability for HSIC to prevent early tool breakage
- Validation of the concept in different industrial applications
- Formulation of a treatment recommendation for the cutting tools

Summary Results:

Different process routes were compared for DCT treatment, differing in the timing of DCT treatment and cooling curves. Effects on material properties could be achieved with all process routes. Depending on the material and the time of DCT treatment, different effects can occur.

The positive effect of DCT treatment on the wear behavior and service life of cutting tools has been confirmed for cutting high strength steel and HSIC on laboratory scale and in different industrial applications. The economic benefit for the different cutting processes depends on the type of tool load and the resulting wear mechanisms. Positive effects can be achieved especially when cutting edge chipping due to fatigue effects and cracking are the limiting wear mechanisms. In this case, a DCT treatment can significantly increase the tool life.

Plasma nitriding of the tools turned out to be another highly effective measure for reducing cutting edge chipping and crack formation in the cutting tools. A precondition for this is the use of nitriding parameters adapted to the tool materials and the load situation of the tools. These were developed within the project.

The aims of the research project were achieved.

Zusammenfassung

Das Schneiden ist in den meisten Industriezweigen ein wesentlicher Bestandteil der Produktion von Teilen und Komponenten. Nahezu jedes aus Blech gefertigte Teil durchläuft mehrere Schneideschritte. Vor allem das Scherschneiden ist aufgrund seiner hohen Effizienz im Vergleich zu anderen Verfahren wie dem Laser- oder Wasserstrahlschneiden in der industriellen Massenproduktion weit verbreitet. Die zunehmenden Anforderungen an das Schneiden von hochfesten Blechwerkstoffen (z.B. hochfester Stahl oder faserverstärkte Werkstoffe) bringen das Scherschneiden jedoch an seine Grenzen. Das Hauptproblem ist die unzureichende Standzeit der Stanzwerkzeuge beim Schneiden von hochbeanspruchten Materialien. Mit zunehmender Härte und Druckfestigkeit der Werkzeugwerkstoffe geht eine abnehmende Bruchzähigkeit einher. Ein frühzeitiger Werkzeugbruch oder ein Ausbrechen der Schneiden ist der limitierende Faktor beim Schneiden hochfester Werkstoffe. Neue hocheffiziente Scherschneidverfahren wie das Hochgeschwindigkeits-Scherschneiden (HSIC) können in der Industrie aufgrund der Grenzen der üblichen Werkzeugwerkstoffe nicht eingesetzt werden.

Es besteht ein großer Bedarf, das Problem des vorzeitigen Werkzeugbruchs bei anspruchsvollen Schneidprozessen durch eine Optimierung der Werkstoffeigenschaften zu lösen.

Im CORNET-Projekt InFiBlank (14. Call) konnte die Standzeit eines hochbelasteten Feinschneidwerkzeugs aus hochlegierten Werkzeugstählen durch eine Tieftemperaturbehandlung (DCT) des Werkzeugmaterials mehr als verdoppelt werden. Insbesondere der Ausbruch der Schneidkanten wurde deutlich reduziert. Dieser Ansatz wurde in diesem Projekt mit angepassten Diffusionsbehandlungen und Beschichtungen kombiniert. Hauptziel waren eine signifikante Erhöhung der Werkzeugstandzeit beim Schneiden von hochfesten Werkstoffen (hochfeste Stähle, faserverstärkte Verbundwerkstoffe) und beim HSIC.

Die Ziele im Einzelnen waren:

- Optimierung und Integration des DCT in den Fertigungsprozess der Werkzeuge
- Kombination des DCT mit Plasmanitrierbehandlungen und Beschichtungen
- Machbarkeitsnachweis am Beispiel des Schneidens hochfester Werkstoffe (Stahl, faserverstärkte Verbundwerkstoffe)
- Nachweis der Eignung für das HSIC zur Verhinderung von frühzeitigem Werkzeugbruch
- Validierung des Konzepts in verschiedenen industriellen Anwendungen
- Formulierung einer Behandlungsempfehlung für die Schneidwerkzeuge

Zusammenfassung Ergebnisse:

Für die DCT-Behandlung wurden verschiedene Prozessrouten verglichen, die sich durch den Behandlungszeitpunkt und die Kühlkurven unterscheiden. Änderungen der Materialeigenschaften konnten mit allen Prozessrouten erzielt werden. Je nach Werkstoff und Zeitpunkt der DCT-Behandlung konnten unterschiedliche Effekte festgestellt werden.

Die positive Wirkung der DCT-Behandlung auf das Verschleißverhalten und die Standzeit von Schneidwerkzeugen konnte für das Schneiden von hochfestem Stahl und das HSIC in verschiedenen Anwendungen nachgewiesen werden. Der wirtschaftliche Nutzen für die einzelnen Schneidprozesse hängt von der Art der Werkzeugbelastung und den daraus resultierenden Verschleißmechanismen ab. Positive Effekte können vor allem erzielt werden, wenn Schneidenausbrüche aufgrund von Ermüdungseffekten und Rissbildung die Standzeit der Werkzeuge limitieren. Hier kann eine DCT-Behandlung die Standzeit signifikant erhöhen.

Als weitere hochwirksame Maßnahme zur Reduzierung der Schneidkantenausbrüche und der Rissbildung in den Schneidwerkzeugen stellte sich das Plasmanitrieren der Werkzeuge heraus. Voraussetzung dafür ist der Einsatz von Nitrierparametern, die auf die Werkzeugwerkstoffe und die Belastungssituation der Werkzeuge abgestimmt sind.

Das Ziel des Forschungsvorhabens wurde erreicht.

List of Figures

Figure 1: Comparison of die cutting methods	11
Figure 2: Increasing use of high strength steels in the automotive industry	15
Figure 3: Use of fibre reinforced composites in the automotive industries and others.....	15
Figure 4: Workplan	21
Figure 5: Interactions within the project	22
Figure 6: Structure of the process chain represented by the user committee.....	24
Figure 7: Lab scale cutting test at Fraunhofer IWU with round tools, high strength steel 1.4310	28
Figure 8: Lab scale cutting test at Fraunhofer IWU with "Dreieckgeometrie", stainless steel 1.4301	29
Figure 9: Lab scale HSIC cutting test at Fraunhofer IWU	29
Figure 10: Lab scale cutting test at Fraunhofer IWU with rectangular tools, composite Tepex ® dynalite	30
Figure 11: Industrial cutting test "Fuelcells" with complex phase steel	30
Figure 12: Industrial HSIC cutting test of solid copper	31
Figure 13: 3-Roll-Wear-Test at IMP Warschau	32
Figure 14: Results of the scratch tests on different steel; SEM-images of steel K110	33
Figure 15: Laser-Specle-Photometrie at IKTS Dresden and speckle analysis of a DCT treated punch.	34
Figure 16: Example of steel samples used for hardening (at right end: identification code).....	37
Figure 17: Hardness of the samples after hardening with and without DCT	38
Figure 18: Retained austenite content after hardening and DCT	39
Figure 19: Tempering diagram of Caldie (left) and K110 (right), without DCT	39
Figure 20: Tempering diagram of K390 (left) and Vanadis 4E (right), without DCT	40
Figure 21: Carbide content after hardening and DCT	40
Figure 22: SEM images of Vanadis 4E, K110 and K390 with and without DCT	41
Figure 23: Impact toughness of steel samples with and without DCT	42
Figure 24: SEM-images of the fracture surface of K110 (HT: left, HT+DCT: right)	42
Figure 25: Set-up of the mobile residual stress measuring apparatus Stresstech	43
Figure 26: Results of residual stress measurements	43
Figure 27: Schematic illustration of the nitriding zone	44

Figure 28: Hardness depth profiles in dependency on the nitriding parameters (T = 520°C)	46
Figure 29: Rockwell-indentation-test of K110 (1.2379); CHT, nitriding temperature 520°C	47
Figure 30: Rockwell-indentation-test of Vanadis 4E; CHT, nitriding temperature 520°C	47
Figure 31: Wear trace after scratch test on plasma-nitrided steel K110 (1.2379) for different DCT treatments (Nitriding: 5% N ₂ , 4 h, 520°C)	48
Figure 32: Hardness depth profiles and Rockwell-indentation-test of nitrided steel K110 (1.2379) with conventional heat treatment (CHT) and DCT	48
Figure 33: Hardness depth profiles in dependency on nitriding parameters and DCT	49
Figure 34: Crack formation in dependency on nitriding parameters and heat treatment	50
Figure 35: Sample preparation and characterization methods used for investigation of DCT influence on the coatings	51
Figure 36: Influence of DCT on hardness and indentation modulus of metal nitride coatings	52
Figure 37: XRD-analysis of the CrAlTiSiN coating before and after DCT	53
Figure 38: Influence of DCT on hardness and indentation modulus of carbon based coatings	53
Figure 39: Schematic diagram of the timing and type of heat treatment	54
Figure 40: Used tool manufacturing fabrication strategies (round tools K390)	55
Figure 41: Lab scale cutting test with round tools. Weight loss and cutting edge radius of the punch after 100.000 strokes in steel 1.4310. Tool material K390 CHT	57
Figure 42: Lab scale cutting test at Fraunhofer IWU with "Dreieckgeometrie" and resulting wear	58
Figure 43: Lab scale cutting test at Fraunhofer IWU with composite material	59
Figure 44: Tool wear after cutting composite material Tepex dynalite	59
Figure 45: High speed impact cutting, parameters	60
Figure 46: High speed impact cutting, punch geometry	60
Figure 47: High speed impact cutting, variation of impact energy	61
Figure 48: High speed impact cutting, variation of cutting gap	61
Figure 49: High speed impact cutting, punch after 35 strokes	62
Figure 50: Optical analysis of wear mechanisms on the tools with "Dreieckgeometrie" after cutting	62
Figure 51: Tool wear "Dreieckgeometrie". Influence of the tool material (uncoated and coated)	64

Figure 52: Tool wear "Dreieckgeometrie". Influence of the tool material (DCT and DCT cyclic)	65
Figure 53: Tool wear "Dreieckgeometrie". Influence of the DCT treatments (K110 / 1.2379)	66
Figure 54: Tool wear "Dreieckgeometrie". Influence of the DCT treatments (Caldie)	67
Figure 55: Tool wear "Dreieckgeometrie". Influence of the DCT treatments (Vanadis 4E)	67
Figure 56: Tool wear "Dreieckgeometrie". Influence of the DCT treatments (K390)	68
Figure 57: Tool wear "Dreieckgeometrie". Influence of the coatings (DCT cyclic, K110 and K390)	69
Figure 58: Tool wear "Dreieckgeometrie". Influence of the tool material (PN and PN + CrTiAlSiN)	70
Figure 59: Cross section tool "Dreieckgeometrie". Influence of DCT (K110 / 1.2379 coated)	72
Figure 60: Cross section tool "Dreieckgeometrie". Influence of DCT and PN (K110 / 1.2379 coated)	73
Figure 61: 3-Roll-Wear-Test at IMP Warschau. Used cryogenic treatments.	74
Figure 62: 3-Roll-Wear-Test at IMP Warschau. Influence of DCT on linear wear (K110 / 1.2379)	75
Figure 63: 3-Roll-Wear-Test at IMP Warschau. Influence of DCT on linear wear (K390)	75
Figure 64: Industrial cutting test "Fuelcells" with complex phase steel. Speckle analysis of the punch before and after DCT treatment	76
Figure 65: Industrial cutting test "Fuelcells" with complex phase steel. Comparison of tool wear (punch 1.2379 CHT and DCT)	77
Figure 66: Rivet (left) and commercial punch (right) for making rivets	77
Figure 67: Punches from the industrial cutting test at Dejong before and after testing	78
Figure 68: Side cutters from the industrial cutting test at Haemers NV (left: XS=DCT), right punching dies with side cutters	78
Figure 69: Punch for industrial test at Stow (left), mounted punches in the die (right)	79
Figure 70: Industrial HSIC cutting test of solid copper. Tool wear after 220.000 strokes (CHT and DCT)	80

List of Tables

Table 1: Comparison of the cutting methods for sheet materials	12
Table 2: Influence of the DCT on the lifetime of tools for different applications	13
Table 3: Economic benefit for one company using hardened tools for cutting operations	18
Table 4: Economic benefit for 1 company in terms of saving costs for an production volume of 500.000 parts per year using HSIC instead of precision cutting	18
Table 5: Association - VOM	24
Table 6: Association - FOSTA	24
Table 7: Association - FGW	25
Table 8: Research Performer - SIRRIIS	25
Table 9: Research Performer - Fraunhofer IST	25
Table 10: Research Performer - Fraunhofer IST	25
Table 11: List of participating companies in Germany and Belgium	26
Table 12: Composition of tool steels for industrial cutting tests in Belgium.....	32
Table 13: Selection matrix for Uddeholm steels.....	35
Table 14: Selection matrix for Böhler steels.....	36
Table 15: Composition of the steels used for lab scale tests	37
Table 16: Hardening parameters for lab scale samples.....	38
Table 17: Typical process parameter for plasma nitriding of tool steels	45
Table 18: Process parameters used for optimizing the PDT	45
Table 19: Selected coatings for cryogenic treatment	51
Table 20: Tool variants used for conventional cutting of high strength steels	56
Table 21: Scientific-technical and economic benefits for SMEs.....	84
Table 22: Dissemination activities during project phase (Germany)	85
Table 23: Dissemination activities during project phase (Belgium)	86
Table 24: Dissemination plan after project phase	87

List of Abbreviations and Symbols

List of Abbreviations

Abbreviation	Relevance
AiF	Arbeitsgemeinschaft industrieller Forschungsvereinigungen
CHT	Conventional Heat Treatment
CrAlN	Chromium Aluminium Nitride
DCT	Deep Cryogenic Treatment
DLC	Diamond Like Carbon
EDM	Electro Discharge Machining
ESR	Electro Slag Refining steel
FGW	Forschungsgemeinschaft Werkzeuge und Werkstoffe e.V.
FOSTA	FOSTA - Forschungsvereinigung Stahlanwendung e. V.
Fraunhofer IST	Fraunhofer Institute for Surface Engineering and Thin Films IST
Fraunhofer IWU	Fraunhofer Institute for Machine Tools and Forming Technology IWU
GRP	Glass fibre Reinforced Plastic
HSIC	High-Speed Impact Cutting
HT	Hardening and tempering (conventional)
PACVD	Plasma Assisted Chemical Vapour Deposition
PDT	Plasma Diffusion Treatment
PM	Powder Metallurgy steel
PVD	Physical Vapour Deposition
RA	Retained austenite
RT	Room temperature
SME	Small and Medium Enterprise
Sirris	Collective Research Center of the Belgian Technological Industry
TiAlN	Titanium Aluminium Nitride
TiCN	Titanium Carbo-Nitride
TiN	Titanium Nitride
UC	User Committee
VOM	Belgische Vereniging voor Oppervlaktetechnieken van Materialen
WC	Wolfram Carbide (= tungsten carbide)
WP	Work Package
XRD	X Ray Diffraction technique

Symbols

Symbol	Relevance	Unit
F_s	shear cutting force	N
v_s	shear cutting velocity	m/s

1 State of the Art and Research

Cutting is an essential part in the production of parts and components in most industrial sectors. Nearly every part made from sheet material runs through several cutting steps. Especially shear cutting is very common for mass production in the industry due to its very high efficiency compared to other methods like laser cutting or water jet cutting. However, the increasing requirements concerning cutting of high strength sheet materials (e.g. high strength steel or fiber-reinforced materials) are pushing the shear cutting method to their limits. The main problem is insufficient lifetime of the blanking tools for cutting of high demanding materials. An increase in hardness and compression strength of the tool materials comes along with a decreasing fracture toughness. Early tool breakage or break out of the cutting edges are the limiting factor for cutting high strength materials. New highly efficient shear cutting methods like high-speed impact cutting (HSIC) cannot be used in the industry due to the limitations of the common tool materials.

1.1 Cutting of sheet materials

Shear cutting: Due to its high cost-effectiveness, shear cutting plays an important role for cutting of sheet materials or flat profiles. Actually, most of these cutting processes base on conventional cutting or fine blanking (Figure 1). The punch movement draws the sheet metal over the cutting edge with a constant force F_s . The die clearance in case of normal cutting is rather high. This generates an edge burr with a curved fracture surface. The die clearance in fine blanking is much smaller. The blank holder, consisting of a guide plate equipped with beads or stingers, is pressed against the sheet with a constant force. This prevents sheet deformation and results in high quality parts (no rework necessary).

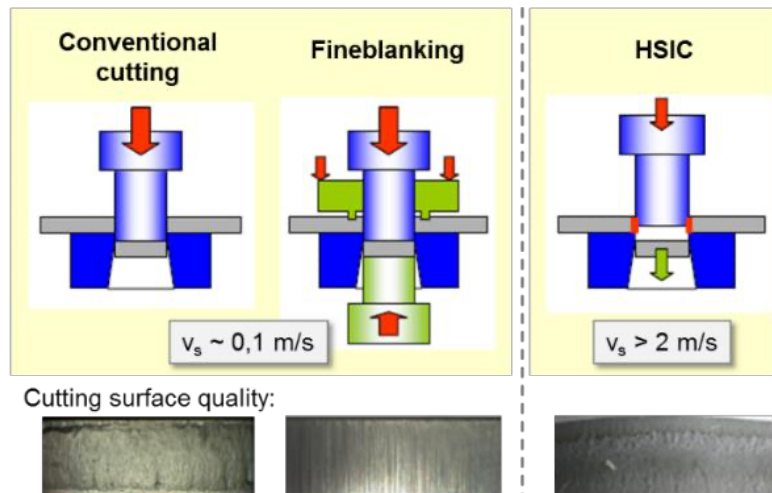


Figure 1: Comparison of die cutting methods

The advantages of high cutting velocities are well known from the literature. In recent years shear cutting processes with cutting velocities $>2 \text{ m/s}$ (High Speed Impact Cutting, HSIC) were developed and show very promising results concerning the part quality and efficiency (see chapter 2.1) [1,2]. This cutting procedure effects so called shear bands, which cause a high quality separation of the material. The development of mobile setups, which can be applied in conventional production presses, offers an easy and cost effective possibility for SMEs

to use the positive effects of HSIC. Limiting factor for using economic shear cutting process is mainly insufficient tool life. Tool fracture in combination with abrasive and adhesive wear is the main issue in most cutting processes especially for high strength materials and HSIC. Tool materials with high toughness, fatigue strength and low adhesive and abrasive wear are needed. Alternatives for cutting high strength materials are mainly laser cutting and waterjet cutting (see Table 1). But, concerning the productivity in mass production and process chain integration they cannot compete with the shear cutting methods.

Table 1: Comparison of the cutting methods for sheet materials

Method	Advantages/Disadvantages
Shear cutting	+ Low cycle times → <i>good for high lot sizes/mass production</i> + Easy to integrate in forming processes + High cutting quality (Fine blanking, HSIC) – Separate tool for each cutting process necessary – Cutting of high strength materials (tool breakage, wear)
Laser cutting	+ Nearly wear free + High flexibility → <i>good for small production series</i> – High cycle times (especially for thick sheet materials) – Limited cutting quality – Degradation of material properties due to high temperatures (annealing/hardening effects, degradation of composites)
Waterjet cutting	+ Nearly material independent + High cutting quality + Low cutting velocity → <i>only for small production series</i> – Cost-intensive (wastewater treatment) – Risk of delamination (composites)

1.2 DCT

A new method to enhance the characteristics of tool equipment are deep cryogenic treatments (DCT). The low temperatures could improve hardness and toughness and subsequent tool life. DCT is a special heat treatment where the metal is slowly cooled to very low temperatures usually the liquid nitrogen boiling temperature ($-196\text{ }^{\circ}\text{C}$), held at that temperature for a specific time and warmed to room temperature at a specific rate. The mechanism for the improvement is attributed to transformation of retained austenite to martensite, the formation of fine eta carbides and the decrease of internal stress during hardening. Table 2 shows the average lifetime of tooling parts with and without the DCT. However, this positive influence is not always observed, certain materials like Co or W containing tool steel do not show the expected improvement.

Table 2: Influence of the DCT on the lifetime of tools for different applications

Method	Tooling material	Average life-time without DCT	Average lifetime with DCT	Gain ratio
Punching S700MC [1]	1.2379	30.000 strokes	100.000 strokes	3.3
Punching 100Cr6 [4]	M2	150.000 strokes	380.000 strokes	2.5
Fine Blanking Nirosta1500 [3]	Vanadis 4E	7.800 strokes	15.600 strokes	2
Punching DC04+Zn [3]	Vanadis 23	8.500 strokes	10.000 strokes	1.2

- [1] F. Wendl et al. *Einfluss einer Cryobehandlung auf die Verschleissbeständigkeit von Stempeln (HTM 2011-4)*
- [2] G. Claus, M. Weber, M. Demmler, *Lifetime Increase of Tools for Fineblanking of Steel Sheet (European Heat Treatment Conference 2016)*
- [3] W. Lausecker *Tiefenperaturbehandlung Anwendungsbeispiele (internal document Cooltech)*

1.3 Tool Materials and Coatings

The tools used for cutting and shearing materials are mostly made of alloyed tool steel because of the high requirements for toughness and hardness. Hard metal and ceramic tools are much too brittle for this application. The wear resistance is related to the toughness. Powder metallurgical steel possesses the highest resistance against wear compared to the conventional and electroslag refined steel.

Currently mainly titanium based tool coatings like TiN, TiCN or TiAlN are used in cutting operations or fine blanking of steel sheet materials. TiAlN coatings are in wide use for fine blanking tools due to their good wear resistance and hardness [1]. These hard tool coatings were mainly deposited by PVD techniques [2]. Tool coatings for cutting materials with high adhesive tendency were often combined with anti-adhesive or dry lubricant coatings, e.g. carbon based DLC coatings. For demanding applications, in recent years CrAlN-based hard coatings were developed [3]. For enhancement the load bearing capacity and supporting the hard coating often a nitriding of the tool is applied [4]. But for preventing embrittlement or edge breakage the nitriding process has to be adjusted.

- [1] G. Erkens, *New approaches to plasma enhanced sputtering of advanced hard coatings, Surface & Coatings Technology 201 (2007) 4806–4812*
- [2] S. PalDey, S.C. Deevi, *Single layer and multilayer wear resistant coatings of (Ti,Al)N: a review, Materials Science and Engineering A342 (2003) 58-79*
- [3] B. Podgornik et al., *Application of hard coatings for blanking and piercing tools, Wear 270 (2011) 850–856*
- [4] Y. He, I. Apachitei, J. Zhou, T. Walstock, J. Duszczek, 2006, *Effect of prior plasma nitriding applied to a hot-work tool steel on the scratch-resistant properties of PACVD TiBN and TiCN coatings; Surface and Coatings Technology, 201: 2534–2539*

1.4 Status of work and results of the previous project “Infiblack”

In a previous Cornet Project “Infiblack”, the lifetime of punches for fine blanking of steel, and stainless steel was studied. The main results can be summarized as follows:

- The lifetime of tools treated by DCT increased in a significant way. Both conventional and post-treatment DCT had a positive effect especially on flaking of punch edges.
- The use of special coatings is an important parameter to decrease the adhesive wear. Several PVD coatings were applied with success after nitriding the tools.
- The surface preparation is another important parameter to reduce the adhesion of the workpiece material. Blasting and polishing of the punches gave the best results.

This new project aim to extend the knowledge to other shearing methods like HSIC and other materials like fiber-reinforced composites and ultra-high strength steels.

2 Scientific-and technical approach

2.1 The scientific and Economic Problem

Targeted Market Sector

Primary targeted is the sector for forming and cutting of high strength sheet materials e.g. high strength steels and fibre reinforced composites. The use of these materials is constantly growing. Manufacturers of complex formed sheet or profile products supply different industrial sectors for example for automotive, train and aircraft equipment, wind turbine components, facade profiles and elements (Figure 2 and Figure 3).

Golf VII (2008 – 2012):

66% high and ultra high strength steel

+ 14%



- 23 kg (Karosserie)

Golf VII (2012 – heute):

80% high and ultra high strength steel

→ Increasing use of high strength steels with tensile strength > 1000 MPa

High and ultra high strength steel in a Golf VII



Figure 2: Increasing use of high strength steels in the automotive industry



Figure 3: Use of fibre reinforced composites in the automotive industries and others

These industrial sectors mainly export their products to all countries in Europe, North America and Asia. The growth of the business in these targeted sectors depends strongly on the attitude of the companies towards innovation and the ability to process the actual materials in an economic way. In the second place the project will also affect companies in the so called 'value chain' of materials, tool manufacturing and coatings. Especially suppliers of tool materials, heat treating and coating companies. Finally yet importantly, there are the toolmakers who design and build the cutting tools and cutting machines.

Estimated size of targeted market sector

This project focuses on SME companies mainly active in forming and cutting of sheet metal and fiber reinforced composite materials in Flanders and Germany.

Market for sheet metal forming and cutting

In Germany the sheet metal forming and cutting industry has more than 5.500 companies, most SME's with currently over 65.000 employees. The turnover for 2014 was 12.9 Bn.€ for Germany and the growing trend is still going on.

In Flanders (Belgium) the estimated number of companies involved in sheet metal cutting is 1.700, the number of employees ca 18.000. The actual economic evolution follows the same trends observed in Germany. Approx. 80% of the companies are SMEs. The turnover in 2016 is estimated at 5 Bn. € and has increased by more than 10% in 2017.

The market for fibre reinforced plastics or composites grew – for the fifth consecutive year – by 2 % compared to the previous year in Europe in 2017. The composite market is dominated by glass fibre reinforced plastics (GRP) accounting for approx. 95 % of its total volume. The volume of GRP manufactured in Europe is 1.118 million tonnes [1]. Significant changes especially in the future in vehicle production or a booming construction sector have a knock-on effect for suppliers and thus for the industry. [1]

[1] Witten, E.: *The European GRP-market 2017. Industrievereinigung Verstärkte Kunststoffe e.V., 2017*

The Need

Tools with increased and high lifetime

The application of cutting process for high strength materials at SME's requires high quality tools with a high lifetime. Following some challenges for SME's are explained:

- Tool fracture is a main issue especially in HSIC due to cyclic high impact forces. Tools with high toughness and fatigue strength are needed to use the advantages of HSIC.
- Adhesive wear can lead to galling and tool fractures. High quality tools with low adhesive wear to reduce the costs for reworking or replacement are needed.
- The higher quality of the tools especially of the cutting edges over a longer production run will ensure a constant and better part quality.

Reduction of waste and energy consumption

DCT offers a higher efficiency of material by less waste during cutting.

- Increased tool life means, decrease of tool material and energy for manufacturing.
- Less distortion of tools due to the dimensional changes after hardening by use of DCT and low temperature PVD coating processes.

Due to ecological and health reasons the use of lubricants should be significantly reduced in all cutting processes. Cutting processes without use of lubricant are also interesting because no post-cleaning is necessary. If DCT of tools can stimulate the use of the HSIC process the amount of lubricants will decrease and an important cost saving is expected as well as an ecological benefit.

Position and pre-competitive character of the project

Cutting is an essential part in the production of parts and components in most industrial sectors. Especially shear cutting is very common for mass production in the industry due to its

very high efficiency compared to other methods like laser cutting or water jet cutting. However, the increasing requirements concerning cutting of high strength materials are pushing the shear cutting method to their limits. The main problem is insufficient lifetime of blanking tools. An increase in hardness and strength of the tool materials comes along with a decreasing fracture toughness. Early tool breakage, break out of the cutting edges are the limiting factor for cutting high strength materials. New highly efficient shear cutting methods like high-speed impact cutting (HSIC) cannot be applied in the industry due to the limitations of the common tool materials.

However, new tool materials, special heat and Deep Cryogenic Treatments (DCT) demonstrated their potential to reduce tool breakage and spalling of the cutting edges significantly. In a previous research project (CORNET 102 EBG - "InFiBlank") with DCT an significant increase of tool life could be demonstrated in selected application. Additionally hard coatings in combination with adapted plasma diffusion treatments (PDT) will reduce abrasive wear and avoid adhesion of the workpiece material.

The pre-competitive character of this project base on these issues. Improving the production process is mostly not applicable for an individual SME due to high costs. The special heat treatment as well as new coatings will be introduced for high performance tools. The results from this research will be disseminated to the involved SME's in the target sector. During and after this research, innovative projects can be started to integrate this technology into their production.

Estimated economic impact

Cutting processes are an economically important part of the production in many branches. Nearly every component is subject to one or more cutting processes during production. Conventional cutting and fine blanking processes are well established. Nevertheless, these established processes have some limitations regarding cutting of high strength materials. The tool life is limited due to break out of cutting edges and tool breakage. Less productive cutting processes like laser trimming or water jet cutting has to be used. However, this is suboptimal in terms of time-, material- and energy-efficiency. Substitution by economical cutting technologies is essential.

The use of advanced materials, heat treatments combined with DCT and coatings for tools will lead to **important benefits in blanking and punching technology**:

- An increase of tool life by more than 100% for cutting high strength materials (high strength steels, fiber-reinforced composites).
- A substantial reduction of the maintenance costs, production downtime and a higher throughput in return (lower time loss for tool regrinding or replacement).
- The lower level of tool wear further reduces the tooling cost. This may lead to cost reduction for blanking tools of approx. 50 %.
- Increase in productivity of approx. 20% due to a major increase in cutting tool life.

The **economic cost saving potential** of DCT in the cutting industry is quite significant: Table 3 gives an estimation of the economic benefit for one company in terms of saving costs for production volume of 500.000 parts per year using DCT (actual market prices).

The total savings in that case is ca. 70.000 EUR per year. For an estimated number of involved companies in Belgium of ca. 125 (5 % of the total target group) and 500 (5 % of the target group) for Germany. The total benefit is more than 43 Mio.€ (625 companies).

Table 3: Economic benefit for one company using hardened tools for cutting operations

Cost (EUR)	Conventional hardening	Hardening + DCT
Number of strokes	10.000	20.000
Weight of tools (kg)	100 kg	100 kg
Cost for hardening	1400 EUR	2000 EUR
Cost for regrinding/replacing	1000 EUR	0 EUR
Total cost per 500000 parts	120.000 EUR	50.000 EUR

By using DCT for optimized tooling it will be possible for SME's to process difficult to cut materials with high productivity and efficiency. The market position will be assured by lowering the costs per work piece by using tools with a higher lifetime. The number of jobs in the sector shall be maintained in both countries in spite of raising personal costs.

Further cost savings should be possible by an use of the innovative High Speed Impact Cutting (HSIC) technology, with cutting velocities over 2 m/s. Actually, the use for high strength materials is mainly limited by early tool breakage. A sufficient HSIC tool lifetime would realize the significant economic cost saving potential:

- One main advantage of HSIC is the quality of the produced parts. They have finely structured, flat interfaces with very small burr, the high dimensional accuracy and low component deformation. Additional post-processing steps are normally not necessary. This means a significant reduction in the process chain.
- High cost-efficiency by high material utilization rate for the sheet material. (With HSIC an advantage of approx. 20% in shear cutting and nearly 50% in fine blanking. [1])
- HSIC works in contrast to conventional shear cutting and especially fine blanking without oiling. Lubricant free cutting means no post-cleaning of the component. [1]

Table 4 gives an estimation of the economic benefit for 1 company in terms of saving costs for an average production volume of 500.000 parts per year using HSIC based on actual market prices. The estimated number of involved companies for Belgium is approx. 75 (5 % of the total target group) and 300 (ca 5 % of the target group) for Germany. The total benefit is more than 40 Mio.€ (375 companies).

Table 4: Economic benefit for 1 company in terms of saving costs for an production volume of 500.000 parts per year using HSIC instead of precision cutting

Expenditures	Expenditures per part			Savings for 500.000 parts		Remark (price/unit)
	HSIC	Cutting	Difference	Amount	Saving cost [€]	
Lubricant [l]	0,000	0,010	0,001	5.000 l	5.000	Estimated price: 1 €/liter
Material [kg]	0,252	0,294	0,042	21.000 kg	105.000	Average material price : 5 €/kg
Total savings					110.000	

[1] Kräusel, V.: *Gestaltung und Bewertung einhubiger Scherschneidverfahren mit starren Werkzeugen unter besonderer Berücksichtigung der Schnittflächenqualität an Blechbauteilen*; Habilitation Dr.-Ing. V. Kräusel; Verlag wiss. Scripten; 2013

2.2 Research Objectives

The proposed research project will mainly focus on the application of DCT as a method to improve the lifetime and wear of tools in combination with adapted coatings for conventional punching, fineblanking and high speed impact cutting (HSIC).

Main target of the project is a significant increase of tool life for cutting high strength materials (high strength steels, fiber-reinforced composites) and for high speed impact cutting.

Objectives in detail are:

- Optimization and integration of DCT treatment in the production process of the tools
- Combination of DCT with high performance plasma diffusion treatments and coatings
- Proof of concept for blanking of high-strength materials (steel, fiber-reinforced composites)
- Proof of suitability for high-speed impact cutting to prevent early tool breakage
- Validation of the concept in different industrial applications
- Formulation of a treatment recommendation for cutting tools for different applications

These objectives will be examined on tool steels, selected by the needs of the shearing technology. Characterization and application in experimental lab scale tests, as well as on experiments tested under production conditions to show their suitability.

The industrial application of DCT depends on the lifetime optimization of tool substrates. Based on the positive results of Infiblack, the partners expect a similar advantage of this technology for processing materials like high strength steels, fiber reinforced plastics and composites as well as for HSIC.

Risks involved

- The deep cryogenic treatment is not standardized. The effect of DCT depends on steel and process parameters. In the worst case, the DCT shows no significant effect.
- Although mechanical cutting processes are well established in SME's of the target sector, laser- and watercutting is an alternative for cutting high demanding materials.
- Since the amount of available commercial tool steels is rather large, only a restricted number of steels will be involved in this study. In consequence of this approach, other not examined tool steels can also have positive responses to the process.
- The amount of PVD coatings is rather large, only a selected number can be involved in this study. Other coatings, which are not examined, could perform even better.

2.3 Innovation Target

Innovative contribution of the targeted research will be:

- Application of DCT for tools made of high alloyed steel with high hardness and toughness. The development of an optimized heat treatment for selected tool steels.
- Implementation of DCT combined with special coatings for the cutting industry.
- The use of DCT to increase the lifetime of tools used for new shearing methods like HSIC as well as for high demanding materials.

2.4 Work Outline

The project will start to collect data about tools and DCT. In the next step Sirris will make a material selection of the tool material which will be used in the project and which is suitable for cutting both metals parts and non-metal parts. The DCT will be studied in detail by several tests at industrial heat treating companies under the supervision of Sirris. The best heat treatment strategy will be selected for test samples. The special coatings and PDT for tools will be studied next. The hardened test samples will be coated at Fraunhofer IST characterized and tested to determine the coating properties. The best materials, heat treatments and coatings will be evaluated in cutting tests on lab scale at Fraunhofer IWU and Under industrial conditions by user committee members in Belgium and Germany. The tests deliver cutting performance of substrate/coating combinations. Finally, an evaluation and a systematization of the results will be summarized, recommendations for industrial users will be derived before writing the final report.

The work within the project is subdivided in nine work packages (WP):

- **Work package 1: Selection and characterization of cutting processes**
In this work package, the process conditions and specifications for cutting of different high strength materials (high strength steels and fiber-reinforced composites) will be collected. The results will be used for the next WP's.
- **Work package 2: Optimization of tool materials (Sirris)**
In this WP2 several tool materials used in industrial cutting operations will be selected for optimization the DCT to improve properties. Temperatures will be varied and sequence for the DCT (before, after tempering/PDT) (Fig.4). The mechanical, structural properties will be analyzed for best combinations for tool manufacturing in WP4.
- **Work package 3: Coating development and optimization (IST)**
The coating development starts with the coating of reference samples and the determination of the coating properties. High wear resistance, low adhesion of workpiece material and good adhesion on the tool surface are required. For excellent coating adhesion an additional plasma diffusion treatment (PDT) will be applied. In the next step, tools for cutting tests on laboratory scale (WP 5) and under production conditions (WP 7) will be coated. Iterative loops will be applied for optimization.
- **Work package 4: Tool manufacturing with different fabrication strategies (Sirris)**
The tools for the application tests in WP5 will be manufactured with different fabrication strategies according to the tool design delivered by Fraunhofer IWU. Hard milling and grinding as well as electro discharge manufacturing will be applied. The best route sequence for the DCT during the complete manufacturing chain (Figure 4) must be defined. Table x shows the simplified test matrix with the amount of test tools for WP5.
- **Work package 5: Laboratory scale cutting tests & characterization of parts (IWU)**
The cutting test on laboratory scale will be performed with conventional cutting and HSIC. In four test series the influence of the tool materials, tool fabrication strategies, heat treatments/DCT and coatings on the tool wear by cutting different high strength steels (> 1000 MPa) and fiber-reinforced composites will be investigated.
- **Work package 6: Investigation of tool wear (IST)**
Detailed investigations of the tool wear are necessary for further optimization of tool materials and coatings in WP 2 and WP 3. The investigations focus on the wear mechanism like fracture, abrasion or adhesion by optical microscopy, SEM and EDX.

- Work package 7: Cutting tests under production conditions (Sirris, IWU)**
 To verify the laboratory scale tests, DCT treated and coated tools will be shipped to the SMEs in each country for application tests under production conditions. These demonstrator tools will be manufactured, heat treated and coated with the best procedures from WP 4. Analysis will be delivered to all project partners.
- Work package 8: Systematization, Evaluation, Guidelines, Final report**
 The results of the above mentioned cutting tests in WP4 and WP 5 will be compared and evaluated in order to determine the performance of the examined combination of substrate, heat treatment, deep cryogenic treatment, fabrication strategies and coating for all cutting methods. Special guidelines for industrial cutting of high strength materials will be derived. At the end of the project all partners will write the final report.
- Work package 9: Project Management, Dissemination and Transfer of results**
 This part will provide professional feedback between the partners and users as well as the dissemination of the results within the user group.

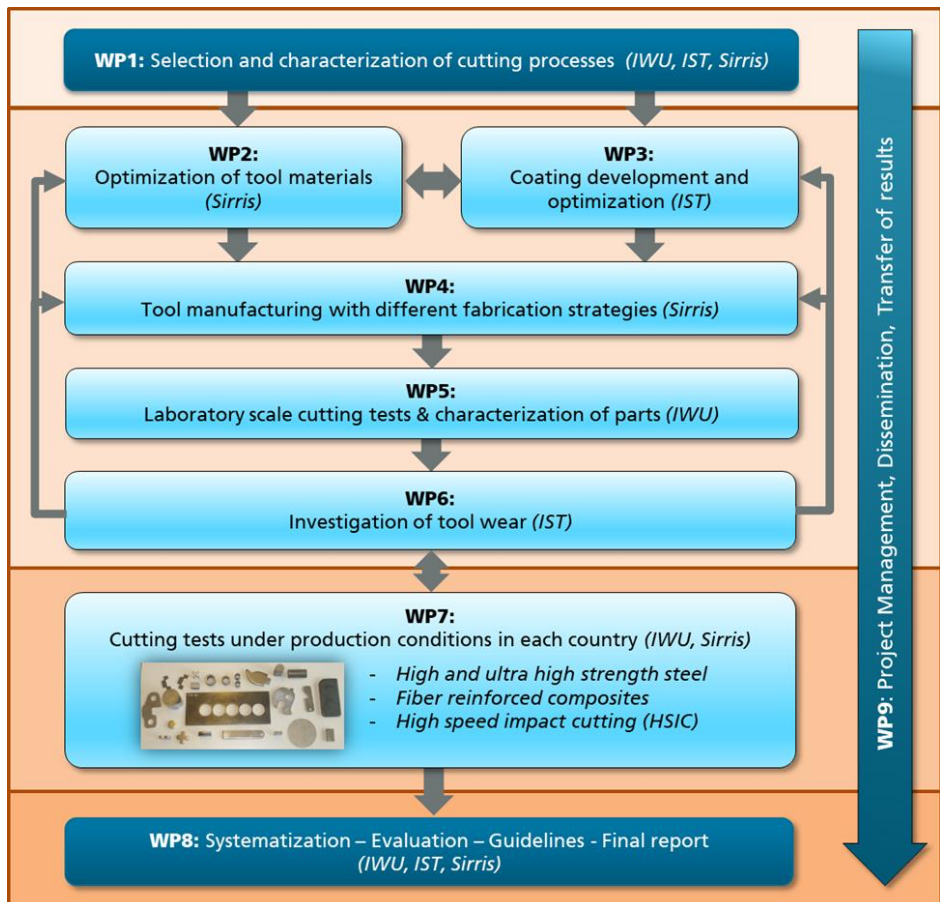


Figure 4: Workplan

3 Project Consortium

3.1 Overview

The expertise of the partners on materials, processes, their technology equipment will contribute to the project goal. The interaction between the partners is shown in Figure 5.

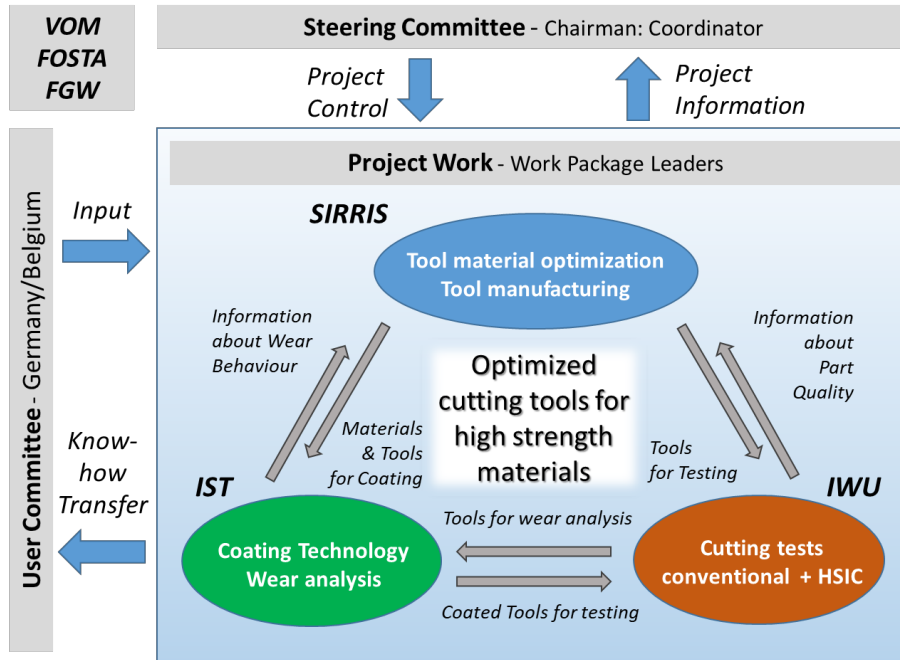


Figure 5: Interactions within the project

The partners involved in this project are:

Associations:

- VOM – Belgische Vereniging voor Oppervlaktetechnieken van Materialen
- FOSTA - Forschungsvereinigung Stahlanwendung e. V.
- FGW - Forschungsgemeinschaft Werkzeuge und Werkstoffe e.V.

Research Performers:

- SIRRIS - Collective Research Center of the Belgian Technological Industry
- Fraunhofer IST - Fraunhofer Institute for Surface Engineering and Thin Films
- Fraunhofer IWU - Fraunhofer Institute for Machine Tools and Forming Technology

User Committee

- Participating SME's from Belgium and Germany

VOM (Coordinating Association): VOM sustain to extend the know-how and experiences of its members. The basic idea is to build networking and joint projects between the industry and research institutes. VOM covers nearly all activities in production. With special attention to related topics such as quality, environment, health and safety. The majority of the 300 members are SME's, e.g. subcontractors, users and suppliers of products as well as universities and research centres, either situated in the French or Dutch speaking part of Belgium. To reach its objectives, VOM organizes conferences, technical lectures, company visits, tailor-made courses and participate at Research programs.

FOSTA (Participating Association 1): The Research Association for Steel Application (FOSTA) is a non-profit and legally autonomous research association within the steel sector. As an association, it represents the steel industry – as well as those of the users of steel materials and its various products – in the field of applied research. FOSTA's research focuses on a wide range of topics, but also oriented upon public issues e.g. resource efficiency, reduction of CO₂ emissions. The FOSTA's profile: material behavior, machining and processing, traffic, the building industry and environmental technology.

FGW (Participating Association 2): The Forschungsgemeinschaft Werkzeuge und Werkstoffe e.V. (FGW), founded in 1952 by the German tool industry as a research and development service provider for SME's. More than 90 companies in the metal working industry are a part of its network. The range of activities covers research, testing, certification and safety-related support. As a member of AiF the FGW covers the area of tools and materials in pre-competitive, collaborative research and works together with companies and universities.

SIRRIS: Sirris is the collective research center of the Belgian technological industry. Sirris supports SME and other companies in the implementation of technological innovations, enabling them to strengthen their competitive position. The experts visit companies and offer them technological advice, initiate innovation projects, and provide technological support. SME's and large industrial groups in Belgium are members of Sirris. Sirris is participating in more than twenty European R&D projects in the last 10 years, notably in the EU Framework Programs FP6 and FP7, Eureka, Interreg, Cornet and ERA-NET.

Fraunhofer IST: The Fraunhofer Institute for Surface Engineering and Thin Films (IST) working in different fields of applied research. The staff of the IST consists of about 100 scientists and engineers. The research activities of the IST concern the deposition and characterization of several types of coatings for tribological, electrical, optical or decorative applications. Some of the main topics of the institute are hard and wear resistant coatings DLC, boron based coatings, transition metal nitride etc. This allows preparing tailored coatings. The research activities cover the deposition and characterization of several types of coatings for tribological tool applications as well as wear analysis.

Fraunhofer IWU: Fraunhofer Institute for Machine Tools and Forming Technology (IWU) performs applied research and development in close cooperation with industry, research centres and government. Innovative solutions involving the entire process chain of production technology. In the field of forming technologies, lightweight structures and the application of new materials play a predominant role, with about 570 highly qualified engineers and scientists, combined with laboratories and research facilities for mechatronics, machine tools, forming technology, micro manufacturing. Fraunhofer IWU has done extensive research in the field of high-strength materials. The development of equipment and process technology for cutting, fine blanking and HSIC of different metal materials has been a main area of research over the past years.

User Committee: The participating SME's (User Committee) from Germany and Belgium of the target sectors give the necessary input concerning their needs and technological requirements in the project work and they will have the opportunity to use the results of this mutual collaboration for their own industrial experience. The structure of the process chain represented by the user committee is summarized in Figure 6:

Structure of the process chain		
Supplier (Transfer)	Workpiece and sheets materials	Tool-Materials
Käppler und Pausch GmbH (D) Westfalia Presstechnik GmbH (D) KWD Automotive GmbH (D) ADZ LüTec Leipzig GmbH (D) Parker Hannifin GmbH (D) SYNTEKS Umformtechnik GmbH (D) Indumess (B)	MSC Metall-Service-Center GmbH (D) WVG Werkzeuge und Maschinen (D) Bond-Laminates/Lanxess-Group (D) IML Verstraete (B)	Enpar Sonderwerkstoffe (D) Böhler & Uddeholm GmbH (D) Uddeholm Belgium (B)
Construction		Coatings and Lubricants
Ideema GmbH (D) Ingenieurbüro Paatz (D) IT Ingenieurtechnik GmbH (D) Dejond (B) Paneltim (B)		CeWOTech GmbH (D) DAW Aerosit Schmiertechnik GmbH (D) Oerlikon Balzers (B)
Heat-Treatment	Toolmaker	User off HSIC
CeWOTech GmbH (D) CoolTech, Stanzach (A) Nitrotechnics (B)	Werkzeugbau Ullmann (D) Werkzeugbau Schmutzler (D) Werkzeugbau Hartmann GmbH (D) Mieruch & Hofmann GmbH (D) WESOBÄ GmbH (D) Tools & Dies (B)	MSA Maschinenbau GmbH (D) SCHERDEL Marienberg GmbH, (D) Nedschroef (B)
33 companies: User consortium from Belgium and Germany (1x Austria)		

Figure 6: Structure of the process chain represented by the user committee

3.2 Contact data

The contact data of the project partners are listed in the tables below.

Table 5: Association - VOM

	Belgische Vereniging voor Oppervlaktetechnieken van Materialen
Address:	Kapeldreef 60, 3001 Leuven, Belgium
Website:	www.vom.be
Project Manager:	Veerle Fincken
Telephone:	+32 16 40 14 20
E-mail:	v.fincken@vom.be

Table 6: Association - FOSTA

	Forschungsvereinigung Stahlanwendung e. V.
Address:	Sohnstraße 65, 40237 Düsseldorf, Germany
Website:	www.stahl-online.de
Project Manager:	Rainer Salomon
Telephone:	+49 211 6707-853
E-mail:	rainer.salomon@stahlforschung.de

Table 7: Association - FGW

	Forschungsgemeinschaft Werkzeuge und Werkstoffe e.V.
Address:	Papenberger Strasse 49, 42859 Remscheid, Germany
Website:	www.fgw.de
Project Manager:	Dr. Christian Pelshenke
Telephone:	+49 (2191) 5921-111
E-mail:	pelshenke@fgw.de

Table 8: Research Performer - SIRRIS

	Collective Research Center of the Belgian Technological Industry
Address:	Reyerslaan 80, 1030 Brussels, Belgium
Website:	www.sirris.be
Project Manager:	Guy Claus
Telephone:	+32 498 91 93 51
E-mail:	Guy.Claus@sirris.be

Table 9: Research Performer - Fraunhofer IST

	Fraunhofer Institute for Surface Engineering and Thin Films
Address:	Bienroder Weg 54E, 38108 Braunschweig, Germany
Website:	www.ist.fraunhofer.de
Project Manager:	Martin Weber
Telephone:	+49 (0)531 2155-507
E-mail:	martin.weber@ist.fraunhofer.de

Table 10: Research Performer - Fraunhofer IST

	Fraunhofer Institute for Machine Tools and Forming Technology
Address:	Reichenhainer Straße 88, 09126 Chemnitz, Germany
Website:	www.iwu.fraunhofer.de
Project Manager:	Matthias Demmler
Telephone:	+49 (0)371 5397 1327
E-mail:	matthias.demmler@iwu.fraunhofer.de

3.3 User committee

The user committee guides the developments, will be actively involved in the reference cases and will evaluate the results.

Table 11: List of participating companies in Germany and Belgium

Germany	SME (X)
Bond-Laminates GmbH	
DAW Aerosit GmbH	x
Scherdel Marienberg GmbH	
ADZ LüTec LEIPZIG GmbH	x
Böhler-Uddeholm Deutschland GmbH	
CeWOTec GmbH	x
Enpar Sonderwerkstoffe GmbH	
Ideema GmbH	x
Ingenieurbüro Paatz	x
IT Ingenieurtechnik GmbH	x
Käppler und Pausch GmbH	x
KWD Automotive GmbH	
Mieruch & Hofmann GmbH	x
MSA Maschinenbau GmbH	x
MSC Metallservice-Center GmbH	x
Parker Hannifin GmbH	
SYNTEKS Umformtechnik GmbH	
Werkzeugbau Hartmann GmbH	x
Werkzeugbau Schmutzler GbR	x
Werkzeugbau Ullmann	x
WESOBÄ Werkzeug- und Sondermaschinen	x
Westfalia Presstechnik GmbH	
WVG Chemnitz Werkzeuge und Maschinen	

Belgium	SME (X)
DEJOND	x
IML Verstraete	x
Indumess	x
Nedschroef NV	
Nitrotechnics	x
Tools&Dies Engineering	x
Uddeholm Benelux	
Paneltim	x
Oerlikon Balzers	
Austria	
CoolTech, Stanzach	x

4 Results in Detail

4.1 Selection and characterization of cutting processes

In this chapter, the process conditions and specifications for cutting of different high strength materials (high strength steels, fiber-reinforced composites) and other additional materials (copper) are collected.

4.1.1 Definition of materials and geometries for lab scale tests and industrial demonstrators

In the following, the data required for the lab scale tests at Fraunhofer IWU and the industrial cutting tests in Belgium and Germany are summarized.

Lab scale cutting tests at Fraunhofer IWU:

For the laboratory scale cutting tests in work package 4, round punches with a diameter of 5 mm and a length of 47 mm initially were selected. Due to the simple geometry, low-cost production is possible. The test tool provided for this purpose allows the comparative investigation of 6 tools in one working stroke. The sheet material selected was the high-strength steel 1.4310 in a thickness of 0.3 mm with a tensile strength of $R_m = 1700 \text{ N/mm}^2$. The tool geometry and test parameters can be taken from Figure 7.

Cutting tests with round tools:

- Tool manufacturing process:
 - hardened, annealed, grinded
- 100.000 Strokes / 2 mm
- Sheet material:
 - High strength steel 1.4310
 - $R_m = 1700 \text{ N/mm}^2$
 - Thickness: 0.3 mm

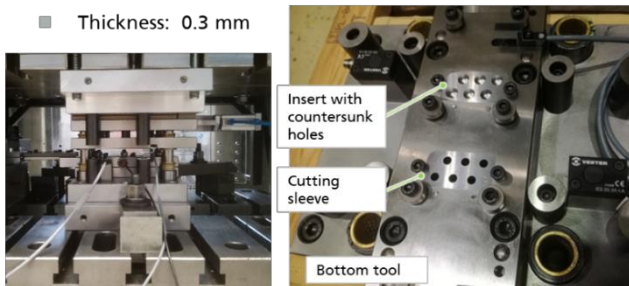
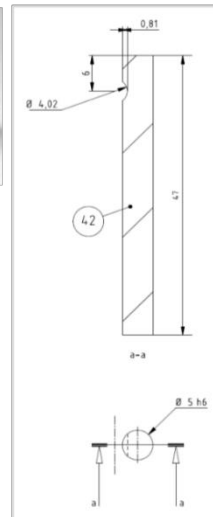


Figure 7: Lab scale cutting test at Fraunhofer IWU with round tools, high strength steel 1.4310

After the initial tests with conventionally treated tools, only minor wear was evident after 100,000 strokes. Therefore, the load on the cutting edges was increased by changing the tool geometry. The round tools were provided with additional flattenings, resulting in a triangular geometry ("Dreieckgeometrie"). The sheet material selected was 1.4301 in a thickness of 0.6 mm. Due to the strong hardening of the material during the cutting process and the greater sheet thickness, there is a higher cutting edge load despite the lower initial strength of 540-750 N/mm^2 . This is reinforced by the strong tendency of material adhesions on the cutting punch. The tool geometry and test parameters in detail can be taken from Figure 8.

Cutting tests with “Dreieckgeometrie”:

- 100.000 Strokes / 2 mm
- Sheet material:
 - Stainless steel 1.4301 (ISO 5445-2)
 - $R_m = 540\text{--}750\text{ N/mm}^2$
 - Thickness: 0.6 mm

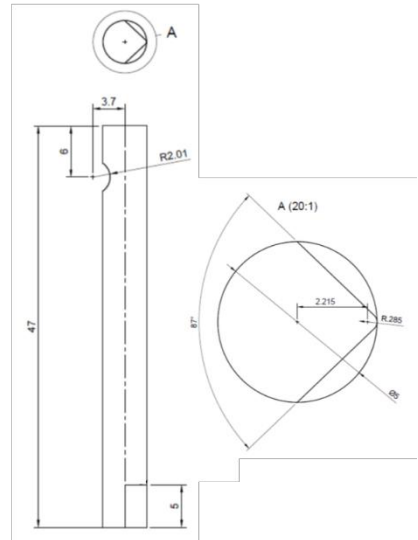


Figure 8: Lab scale cutting test at Fraunhofer IWU with “Dreieckgeometrie”, stainless steel 1.4301

Lab scale HSIC cutting test at Fraunhofer IWU:

For high speed impact cutting on laboratory scale, an ADIA flex HSIC machine from ADI-APress was used. The relevant machine data can be found in Figure 9. Round punches with a diameter of 20 mm made of the PM steels ASP 23 and S290 were used as cutting tools. The sheet material was the boron-alloyed steel 22MnB5 with a thickness of 3 mm.



- Energy: 0,2 – 2 kJ
- Acceleration unit: high speed hydraulics
- Velocity: up to 10 m/s
- Tool material: ASP 23, S290 (no coating)
- Sheet material: 22MnB5, 3 mm



Figure 9: Lab scale HSIC cutting test at Fraunhofer IWU

Lab scale cutting test of composite material at Fraunhofer IWU:

Lab scale cutting tests with composite material were carried out with a TruPunch 5000 with rectangular stamps. The composite material was Tepex dynalite 104-RG600(4) a polypropylene (PP) material with 47% fibre volume content. Further details see Figure 10.

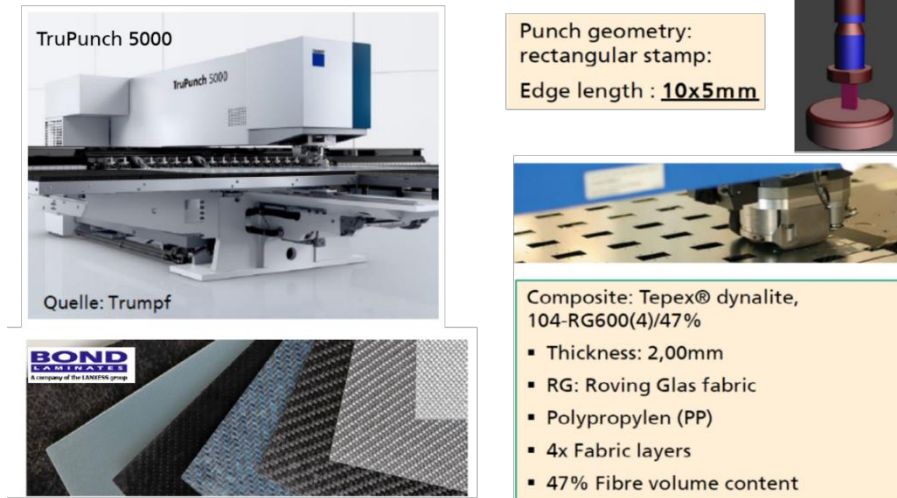


Figure 10: Lab scale cutting test at Fraunhofer IWU with rectangular tools, composite Tepex ® dynalite

Industrial cutting test “Fuelcells” with complex phase steel

Industrial cutting tests with high strength sheet material in Germany were carried out at company Bernd Flach Präzisionstechnik. The complex-phase steel CR900Y1180T-CH with a tensile strength >1.100 MPa is used for Fuelcells. Punch material was cold working steel 1.2379. Different cutting gaps were tested. Details see Figure 11.

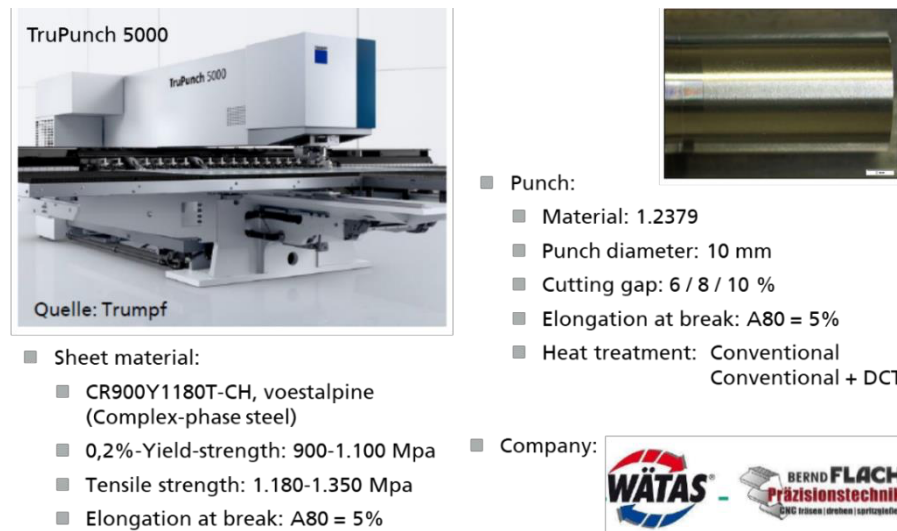


Figure 11: Industrial cutting test “Fuelcells” with complex phase steel

Industrial HSIC cutting test of solid copper:

Precision forging requires blanks with very small volume deviations. High-Speed Impact Cutting with its very flat cutting surfaces is ideal for this. Wear on the cutting tools causes deviations in the volume of the cut parts. Low tool wear is a precondition for using the advantages of the cutting process. Industrial HSIC tests were carried out at the MSA company when cutting round bars of solid copper. Further details see Figure 12



- HSIC of high-precision copper pre-material for the following precision forging process
- Punch failure causes incorrect cut-off volumes and thus scrap parts

Figure 12: Industrial HSIC cutting test of solid copper

Industrial cutting tests Belgium

Four tests were initially programmed to investigate the benefits of DCT and coatings on the performance of tools for punching.

The company IML Verstraete uses special punches made of K390 and K340 steel to cut bundles of printed PP foils for in-mould-labelling of food containers. During punching sometimes flaking at the corners of the punching die occurs. Due to confidential reasons these tests could not be performed under the collective research conditions.

The next application is the production of stainless steel rivets at the company Dejond/Tubtara in Antwerp. The punch used for this operation was made of PM steel ASP23 and has a diameter of 5 mm. The test punches were treated according to the variant method 4 (post DCT with constant temperature).

The second application was a side cutter used in a punching machine for making steel rings at the company Haemers in Moorsele. By sidecutting a steel sheet is moved in steps in order to make steel rings at regular positions. Two tests were performed: using hot rolled construction steel sheet made of S235 at 8 mm thickness and high strength steel S700MC and 1,5 mm thickness.

The third and last application was organized at the company Stow in Mouscron, a producer of large industrial steel storage racks. The punches were prepared by the company Denoo Matrijzen in CPM4V and coated with Variantic duplex TiAlN/TiCN coating by Eifeler in Germany. The steel CPM4V is an American PM steel with composition shown in the table below.

Table 12: Composition of tool steels for industrial cutting tests in Belgium

Steel	%C	%Cr	%Mo	%V	%W
ASP23	1.3	4.2	5	3.1	6.4
CPM4V	0.8	7.5	1.3	2.8	0
K110	1.55	11.3	0.75	0.75	0

4.1.2 Definition of wear characterisation tests / component quality determination

The geometry changes of the cutting edges of the tools for the lab scale tests were evaluated by optical measurements before and after testing. After the lab scale and production tests the tools were examined by visual inspection using a digital microscope.

After superficial analysis of the tools a selection were made of tools with typical wear mechanisms. These tools were investigated by cross-sections of the wear zones by using stereomicroscopy and SEM-analysis

The quality of the cut surfaces (edge indentation, flatness of the cut surfaces, burr formation) was evaluated with the aid of light microscopic images. If necessary, cross-sections of the cut parts were made for this purpose.

3-Roll-Wear-Test at IMP Warschau

In addition, wear tests were carried out with a 3-roller test rig at IMP Warschau (see Figure 13). The wear volume was determined as a function of the heat or cryogenic treatment and the pressure.

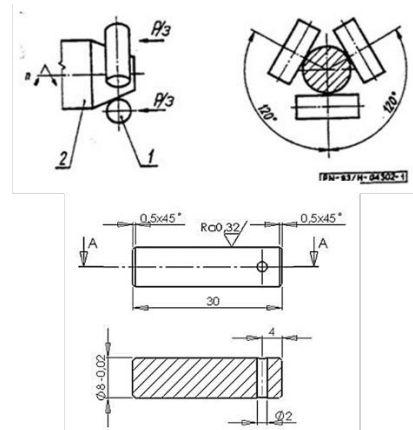


Figure 13: 3-Roll-Wear-Test at IMP Warschau

Scratch tests at Sirris

A Revestest with constant load was performed on the hardened steel samples for lab tests (without coating) from 4.2.2. With this test scratches of 4 mm were made in the surface of the steel samples to evaluate the cracking behaviour. The conditions were as follows: speed 10 mm/min, load 18 kg, radius 0,2 mm.

The Figure 14 above shows the results of the measurements expressed as depth, width and roughness Rt of the scratches. The conventional steel K110 gives the least deep scratches but the highest roughness compared to the other steels.

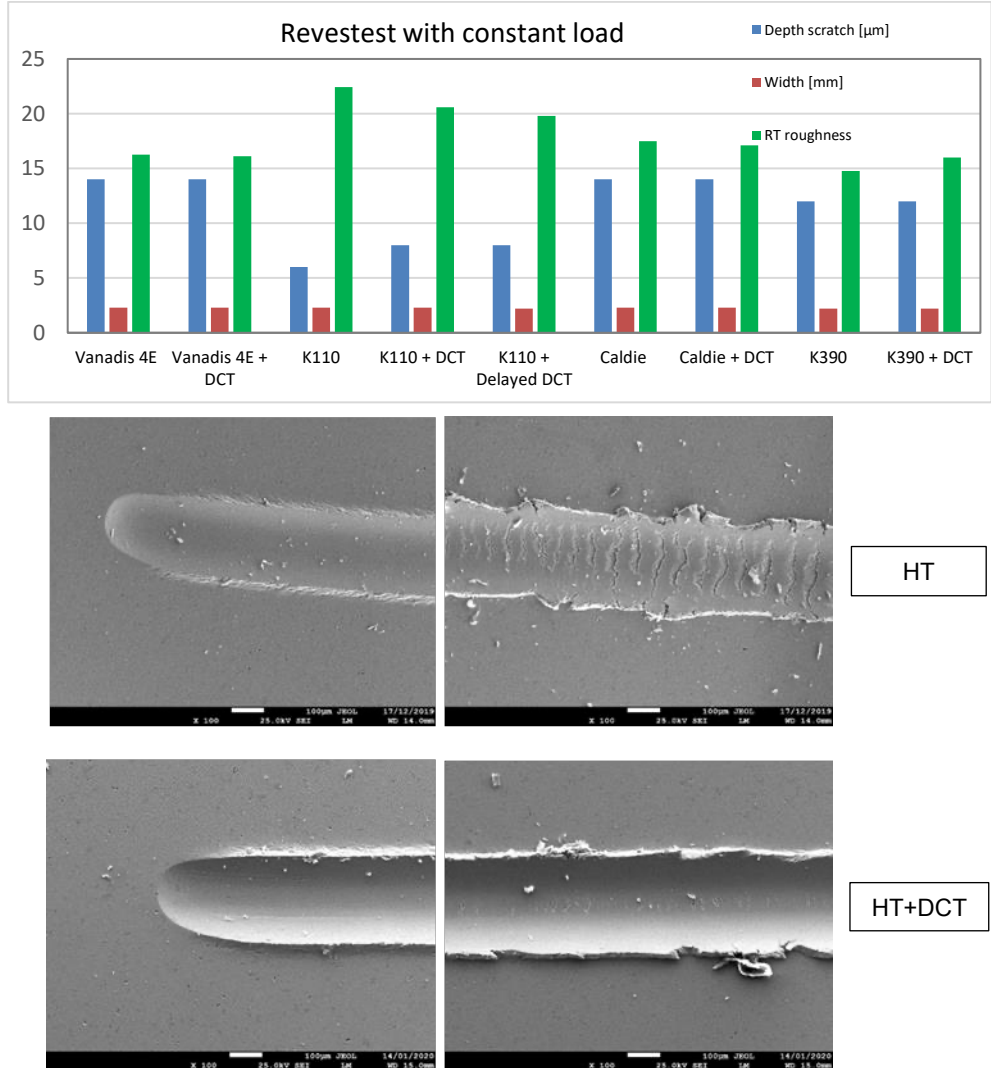


Figure 14: Results of the scratch tests on different steel; SEM-images of steel K110

The Figure 14 below shows some SEM-images of the observed scratches in K110 at low magnification. It can be noticed that this steel shows fine parallel cracks at the end of the scratch while the other steel types were all free of cracks. The brittle behaviour of this steel can be due to the presence of high amount of coarse carbides. After DCT the depth and width of the cracks seems to be smaller than with HT.

Laser-Speckle-Photometrie at IKTS Dresden

Laser-speckle photometry (LSP) is a new rapid, non-contact, low-cost approach for recording material properties, such as stress, surface defects, and geometric dimensions. Fraunhofer IKTS utilizes LSP as a basis for developing novel measurement and test solutions for quality assurance.

In laser speckle photometry, the change in interference patterns (speckle patterns) over time is analyzed to yield information about structural properties of a component (porosity, internal stress, hardness, roughness, degradation, and inhomogeneity). The method is based on measurement of changes in the thermal diffusivity of the material structure with high temporal and spatial resolution (see Figure 15).

LSP can be used for analysis of metals and non-metals as well as composites and organic substances. Depending on the material, resolutions down to approx. 10 microns are possible.

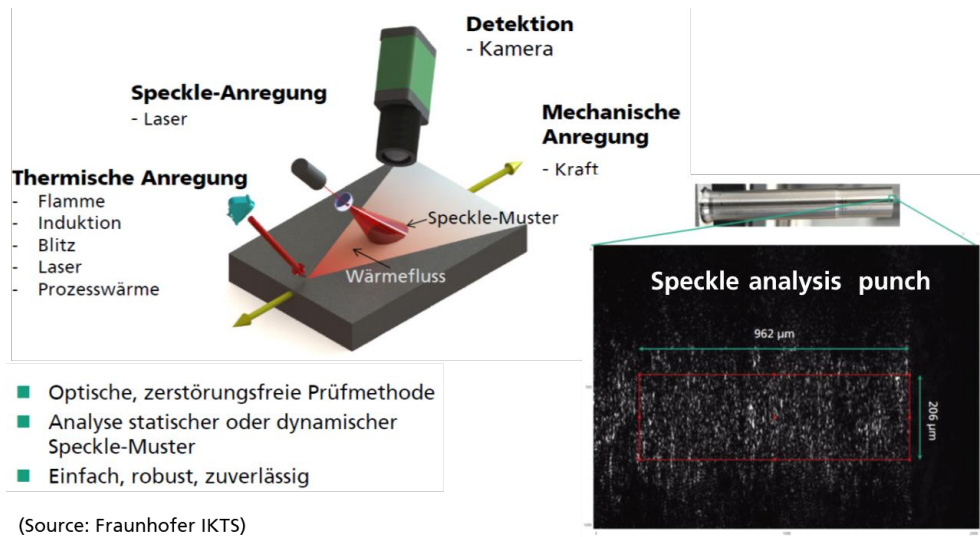


Figure 15: Laser-Speckle-Photometrie at IKTS Dresden and speckle analysis of a DCT treated punch.

4.2 Optimization of the Tool Material (Sirris)

4.2.1 Material selection and acquisition

In order to reduce the number of test samples four high quality cold work steels were selected based on former experience from the Infiblack project as well as from experience with the industrial companies in both countries. The requirements for selection were high abrasive and adhesive resistance, high toughness, compressive strength and dimensional stability. Two main steel suppliers were involved in the supply of these steels namely Uddeholm AB (Sweden) and Böhler (Austria) both are part of the Voest-Alpine Steel Group. Table 13 and Table 14 show the requirements for both Uddeholm and Böhler commercial steels used for cold work operations.

Table 13: Selection matrix for Uddeholm steels

[illegible]

Table 14: Selection matrix for Böhler steels

Marke / Grade BÖHLER	Verschleißwiderstand abrasiv Wear resistance abrasive	Verschleißwiderstand adhäsiv Wear resistance adhesive	Zähigkeit Toughness	Druckbelastbarkeit Compressive strength	Maßbeständigkeit bei der Wärmebehandlung Dimensional stability during heat treatment
BÖHLER K100	***	**	*	**	**
BÖHLER K105	**	**	*	**	**
BÖHLER K107	***	**	*	**	**
BÖHLER K110	***	**	*	**	**
BÖHLER K245	*	*	*****	*	*
BÖHLER K305	*	*	*****	*	*
BÖHLER K306	*	*	*****	*	*
BÖHLER K329	**	*	*****	*	*
BÖHLER K340 ISO DUR	***	****	***	****	***
BÖHLER K353	***	***	*****	**	**
BÖHLER K360 ISO DUR	****	****	**	****	***
BÖHLER K390 MICROCLEAN	*****	*****	*****	*****	*****
BÖHLER K455	*	*	*****	*	*
BÖHLER K460	*	*	*****	*	*
BÖHLER K600	*	*	*****	*	*
BÖHLER K605	*	*	*****	*	*
BÖHLER K720	*	*	****	*	*
BÖHLER K890 MICROCLEAN	***	**	*****	****	*****
BÖHLER K700	Austenitischer Manganstahl, der seine charakteristischen Eigenschaften durch Kaltverfestigung bei Schlag- und Druckbeanspruchung erhält. Deshalb ist ein Vergleich mit den härtbaren Stählen in dieser Form nicht möglich. Austenitic manganese steel maintaining its characteristic properties by work hardening under impact and compressive stresses. Therefore it is not comparable with the hardenable steels in this form.				

Based on these evaluation tables, the following steels were selected for the cutting tests on laboratory scale (see red rectangles): Caldie (ESR), Vanadis 4E Extra (PM) from Uddeholm, K110 (conventional) and K390 (PM) from Böhler. The steel K110 is equivalent to DIN 1.2379 and is frequently used by customers in Belgium and Germany. The low cost of this steel makes its popular amongst many die and toolmakers. It has the lowest price compared to the other ESR and PM steels (ca 5 to 65 EUR/kg) followed by Caldie, Vanadis 4E and K390.

The steels were supplied as long bars with different diameters: 10 mm (K110), 12.7 mm (Caldie), 5.3 mm (Vanadis 4E) and 15.5 mm (K390). The bars were cut to length and machined to a smaller diameter (ca 5,2 mm).

The composition of the different steels is given in Table 15. Some values of typical elements are indicated in circles. The reference material K110 contains the highest amount of chromium i.e. 12 % whereas Vanadis 4E has equal amounts i.e. 4% of chromium, molybdenum and vanadium. The ESR steel Caldie has the lowest and K390 the highest carbon content combined

with the highest amount of vanadium, tungsten and also cobalt. Both vanadium and tungsten form very hard carbides in steel.

Table 15: Composition of the steels used for lab scla tests

	C	Si	Mn	Cr	Mo	V	W	Co
K110 (1.2379)	1,55	0,3	0,3	11,3	0,75	0,75	0,0	0,0
Caldie	0,7	0,2	0,5	5,0	2,3	0,5	0,0	0,0
Vanadis 4E	1,4	0,4	0,4	4,7	3,5	3,7	0,0	0,0
K 390	2,47	0,55	0,4	4,2	3,8	9,0	1,0	2,0

4.2.2 Heat treatment and deep cryogenic treatment of tool steels

From each steel bar the smaller bars with diameter of 5.2 mm. After hardening they were machined by EDM (see Figure 16). The samples were identified by a four digit code.



Figure 16: Example of steel samples used for hardening (at right end: identification code)

The company Harderij Ventec in Moorsele, Belgium performed the hardening operation using a vacuum furnace and tempering furnace. The hardening was combined with a DCT, performed by another company Nitrotechnics in Tubize, Belgium.

Three variants of the cryogenic treatment were executed (see further 4.3.3): without DCT (var 1), DCT directly after hardening (var 2), DCT with a time delay of ca 1 day after hardening (var 5). For variant 2 and 5 a transport between both companies was organized. After the DCT the samples returned to the hardening company for the final tempering. Table 16 shows the process conditions of the four steel types with the measured hardness. The hardening temperature was set at a constant temperature of 1050°C for all steels. Three tempering steps were performed (standard procedure) after hardening and DCT. The tempering temperatures were adapted to obtain as well as possible the required hardness of 59+2 HRC.

The standard DCT cycle at Nitrotechnics is composed of: Cooling from room temperature (RT) to -196°C in 3 hours, cooling at -196°C during 24 hours and finally heating from -196°C to RT in 45 hours.

Table 16: Hardening parameters for lab scale samples

Material	Code	Measured hardness (HRC)	Hardening temperature (°C)	DCT	1° tempering (°C)	2°tempering (°C)	3°tempering (°C)
Vanadis 4E	X11X	60-61	1050	no	560	540	540
	X12X	59-60	1050	yes	560	540	540
K110	X21X	59-61	1050	no	510	510	510
	X22X	57-58	1050	yes	510	510	510
	X25X	57-58	1050	delayed	510	510	510
Caldie	X31X	60-61	1050	no	540	540	540
	X32X	59-60	1050	yes	540	540	540
K390	X41X	60-61	1050	no	540	560	560
	X42X	60	1050	yes	540	560	560

4.2.3 Hardness and determination of retained austenite

After hardening the hardness of the samples was measured at Sirris as well as the determination of the retained austenite using XRD. The results of these measurements are shown in Figure 17. It can be seen that after DCT the hardness of Vanadis 4E, K110, Caldie and K390 is 1 to 2 HRC lower than without DCT. This tempering phenomenon is typical for DCT and described in the literature (hardness shift).

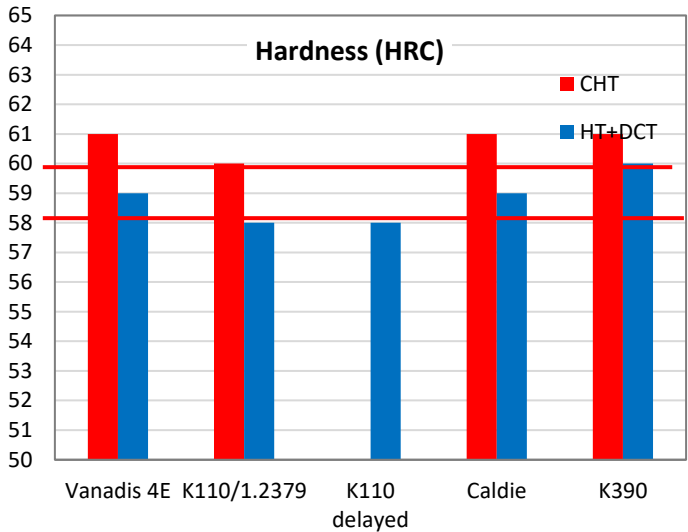


Figure 17: Hardness of the samples after hardening with and without DCT

The amount of retained austenite (fraction of austenite that was not transformed into martensite) was measured by XRD method on small samples. Figure 18 shows the result for both group of treatment. It is obvious that the amount of RA is always lower than 1% (normally ca 10-20 % depending on the steel type). This fact is due to the triple tempering treatment after hardening. The DCT seems to decrease the RA slightly for Vanadis 4E and Caldrie. However for K110 and K390, there is no significant decrease even a small increase in case of K390. This can be attributed to the presence of cobalt in the steel which influences the tempering behaviour after hardening.

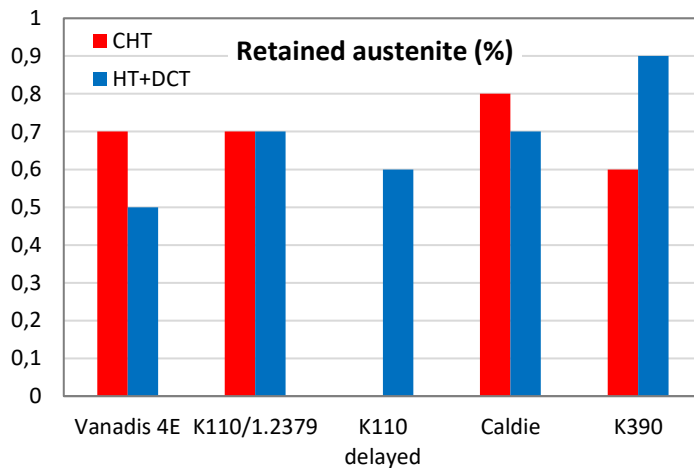


Figure 18: Retained austenite content after hardening and DCT

Figure 19 and Figure 20 shows that the RA for Caldrie, K110 and Vanadis 4E (no data for K390). At high tempering temperature of 550°C, the RA is very low for these steels even without the use of DCT.

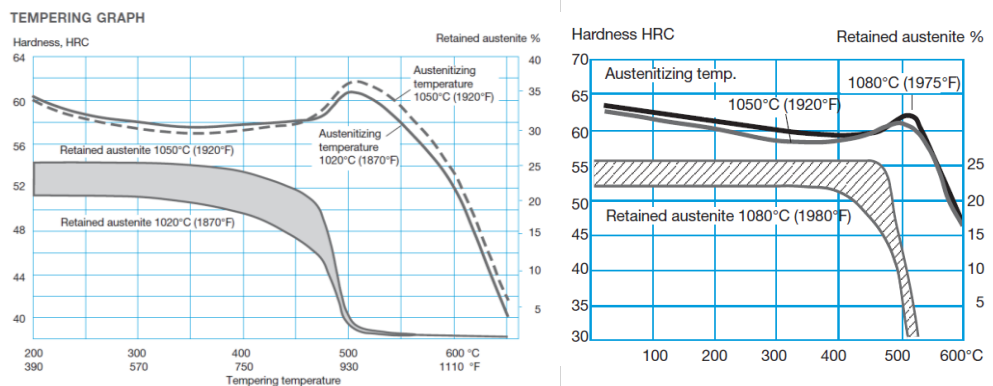


Figure 19: Tempering diagram of Caldrie (left) and K110 (right), without DCT

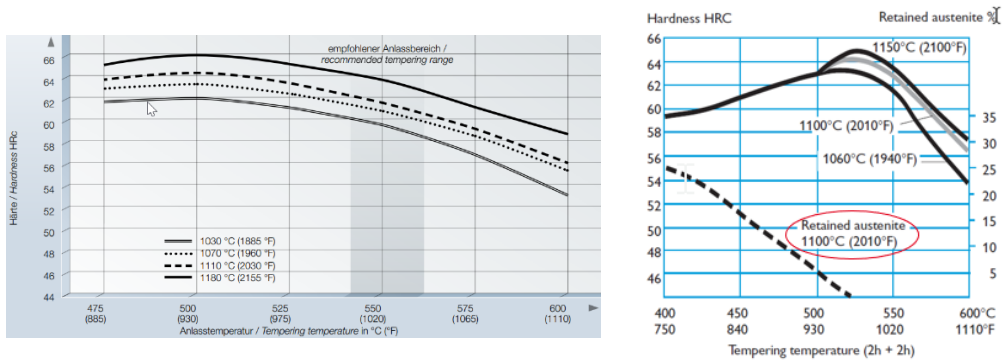


Figure 20: Tempering diagram of K390 (left) and Vanadis 4E (right), without DCT

The amount of carbides was also measured by XRD. It can be observed that the percentage of carbides in the samples treated by DCT is slightly higher than in the samples without DCT (see Figure 21).

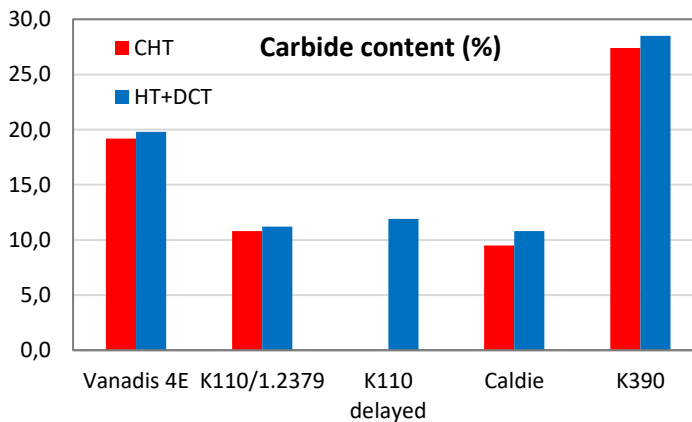


Figure 21: Carbide content after hardening and DCT

The SEM observations on cross-sections (see Figure 22) and visual counting of the amount of carbide particles could not confirm this result because in most cases the amount was almost constant with and without DCT. In case of Caldie steel, the amount of the fine carbides was so difficult that visual counting could not be performed. Figure 22 shows some SEM-images of the structure for three hardened steel samples.

It is clear that the PM steels Vanadis 4E and K390 contain spherical and fine carbides whereas K110 has more coarse and sharp carbides. The matrix of all the samples is composed of tempered martensite.

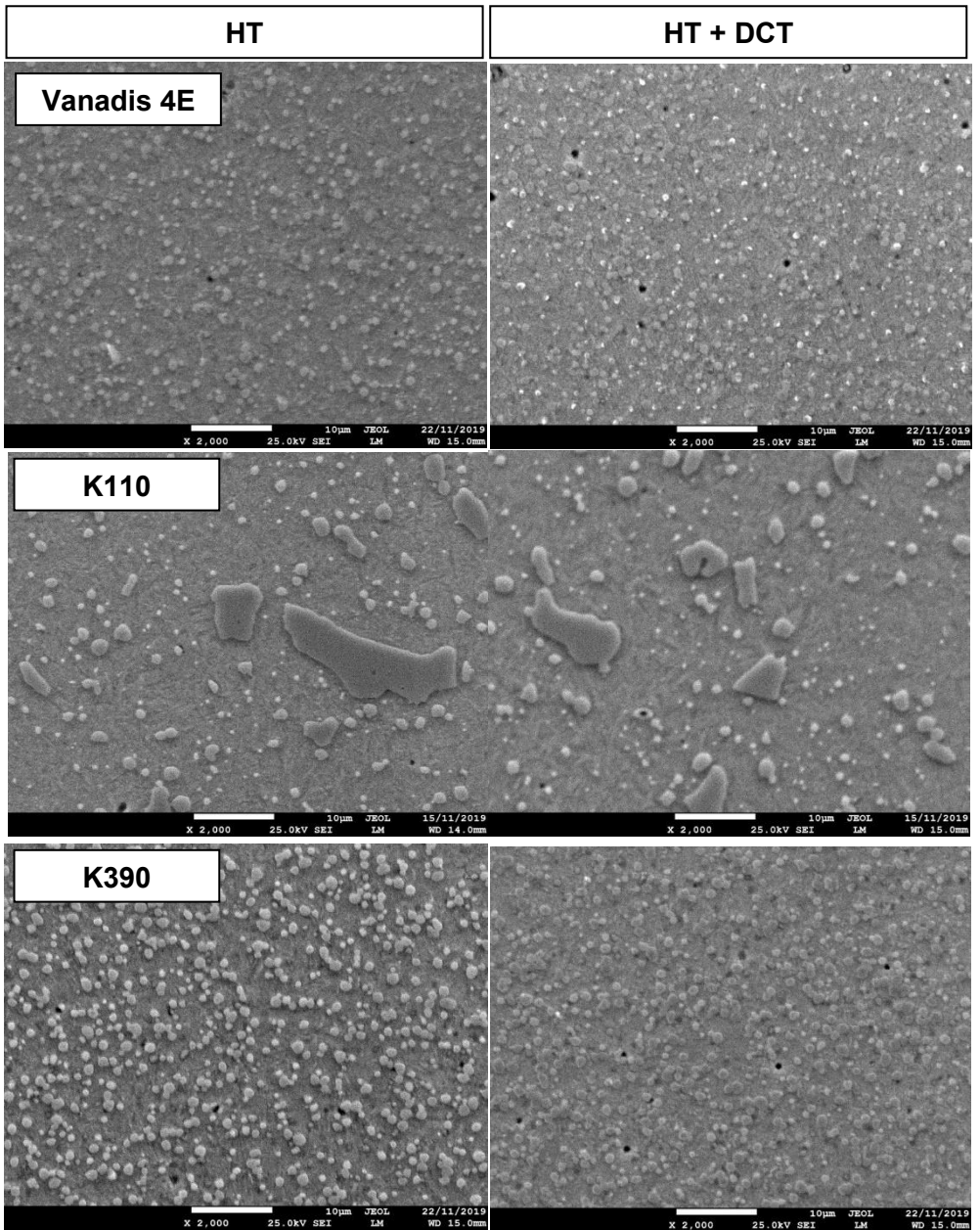


Figure 22: SEM images of Vanadis 4E, K110 and K390 with and without DCT

The toughness of the samples was measured by a Charpy impact test with unnotched samples of 7 mm x 7 mm, machined by EDM.

The impact toughness expressed as J/cm² is shown in Figure 23. It can be seen that the highest value is obtained with Caldrie, the lowest value with K390 and K110 steel. The reason of this difference in behaviour is the high carbon content of these steels compared to the other two steels. The DCT is beneficial for the toughness in case of the Caldrie steel but less for Vanadis 4E and seems to have no influence on the toughness of K110 and K390.

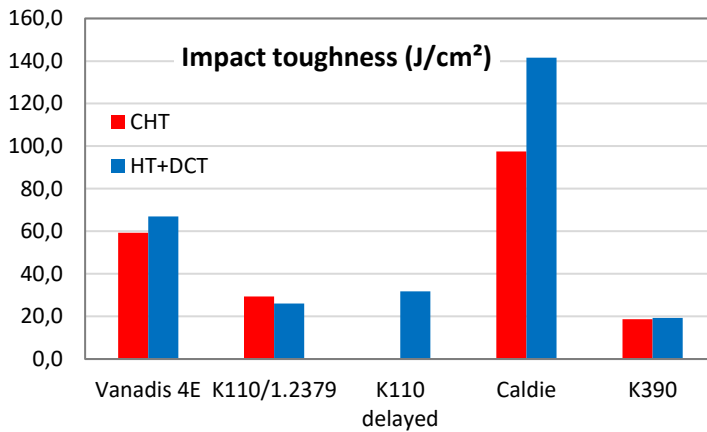


Figure 23: Impact toughness of steel samples with and without DCT

Figure 24 shows some SE-images of the fracture surface of K110. As for all steels no clear difference in the fracture aspect was observed between HT and HT+DCT the treatments.

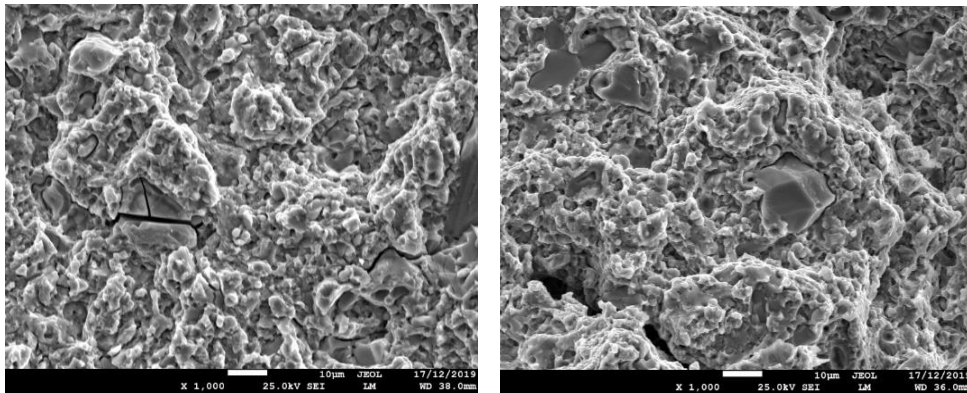


Figure 24: SEM-images of the fracture surface of K110 (HT: left, HT+DCT: right)

4.2.4. Residual stress measurements

In order to evaluate the residual (internal) stress at the surface of the steel samples treated with and without DCT, some measurements using a XRD based system from Stresstech was used. The Figure 25 shows the set-up of the apparatus. Two materials were measured according to the $\sin^2\Psi$ -method, namely K110 and K390 in two directions and three different hardening variants. Figure 26 gives the results of the measured stress at the surface expressed in MPa. All stresses are lower than 100 MPa or ca 4 % of the yield point of the steels (ca 2500 MPa). It also shows that the DCT has only a minor influence on the K110 steel and almost no influence on the PM steel K390.



Figure 25: Set-up of the mobile residual stress measuring apparatus Stresstech

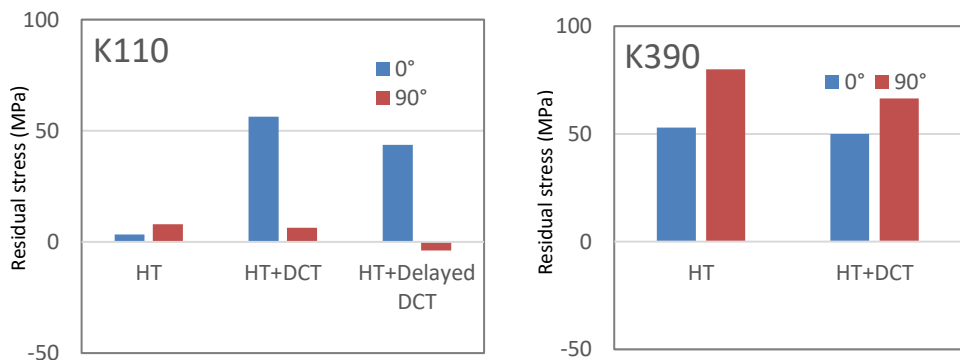


Figure 26: Results of residual stress measurements

4.3 Coating development and optimization (IST)

The requirements for surface treatment to improve tribological properties are complex and include high wear resistance, low adhesion of the workpiece material and good adhesion to the tool surface. For this reason, two solution approaches were combined in this research project to achieve several goals:

Plasmanitriding:

- increased coating adhesion
- increased surface hardness without reduction in crack resistance
- clarify influence of DCT on the nitriding result?

Coating:

- increased wear resistance
- reduced adhesion of workpiece material

This development process starts with optimization of the plasma diffusion treatment of the base material. In parallel, reference samples are coated and their coating properties determined. In the next step, these are combined with the cryogenic treatment, tested and evaluated. This is done first by standardized tests on round test specimen and then by laboratory scale cutting tests (WP 5/Chapter 4.5). Iterative loops are used to achieve optimum wear behavior.

4.3.1 Optimization of the plasma diffusion treatment

Overview plasma diffusion treatment

Plasma diffusion treatments (PDT) are thermochemical processes for modifying the surface properties in the workpiece. The most common variant for toolmaking is plasma nitriding. The nitrogen is dissociated by a plasma and diffuses into the component, driven by temperature. This results in a chemical reaction of the nitrogen with the base material. The nitriding zone is divided into two areas. The compound layer near the surface, consisting of iron nitrides (typically up to approx. 8 μm) and the diffusion zone below, which can consist of both iron and special nitrides of the alloying elements (typically up to 200 μm), see Figure 27.

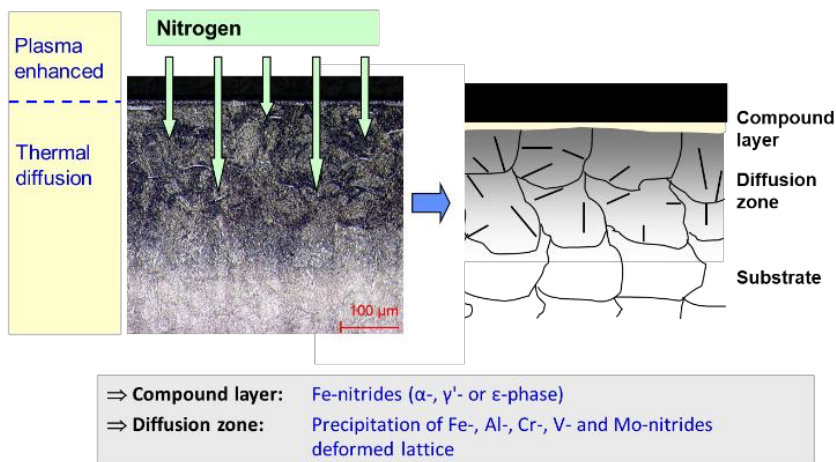


Figure 27: Schematic illustration of the nitriding zone

The formation of the nitriding zone can be influenced by the process parameters in the nitriding process. The most important process parameters are: Temperature, process duration, ratio of nitrogen to hydrogen in the process gas, pressure and voltage. Typical process parameters are shown in Table 17.

Table 17: Typical process parameter for plasma nitriding of tool steels

Process parameter	Value
Temperature	480 ... 560 °C
Nitriding time	1 ... 64 h
Nitrogen amount (rest H ₂)	5 % ... 90 %
Pressure	300 ... 500 Pa
Voltage	500 V

Test Serie 1 (1.2379, Vannadis 4E; CHT)

The improvement in coating adhesion can be achieved by optimizing the plasma diffusion process. It is known from previous experience that a not very intense nitriding without compound layer formation is advantageous, so that the process control required for this could be determined on the basis of a reduced test matrix. For this purpose, the conventionally heat-treated steels K110 (1.2379) and Vanadis 4E were used as representatives. In addition to the temperature, the treatment time and the nitrogen content were varied. The experimental matrix is shown in Table 18.

Table 18: Process parameters used for optimizing the PDT

Processparameter	Value
Temperature	520°C
Nitriding time	1 / 4 h
Nitrogen amount (rest H ₂)	5 / 10 %

The material behavior at the surface was analyzed by using the Rockwell indentation test and correlated with the nitriding zone, which was characterized by cross-section analysis and hardness depth profiles.

Figure 28 shows exemplary hardness depth profiles for the two steels used under variation of nitriding time and nitrogen content. It can be seen that low nitrogen contents of 10 % (blue curves) lead to a significant increase of the surface hardness, whereas the formation of a plateau can at most be guessed at below 10 % and 16 h. Nitrogen contents of 5 % (green curves) also lead to a significant increase in hardness in the boundary zone under long nitriding durations. The weakest nitration (5 % and 4 h) shows only a slight increase in hardness in the marginal zone, which drops most rapidly to the base level.

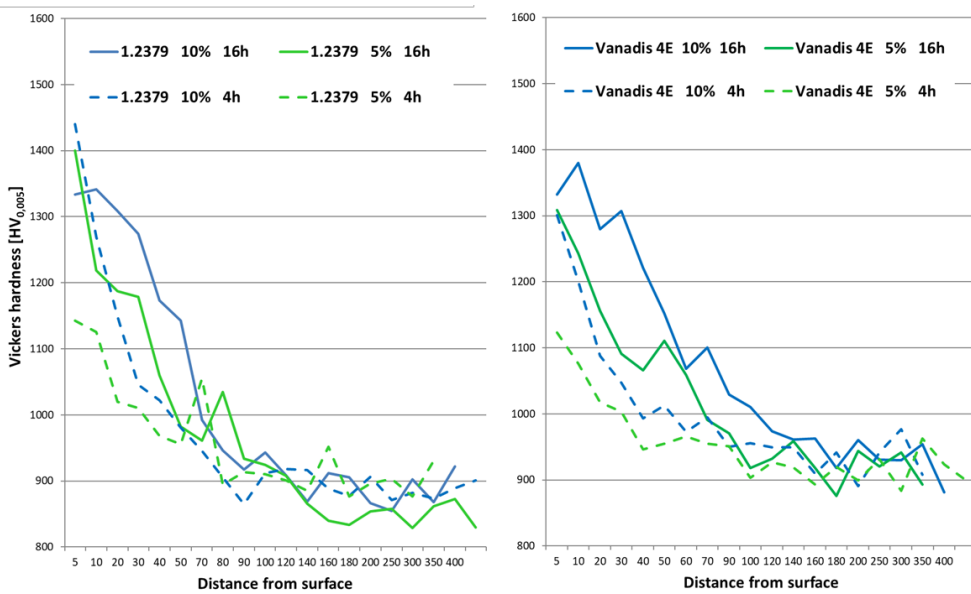


Figure 28: Hardness depth profiles in dependency on the nitriding parameters ($T = 520^{\circ}\text{C}$)

More detailed analyses of the nitriding zones confirm that under the selected parameters there is no compound layer formation. The nitriding hardness depth increases with the nitriding duration and nitriding time. The maximum hardness is reached directly at the surface. In the parameter range investigated, it is largely dependent on the material. Only with short nitriding times (4 h) and low nitrogen supply (5%) is the hardness at the surface lower. These findings correspond to the material behavior on the surface. Figure 29 and Figure 30 show the results of the Rockwell indentation tests. The untreated material shows no cracks. The more pronounced the nitriding, the stronger the cracking or embrittlement of the surface. Only the weakest nitriding shows no crack formation like the material without nitriding.

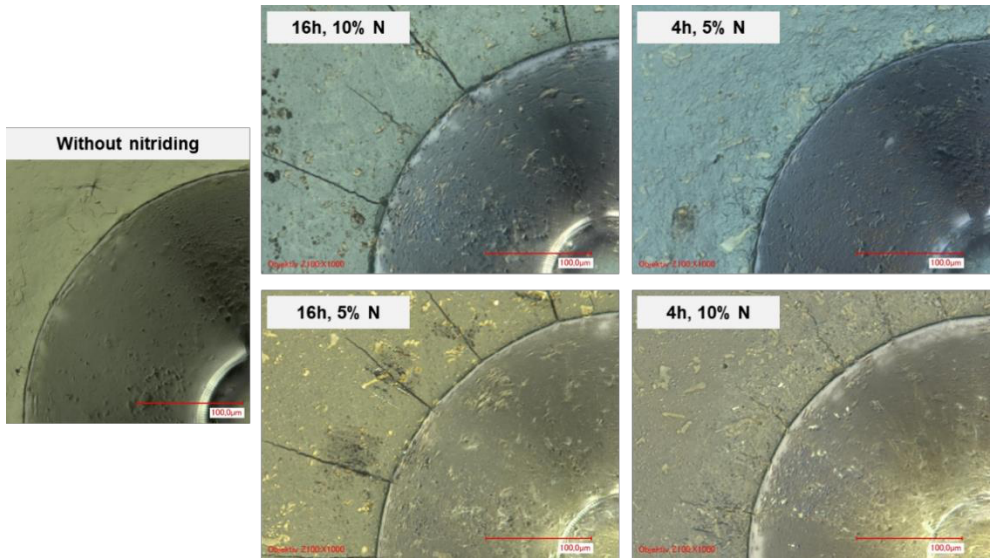


Figure 29: Rockwell-indentation-test of K110 (1.2379); CHT, nitriding temperature 520°C

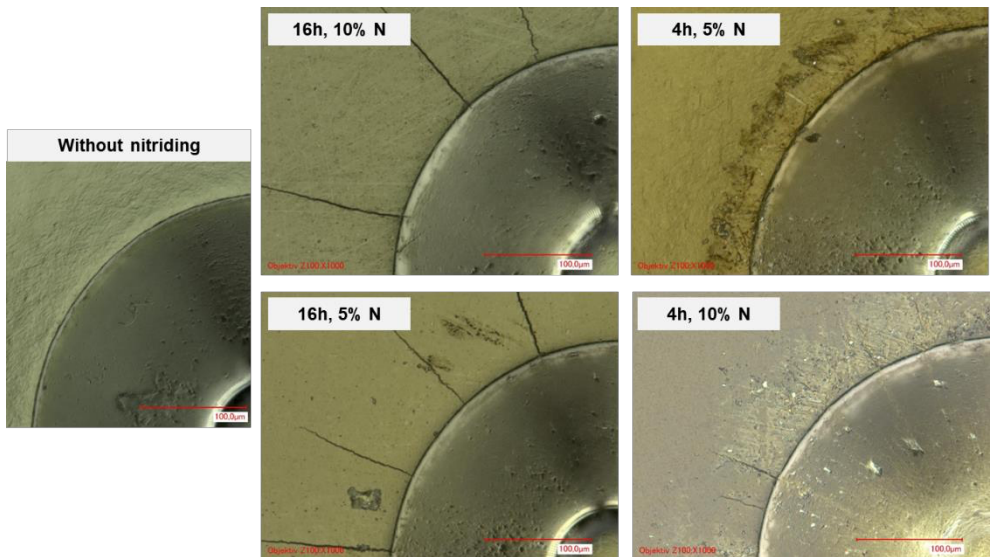


Figure 30: Rockwell-indentation-test of Vanadis 4E; CHT, nitriding temperature 520°C

In order to verify if plasma nitriding is also suitable in combination with DCT, additional scratch tests were carried out on K110. It was found that the time sequence has an influence on the crack formation. If the cryogenic treatment was performed prior to plasma nitriding, no significant changes were found compared to the conventional treatment. However, if the DCT was carried out after plasma nitriding (5% N₂, 4 h, 520°C), there are more cracks, which are more pronounced. This damage pattern was accompanied by a different type of material deformation at the boundaries of the scratch. A visual representation can be seen in Figure 31.

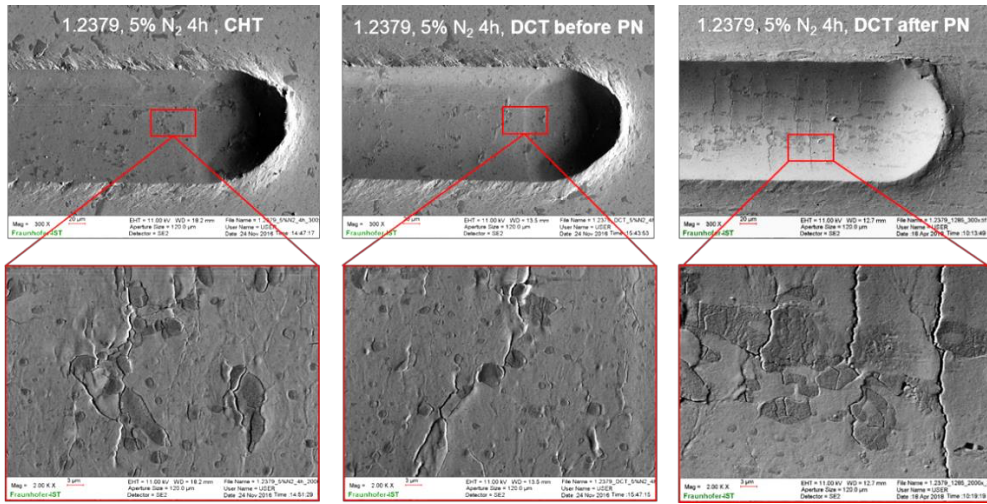


Figure 31: Wear trace after scratch test on plasma-nitrided steel K110 (1.2379) for different DCT treatments (Nitriding: 5% N₂, 4 h, 520°C)

In contrast, the opposite effect was also observed for other nitriding parameters that cause more intensive nitriding (Figure x). Here, the DCT treatment after nitriding led to a hardness decrease in the edge zone and the crack formation in the Rockwell penetration test could be completely prevented.

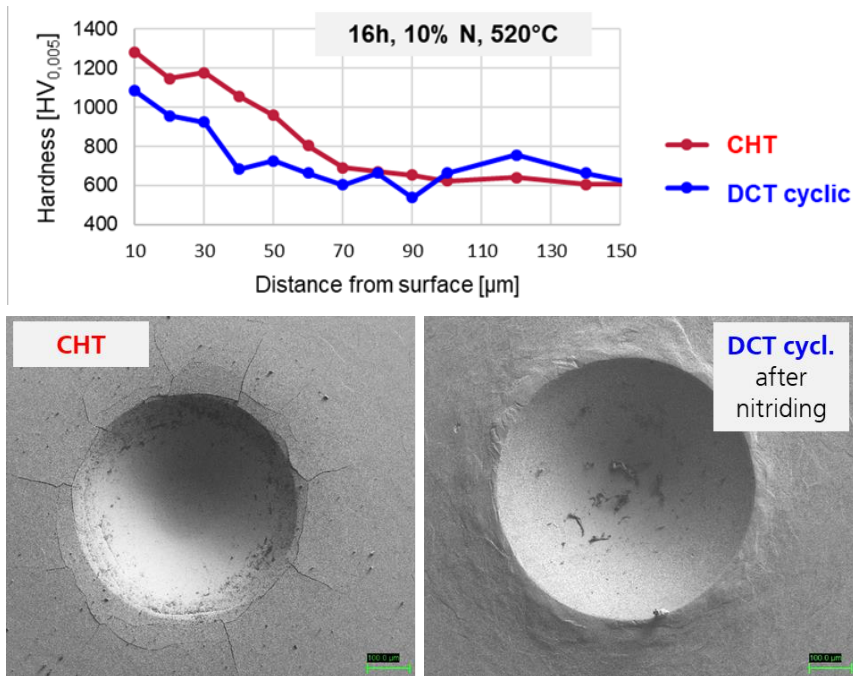


Figure 32: Hardness depth profiles and Rockwell-indentation-test of nitrided steel K110 (1.2379) with conventional heat treatment (CHT) and DCT

Test Serie 2 (All materials; DCT)

The tests of the first test series have shown that an increase in hardness of the edge zone is possible with an adapted plasma nitriding without significantly increasing the crack sensitivity of the surface. In a second test series the nitriding behavior of the steels K110, Vanadis 4E, Caldrie and K390 were investigated. Based on the previous results, a nitriding temperature of 520 °C and a nitriding time of 4 h with variation of the nitrogen content between 5 and 10 % were selected. The time of the cryogenic treatment was fixed between hardening and tempering. For comparison purposes, conventional heat treatment was also considered.

The hardening depth profiles can be seen in Figure 33. The results are analogous to those of test series 1. The surface hardness depends on the nitrogen content in the process gas. At a nitrogen content of 10%, the hardness increases. The strong variations within the K110 measurements can be explained by the bigger carbides, which are incorporated in the material. An increase in hardness due to the additional cryogenic treatment could not be reproducibly demonstrated.

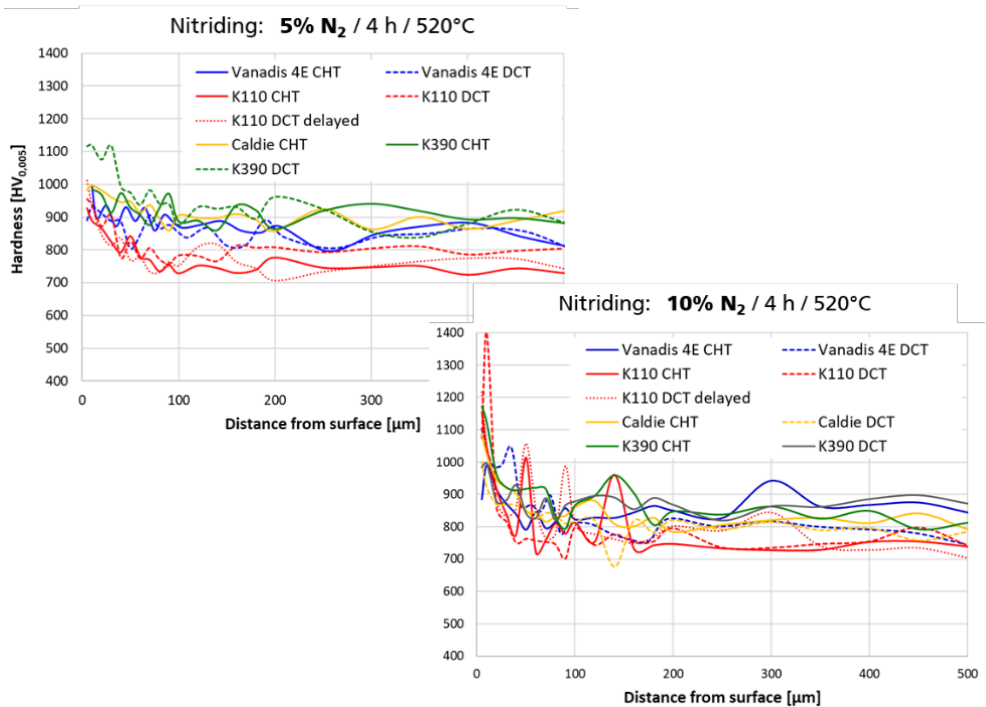


Figure 33: Hardness depth profiles in dependency on nitriding parameters and DCT

Figure 34 shows the crack formation as a function of the nitriding parameters and the heat treatment based on Rockwell indentations. At the weakest nitriding (5 % and 4 h) there is no deterioration in crack growth compared to the reference material. Moreover, this effect is not dependent on the DCT treatment. With an increase in the nitriding intensity, a crack network is formed, whereby no influence of DCT or the material used is apparent. Based on these results, a nitriding treatment with 5% N₂, 4 h and 520°C was selected for the laboratory-scale cutting tests.

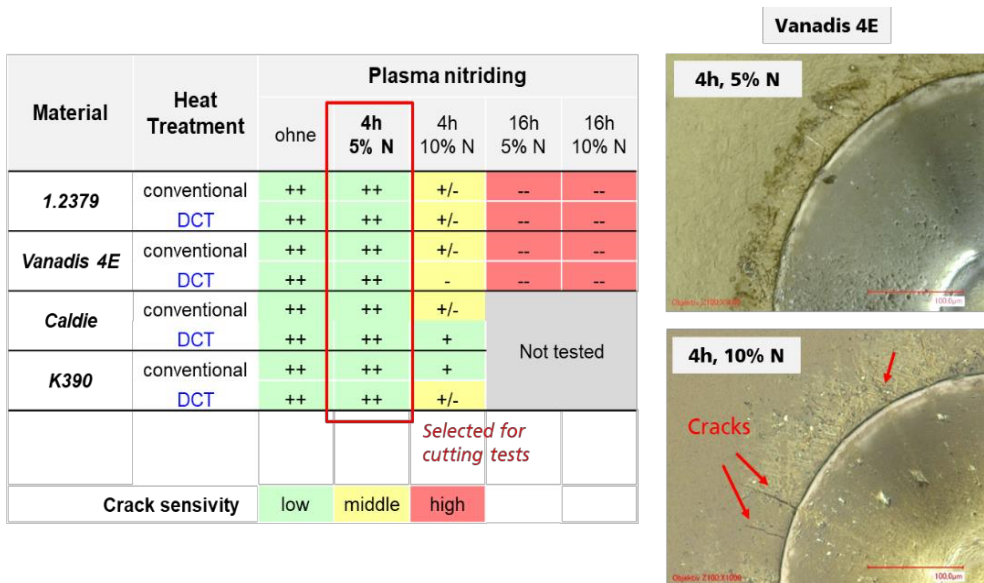


Figure 34: Crack formation in dependency on nitriding parameters and heat treatment

4.3.2 Cryogenic treatment of coatings

Based on previous research projects and suitable coating systems were selected. These included modified metal nitride coatings and carbon-based coatings.

Metal nitride coatings

Metal nitride coatings especially Cr- and Ti-(X)N coatings as are widely used for cutting and forming tools for steel processing. The individual coating systems have their own advantages, which make them suitable for different applications. The coating systems are based on TiN, CrN or other metal nitrides, to which further elements are added to adapt the properties to specific requirements. Examples of such elements are:

- X = Al, Si, Ti, Cr → increased heat resistance (~ 900...1000°C)
- X = W, V, Mo, B → reduced friction and adhesions

Carbon-based coatings

Carbon-based coatings are often used to prevent material adhesion of the workpiece material on cutting or forming tools, especially when processing highly adhesive materials. They can be widely adapted to the respective load spectrum. In this research project, hydrogenated amorphous carbon coatings (Diamond Like Carbon = DLC) were used, which were partially doped with metal (Me). With higher metal contents, they are called metal carbide coatings such as WC.

The coating systems were selected by considering the effects of individual elements on the coating properties. This results in the test matrix shown in

Table 19. The coatings were deposited by PVD (magnetron sputtering) or PACVD with different coating design on round test specimen (Ø 35 x 5 mm). The coating parameters were varied to optimize the coating properties, e.g. hardness, wear resistance and anti-stick properties. After coating, the samples were divided into two halves, one of which was DCT treated (see Figure 35).

Subsequently, the coating properties were characterized. The coating hardness and the coating adhesion were determined. XRD analyses were also carried out on individual samples to determine phase changes as a result of the DCT treatment.

Table 19: Selected coatings for cryogenic treatment

	Coating	Variation	Adhesion layer	Process	Hardness [HV]
Metal nitride coatings					
1	TiN	TiN	Ti	PVD	2200
2	TiAlN	TiAlN	TiAl	PVD	3000
3		AlTiN	TiAl	PVD	2800
4	TiAlXN	TiAlBN	TiAl	PVD	1800
5		TiAlSiN	TiAl	PVD	2900
6	CrN	CrN	Cr	PVD	1300-1400
7	CrTiAlXN	CrAlTiSiN	ohne	PVD	2500
8	CrVN	CrVN (30% V)	Cr	PVD	2200-2400
9		CrVN (21% V)	Cr	PVD	2100-2200
10	MoN	MoN (14% N)	Cr	PVD	2200-2300
11		MoN (27% N)	Cr	PVD	2600-2800
Carbon-based coatings					
12	a-C:H	a-C:H	Ti	PVD + PACVD	2600-2800
13		a-C:H	a-C:H:Si	PACVD	
14		a-C:H (PVD)	Cr	PVD	
15	a-C:H:W	WC (metal carbide)	Cr	PVD	2500-2700
16		a-C:H:W	Cr	PVD	1400-1600
17		CrN + a-C:H:W	Cr+CrN	PVD	
18		a-C:H:W:Si	Cr	PVD	3100-3200
19	a-C:H:Mo	a-C:H:Mo	Mo	PVD	1700-2200
20	a-C:H:V	a-C:H:V	V	PVD	1900

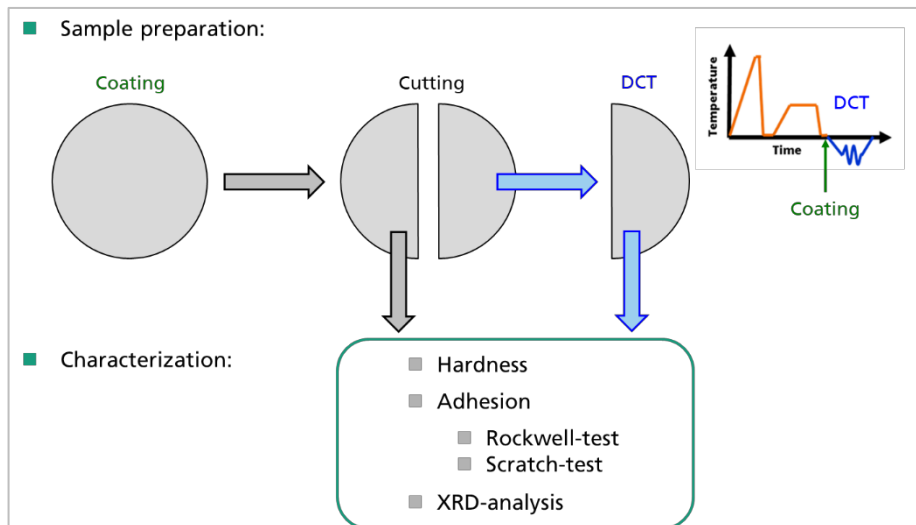


Figure 35: Sample preparation and characterization methods used for investigation of DCT influence on the coatings

Influence of DCT on metal nitride based coatings

Figure 36 shows the percentage change in hardness and indentation modulus of different nitride coatings after cryogenic treatment. A clear increase in hardness can be seen in two cases, TiAlSiN and CrAlTiSiN. A strong increase in the indentation modulus E_{IT} is visible in the case of TiAlSiN (~ 18 %), whereas small increases are seen in the TiAlN, AlTiN and CrTiAlSiN coating systems (2 - 6 %). A significant influence on the adhesion behavior could not be observed, either by using Rockwell indentation nor scratch test.

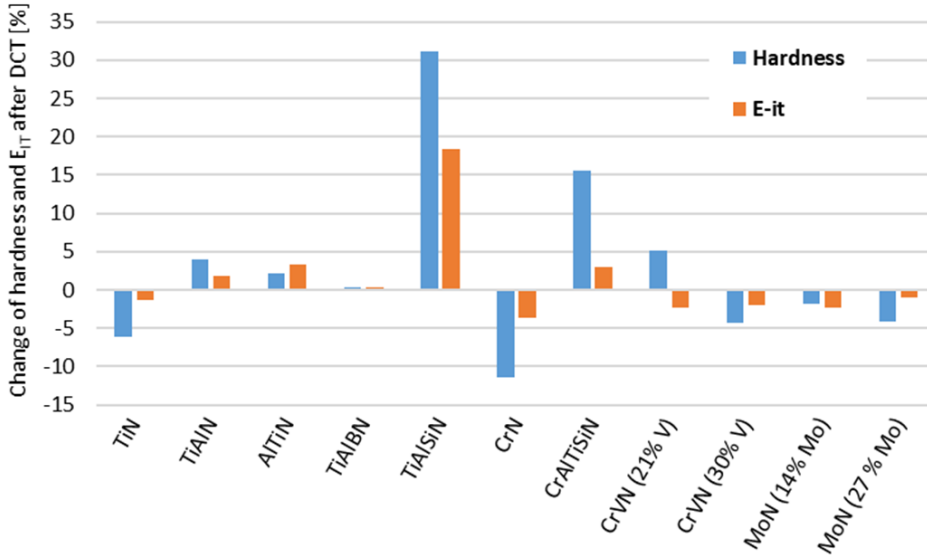


Figure 36: Influence of DCT on hardness and indentation modulus of metal nitride coatings

In order to correlate these changes in properties with the microstructure, additional XRD measurements were performed before and after cryogenic treatment. In the case of the TiAlN and AlTiN coatings, no differences in the patterns could be detected, so that the changes in hardness and Young's modulus cannot be clearly attributed to changes in microstructure. In the case of the (Cr)TiAlSiN coating, there are changes in the ratios of the individual peaks (see Figure 37). This suggests a change in grain orientation, which results in more advantageous properties.

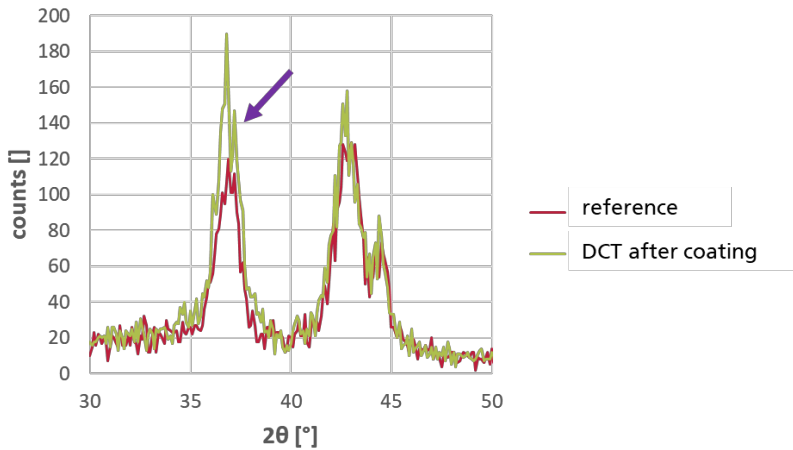


Figure 37: XRD-analysis of the CrAlTiSiN coating before and after DCT

Influence of DCT on carbon coatings

Figure 38 shows, in analogy to Figure 36, the percentage change in hardness and Indentation modulus after cryogenic treatment for different carbon based coatings. A significant increase in hardness of more than 10% can only be seen in the case of WC. However, the changes in hardness and indentation modulus of the other coatings are rather small and within the error mark, so this is not pursued further.

A significant influence of the cryogenic treatment on the adhesion behavior could not be proven either by Rockwell indentation nor by scratch tests.

XRD analysis was not possible for the DLC coating systems due to their mainly amorphous structure.

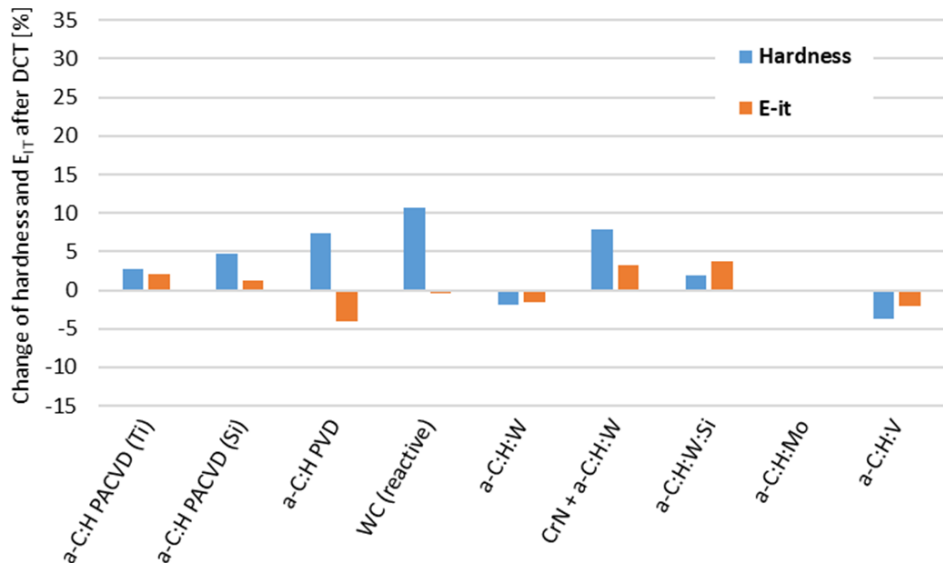


Figure 38: Influence of DCT on hardness and indentation modulus of carbon based coatings

4.3.3 PDT and coating of test and production tools

Based on the results from the previous sections, the following surface treatments were selected for all four steels for the Conventional cutting of different high strength materials (see Chapter 4.5.1):

- Reference (uncoated)
- WC
- CrTiAlSiN
- PN + CrTiAlSiN
- PN (with PN = Plasmanitriding 5% N₂, 4 h and 520°C)

In addition, the time and type of heat treatment were varied. This is illustrated in Figure 39. The number above the respective graph is used for the nomenclature of heat or cryogenic treatment and is as follows:

1. CHT
2. DCT
3. DCT cyclic
4. DCT after annealing
5. DCT with time delay

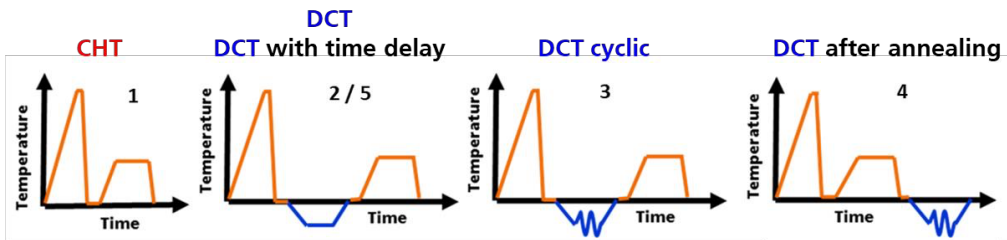


Figure 39: Schematic diagram of the timing and type of heat treatment

4.4 Tool manufacturing with different fabrication strategies (IWU)

Three different tool manufacturing strategies (see Figure 40) were used for the laboratory scale cutting tests in Chapter 4.5. The manufacturing strategy was selected separately for each cutting process depending on the tool geometry and the number of available tools.

Variant 1: Eroding, glass bead blasting, front face edges, grind sharply

Variant 2: Eroding, cylindrical surface Cylindrical grinding, front surface, Sharpen edges

Variant 3: Eroding, micro-blasting (including compacting), Sharpen the edges of the front face



Figure 40: Used tool manufacturing fabrication strategies (round tools K390)

4.5 Laboratory scale cutting tests & characterization of produced parts (IWU + IST)

The laboratory scale cutting test were carried out by conventional cutting and high speed impact cutting with different high strength materials. Details of the used cutting processes see chapter 4.1.1 "Definition of materials and geometries for lab scale tests and industrial demonstrators".

4.5.1 Conventional cutting of different high strength materials (IWU)

Conventional cutting tests were carried out with two different high strength steels and a typical glass fiber reinforced thermoplastic composite used in the automotive industry.

The following test matrix was used for the cutting tests with high strength steels (Table 20).

Table 20: Tool variants used for conventional cutting of high strength steels

Tool Nr.	Tool material	Heat treatment / DCT			Grinding	DCT	Grinding	Coating
		Hardening	DCT	Annealing				
111	Vanadis 4E	x		x	x			PN
112		x		x	x			WC CtIASIN PN + CtIASIN
121		x	const. without time delay	x	x			
122		x	const. without time delay	x	x			WC CtIASIN PN + CtIASIN
131		x	cycl.	x	x			PN
132		x	cycl.	x	x			WC CtIASIN PN + CtIASIN
141		x		x	x	cycl. after annealing		PN
142		x		x		cycl. after annealing	x	
211	K110 / 1.2379	x		x	x			
212		x		x	x			WC CtIASIN PN + CtIASIN
221		x	const. without time delay	x	x			
222		x	const. without time delay	x	x			WC CtIASIN PN + CtIASIN
231		x	cycl.	x	x			PN
232		x	cycl.	x	x			WC CtIASIN PN + CtIASIN
241		x		x	x	cycl. after annealing		PN
242		x		x		cycl. after annealing	x	
251	Caldie	x	const. with def. time delay	x	x			WC CtIASIN PN + CtIASIN
252		x	const. With def. time delay	x	x			PN
311		x		x	x			PN
312		x		x	x			WC CtIASIN PN + CtIASIN
321		x	const. without time delay	x	x			
322		x	const. without time delay	x	x			WC CtIASIN PN + CtIASIN
331		x	cycl.	x	x			PN
332		x	cycl.	x	x			WC CtIASIN PN + CtIASIN
341	K390	x		x	x	cycl. after annealing		PN
342		x		x		cycl. after annealing	x	
411		x		x	x			PN
412		x		x	x			WC CtIASIN PN + CtIASIN
421		x	const. without time delay	x	x			
422		x	const. without time delay	x	x			CtIASIN WC PN + CtIASIN
431		x	cycl.	x	x			PN
432		x	cycl.	x	x			WC CtIASIN PN + CtIASIN
441		x		x	x	cycl. after annealing		PN
442		x		x		cycl. after annealing	x	

Lab scale cutting test at Fraunhofer IWU with round tools and high strength steel

The tools for the cutting tests with round geometry were produced using three different manufacturing variants. In the first step, the initial shape was eroded. Subsequently, the shell surface was posttreated by glass bead blasting (Variant 1), grinding (Variant 2) or microblasting with compacting of the surface (Variant 3). The cutting edges were then sharpened by grinding the front surface and the edges were removed.

After 100,000 strokes in 1.4310 steel with a thickness of 0.3 mm, the wear on the cutting edges was very low (see **Fehler! Verweisquelle konnte nicht gefunden werden.** below). Both the measurement of the cutting edges before and after the tests and the determination of the change in mass of the tools showed no significant differences between the variants investigated (Figure 41). Therefore, no further tests were carried out with the round tools. The tool geometry and the sheet material were changed for the further cutting tests with steel materials in order to increase the conditions for cutting edge loading.

Cutting tests with round tools:

- 100.000 Strokes
- Sheet material: 1.4310 / 0.3 mm
($R_m = 1.700 \text{ N/mm}^2$)
- Tool material: K390 CHT

Weight loss of the punch

Tool variant	50.000 strokes	100.000 strokes	Δm in g
K390 V1-1	6,9662	6,9659	- 0,0003
K390 V1-2	6,9674	6,9674	- 0,0000
K390 V1-3	6,9668	6,9664	- 0,0004
K390 V2-1	6,9703	6,9701	- 0,0002
K390 V2-2	6,9646	6,9645	- 0,0001
K390 V2-3	6,9562	6,9559	- 0,0003
K390 V3-1	6,9618	6,9616	-0,0002
K390 V3-2	6,9579	6,9576	-0,0003
K390 V3-3	6,9234	6,9233	-0,0001

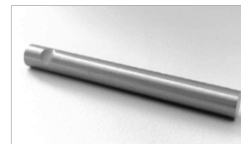
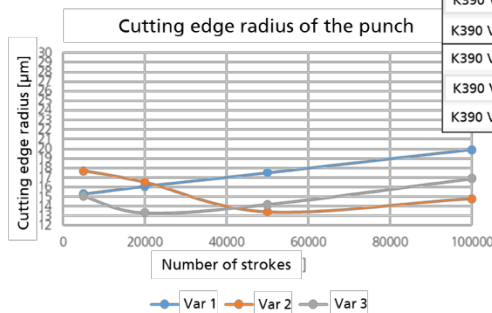


Figure 41: Lab scale cutting test with round tools. Weight loss and cutting edge radius of the punch after 100.000 strokes in steel 1.4310. Tool material K390 CHT

Lab scale cutting test at Fraunhofer IWU with "Dreieckgeometrie" and high strength steel

After the preliminary tests with round tools, the tool geometry was changed to increase the load in some areas of the cutting edge. In addition, a different sheet material was used, steel 1.4301 instead of 1.4310. The material 1.4301 has a greater tendency to material adhesion to the tool. This increases the load on the lateral surface of the tool. The lower strength of the material is compensated by the increase in sheet thickness. In addition, there is a strong material hardening as a result of the deformation during the cutting process.

These measures significantly increased the wear on the cutting edge and the lateral surface of the cutting punches. The cutting parameters and an example of tool wear are shown in Figure 42.

Cutting tests with "Dreieckgeometrie":

- 100.000 Strokes / 2 mm
- Sheet material:
 - Stainless steel 1.4301 (ISO 5445-2)
 - $R_m = 540\text{--}750 \text{ N/mm}^2$
 - Thickness: 0.6 mm

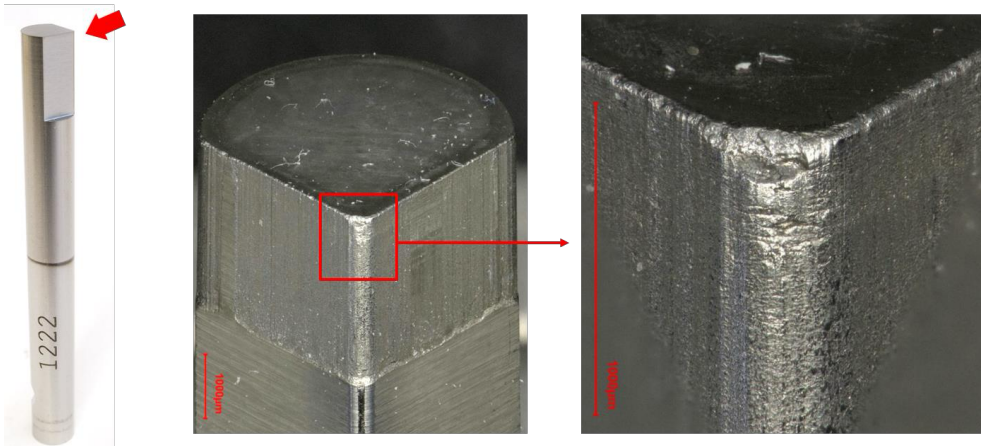


Figure 42: Lab scale cutting test at Fraunhofer IWU with "Dreieckgeometrie" and resulting wear

After the cutting tests were carried out according to Table 20, the analysis of the wear phenomena on the tools was carried out at the Fraunhofer IST, see Chapter 4.6. The effects of different tool materials and DCT treatments on tool wear behavior are explained there.

Lab scale cutting test at Fraunhofer IWU with composite material

Lab scale cutting tests with composite material were carried out with a TruPunch 5000 with commercially available rectangular stamps made from Standard Trumpf TruPunch HSS-steel with an edge length of 10 x 5 mm. DCT treatment was performed on the finished punches after hardening and tempering. The composite material was Tepex dynalite 104-RG600(4) a polypropylene (PP) material with 47% fibre volume content delivered by the company BOND Laminates. Details of the punch geometry and the composite material see Figure 43.

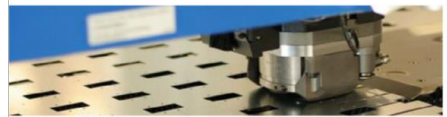
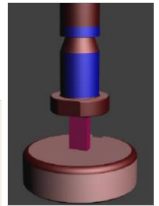
Wear on the cutting punches was very low. Even after 60,000 cutting strokes, no significant signs of wear affecting the cutting quality could be detected (Figure 44).

In order to be able to make statements about the effects of the DCT treatment on the service life of the tools, either the loading regime must be changed (modification of the cutting gap) or the number of cuts must be significantly increased. The change of the cutting gap resulted mainly in a deterioration of the cut surface quality. Therefore, this approach was not pursued. There was not enough composite material available to sufficiently increase the number of cuts, and with the limited project funds, it was not possible to procure a larger quantity. Therefore, further investigations with this material were not carried out.

Cutting tests with composite material:



Punch geometry:
rectangular stamp:
Edge length : 10x5mm



Composite: Tepex® dynalite,
104-RG600(4)/47%

- Thickness: 2,00mm
- RG: Roving Glas fabric
- Polypropylen (PP)
- 4x Fabric layers
- 47% Fibre volume content

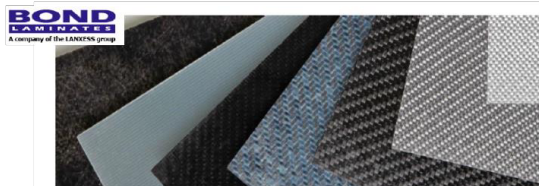
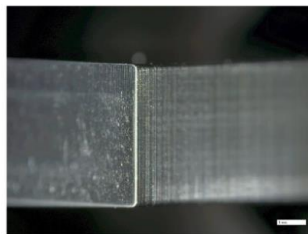


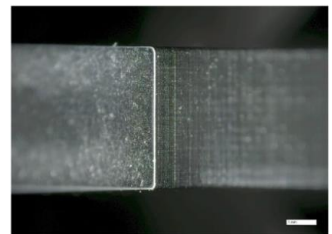
Figure 43: Lab scale cutting test at Fraunhofer IWU with composite material



0 strokes



30.000 strokes



60.000 strokes

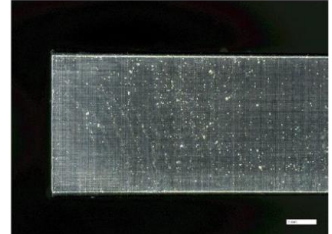
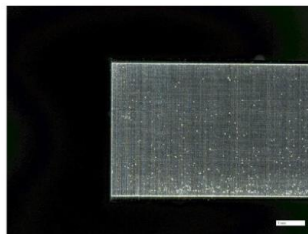
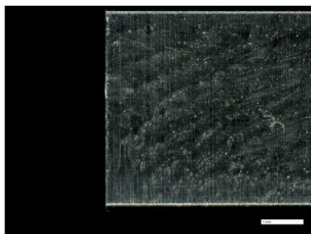


Figure 44: Tool wear after cutting composite material Tepex dynalite

4.5.2 High speed impact cutting (IWU)

For high speed impact cutting on laboratory scale at Fraunhofer IWU, an ADIA flex HSIC machine from ADI-APress was used. The relevant machine data can be found in Figure 45. Round punches with a diameter of 20 mm made of the PM steels ASP 23 and S290 were used as cutting tools (Figure 46). Tests were made with and without DCT treatment of the tools. The DCT treatment was performed on the finished punches after hardening and tempering. The sheet material was the boron-alloyed steel 22MnB5 with a thickness of 3 mm. The impact energy was varied between 200 and 1000 J, the cutting gap relative to the sheet thickness between 1.67 and 15%.

High Speed Impact Cutting: Parameters

- Acceleration unit: high speed hydraulics
- Velocity: up to 10 m/s
- Energy: 200 – 1000 J
- Punch diameter: 20 mm
- Cutting gap: 1.67 – 15.00 %
- Tool material: ASP 23, S290 (no coating)
- Sheet material: 22MnB5, 3 mm



Figure 45: High speed impact cutting, parameters

High Speed Impact Cutting: Punch geometry

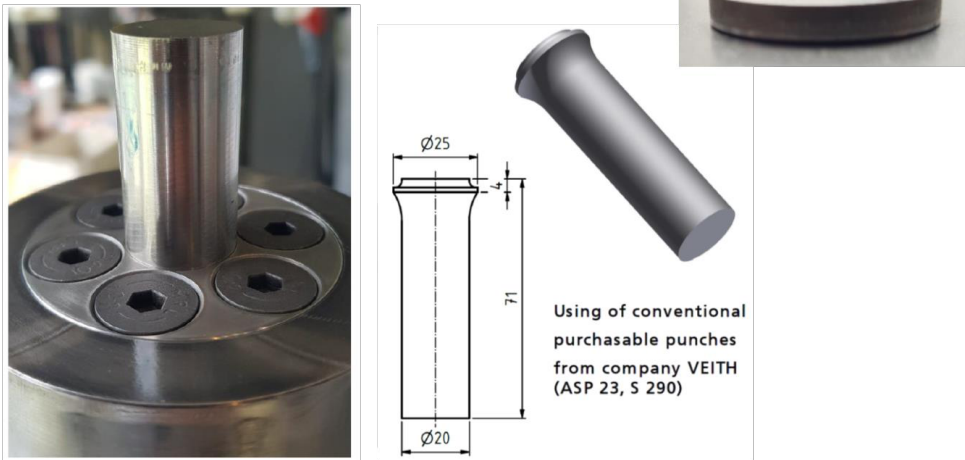


Figure 46: High speed impact cutting, punch geometry

In the first step, the cutting energy was varied at a constant cutting gap. The aim was to determine the minimum cutting energy at which nearly perpendicular cutting surfaces are produced. Very high cutting energies then result in increased damage to the cutting punches (see Figure 47). At a cutting energy of 200 J, the cut surface is still very wavy. The increase

to 250 J leads to almost vertical and flat cutting surfaces with the preweighted cutting gap of 1.67 %. A further increase in energy has no further effect on the geometry of the cut surfaces. At 1000 J, the cutting punches fail after only a few cutting strokes. Therefore, a cutting energy of > 750 J was selected for the comparative tool tests with and without DCT treatment.

High Speed Impact Cutting: Variation of impact energy (cutting gap 1.67 %)

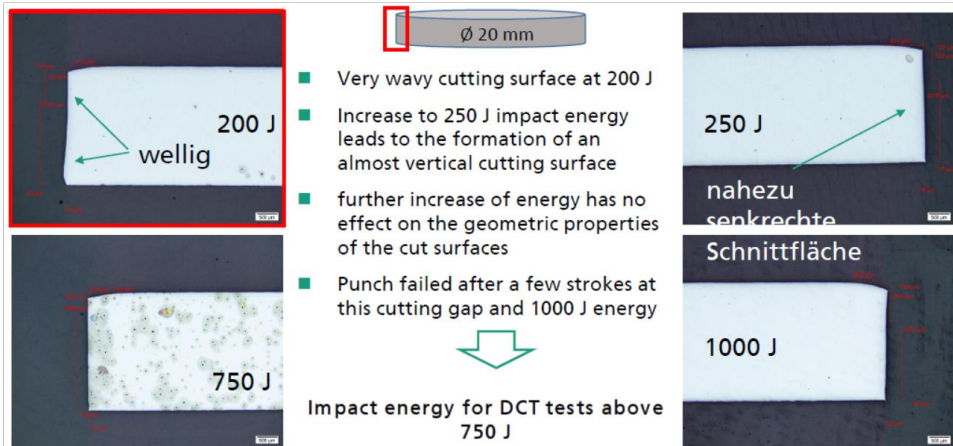


Figure 47: High speed impact cutting, variation of impact energy

In the next step, the cutting gap was increased at a given cutting energy of 1000 J (see Figure 48). As the cutting gap increases, the angle α becomes larger and larger. As a result, the quality of the cut surface decreases and the fractional area increases. At the same time, the required cutting force decreases significantly.

High Speed Impact Cutting: Variation of cutting gap from 1.67 to 15.00 %

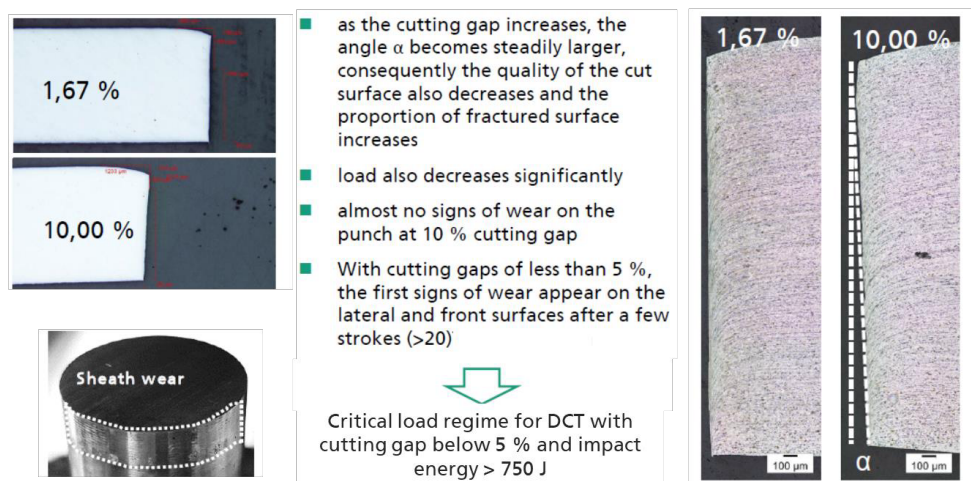


Figure 48: High speed impact cutting, variation of cutting gap

At 10% cutting gap, almost no more wear occurs on the cutting punch. With cutting gaps of less than 5%, the first signs of wear appear on the face and lateral surface of the cutting punch after only a few cutting strokes (> 20). It follows that the critical load for the cutting punch is at cutting gaps $< 5\%$ and cutting energies $> 750\text{ J}$ (see Figure 49).

High Speed Impact Cutting:

- Punch after 35 strokes, with a very small cutting gap $\leq 3\%$
- Extensive spalling on the front face of the punch



Figure 49: High speed impact cutting, punch after 35 strokes

Comparative tests with punches with and without DCT treatment in this load range showed a significant increase in tool life with DCT treatment. The tool life could be increased by approx. 50-200 %. In particular, chipping of the cutting edge occurred later.

4.5.3 Optical analysis of wear mechanisms (IST)

The analysis of the wear mechanisms at the Fraunhofer IST focused on the tools for the laboratory-scale cutting tests with "Dreieckgeometrie". For these the widest range of tool materials, heat treatments, DCT treatments and coatings could be investigated (see Table 20).

After the lab scale tests the tools were examined by visual inspection using a digital microscope. For comparison, two images were taken of each tool at different magnifications (see Figure 50). The first image shows an overview of the entire wear zone from the particularly wear-critical cutting edge corner. The second image shows the cutting edge corner at a higher magnification, thus revealing the cracks and chipping that occur there preferentially.

After superficial analysis of the tools a selection were made of tools with typical wear mechanisms. These tools were investigated by cross-sections of the wear zones by using stereomicroscopy (see Chapter 4.5.4.).

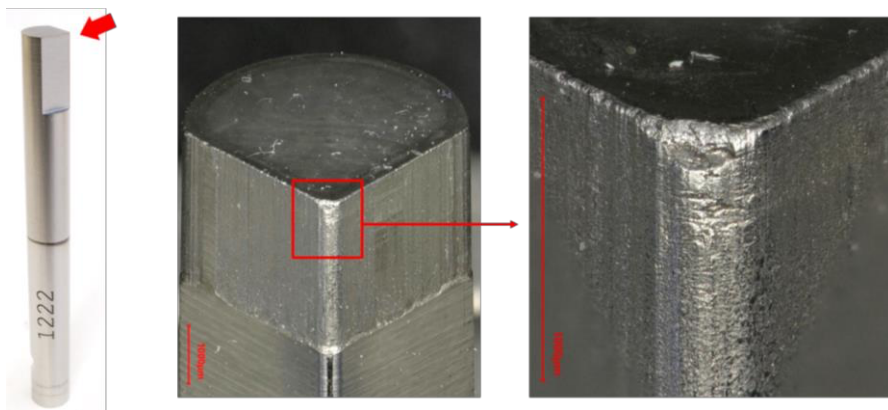


Figure 50: Optical analysis of wear mechanisms on the tools with "Dreieckgeometrie" after cutting

In the following, the influence of the different tool materials, heat and DCT treatments, coating as well as an additional plasma nitriding on the tool wear is shown on the example of comparative images. The main effects are summarized in key words on the pictures.

When evaluating the wear phenomena, it should be noted that only a few tools (1-3) of each variant could be tested and the results are subject to production-related scatter. This can be caused, for example, by slight differences in dimensions, surface topography and cutting edge preparation. The latter are partly visible on the pictures and must be taken into account in the evaluation.

Influence of the tool material on the wear behavior

The four tool materials investigated, K110 (1.2379), Caldie, Vanadis 4E and K390, have a significant influence on wear behavior, especially on the occurrence of cracks and chipping in the highly loaded cutting edge areas (Figure 51 and Figure 52). K110 and Caldie are more prone to cracking and chipping than the two PM steels Vanadis 4E and K390. This difference is maintained regardless of the type of DCT treatment and coating, but can be reduced by DCT treatment.

The applied coatings has only a minor influence on the wear mechanism, because the wear is dominated by the failure of the tool material (Figure 51). The differences between the DCT treatments before annealing (DCT and DCT cyclic) are very small and within the scatter between the single tests (Figure 52).

Overall, the ranking between the materials is as follows:

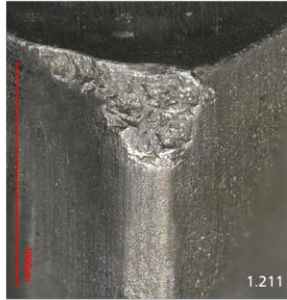
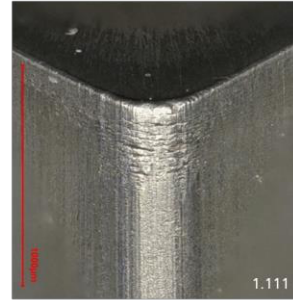
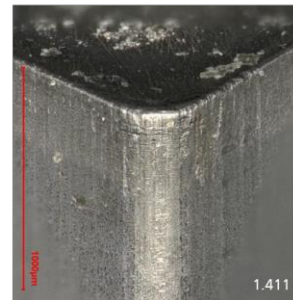
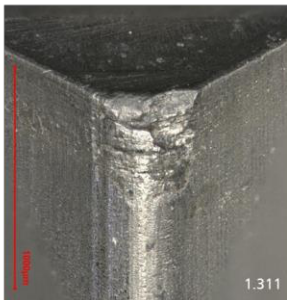
- K110 (1.2379): strongest tendency to form cracks and chipping
 significant improvement by DCT treatment.
- Caldie: lower tendency to form cracks and chipping compared to K110
- Vanadis 4E, K390: significantly reduced wear compared to K110 and Caldie,
 only slight improvement by DCT treatment

CHT

Tool wear after
100.000 strokes in
1.4301 / 0,6 mm:

Influence of material

→ *Clear differences
in wear behavior
between the
materials*

**Caldie****K390****CHT + CrTiAlSiN**

Tool wear after
100.000 strokes in
1.4301 / 0,6 mm:

Influence of material

→ *Clear differences
in wear behavior
between the
materials*

→ *Minor influence
of coating due to
failure of the tool
material*

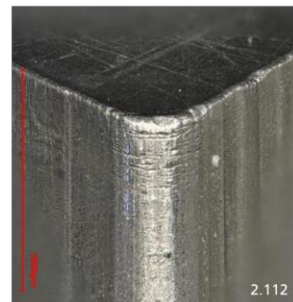
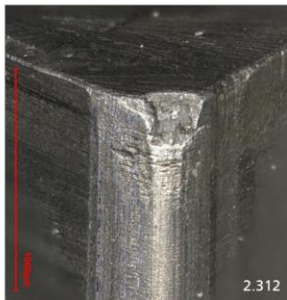
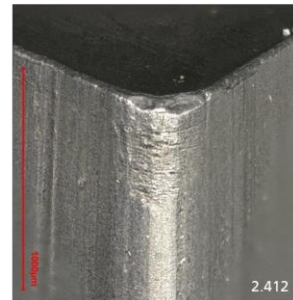
K110 / 1.2379**Vanadis 4E****Caldie****K390**

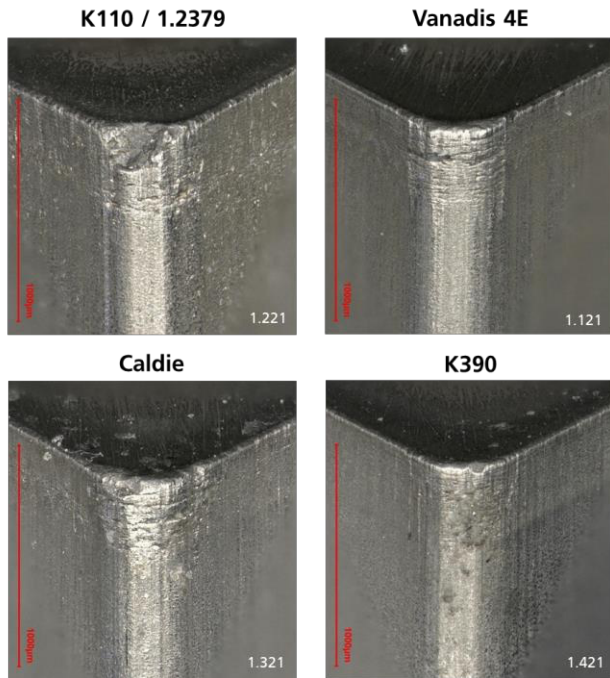
Figure 51: Tool wear "Dreieckgeometrie". Influence of the tool material (uncoated and coated)

DCT

Tool wear after
100.000 strokes in
1.4301 / 0,6 mm:

Influence of material

- *Less wear with K110 and Caldie compared to CHT*
- *Reduced differences between the materials*

**DCT cycl.**

Tool wear after
100.000 strokes in
1.4301 / 0,6 mm:

Influence of material

- *Similar to DCT without cycling*

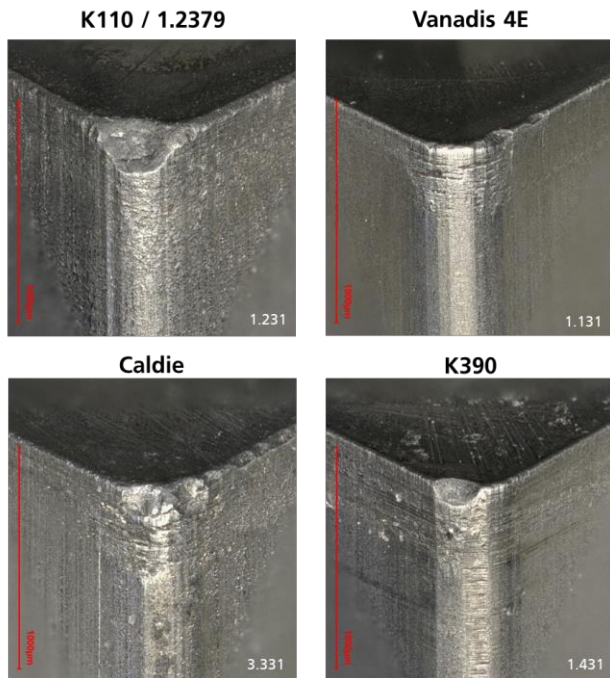


Figure 52: Tool wear "Dreieckgeometrie". Influence of the tool material (DCT and DCT cyclic)

Influence of the different DCT treatments on the wear behavior

The following figures show for each of the four materials the effects of the different DCT treatments on the wear behavior of the "triangular geometry" cutting punches after 100,000 cutting strokes in sheet material 1.4301 with a thickness of 0.6 mm (Figure 53 to Figure 56). The differences between the DCT treatments are shown in Figure 39.

On the materials K110 (1.2379) and Caldie, a positive effect of the DCT treatment compared to the conventional heat treatment (CHT) can be seen in the lower tendency to cutting edge chipping. For the two PM steels Vanadis 4E and K390, on the other hand, only very slight differences are visible.

The differences between the two cryogenic treatments performed before tempering (DCT and DCT cyclic) are small. For the cryogenic treatment performed after annealing (DCT cycl. after annealing), the result is inconsistent. K110 (1.2379) seems to be slightly more prone to breakouts in this case than in the DCT treatments before annealing (DCT and DCT cyclic). For the other materials, the DCT treatment after tempering seems to be more beneficial.

The timing of grinding during tool production (Grinding before or after DCT) does not seem to have any influence on the wear behavior.

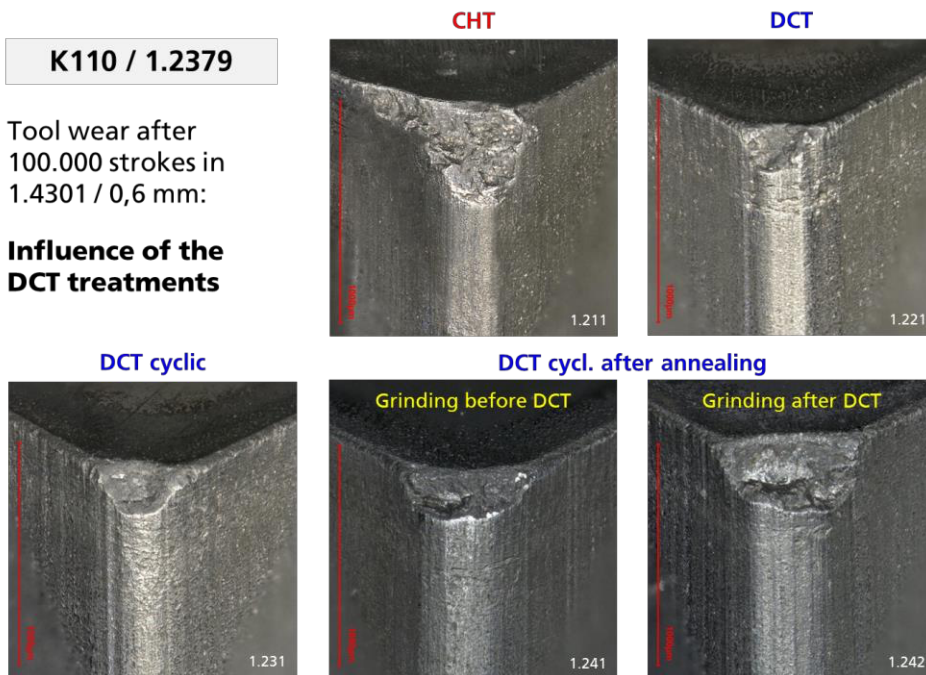


Figure 53: Tool wear "Dreieckgeometrie". Influence of the DCT treatments (K110 / 1.2379)

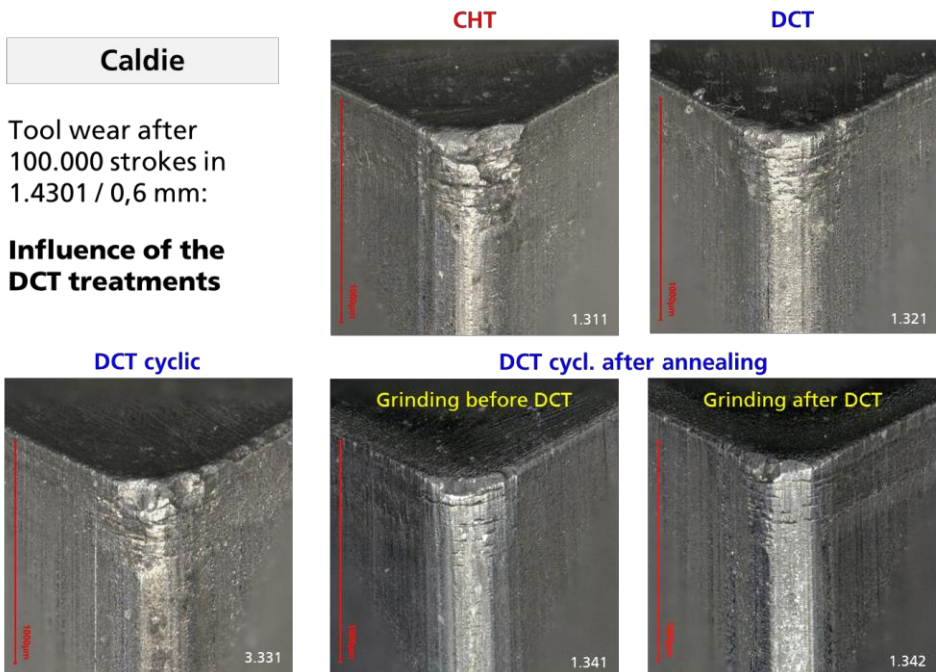


Figure 54: Tool wear "Dreieckgeometrie". Influence of the DCT treatments (Caldie)

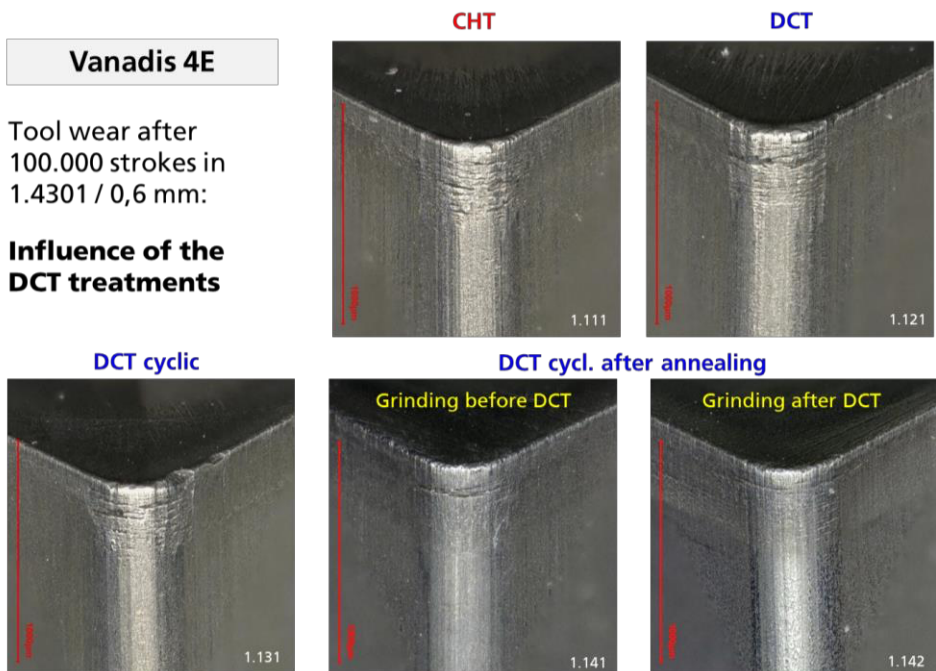


Figure 55: Tool wear "Dreieckgeometrie". Influence of the DCT treatments (Vanadis 4E)

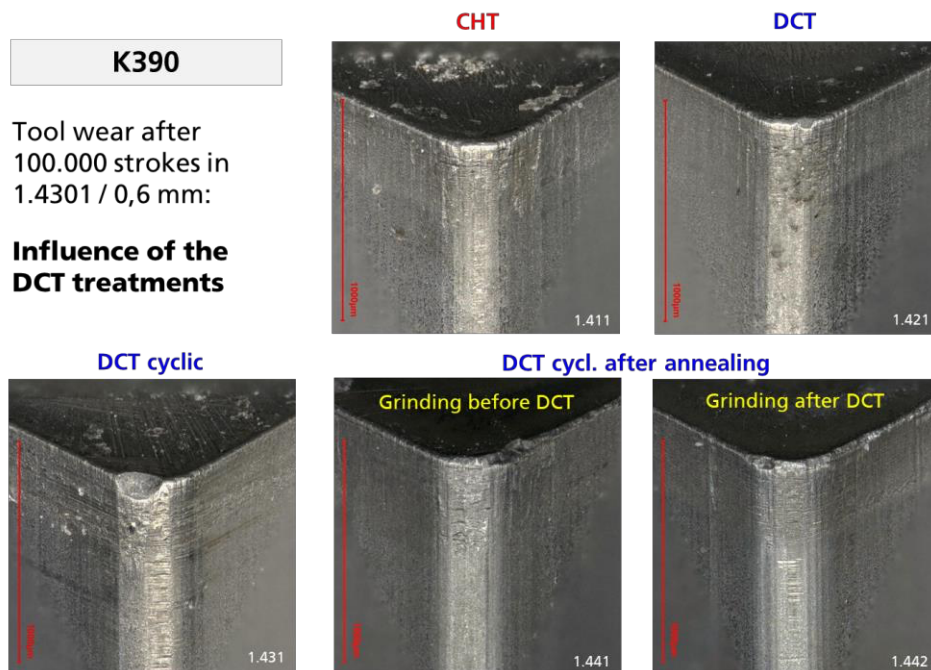


Figure 56: Tool wear "Dreieckgeometrie". Influence of the DCT treatments (K390)

Influence of the coatings and plasma nitriding on the wear behavior

The influence of tool coatings on the wear behavior of tools with "triangular geometry" was investigated using a CrTiAlSiN and a WC coating as examples (for details on the coatings and coating selection, see chapter 4.3.2 and 4.3.3). Furthermore, the effects of plasma nitriding developed within the project on tool properties were considered, both as a stand-alone treatment and as a pre-treatment prior to coating. For details on plasma nitriding, see chapter 4.3.1).

The comparison in Figure 57 shows the influence of the coatings and a coating with prior plasma nitriding treatment on tool wear compared to uncoated tools using the example of the materials K110 / 1.2379 and K390 with cyclic DCT treatment. The other two materials, Caldie and K390, show similar behavior, so their presentation is omitted.

It can be seen that the coatings without prior plasma nitriding have little effect on tool wear in the cutting operation tested. Slight advantages can be seen with the WC coating. This can be explained by the friction-reducing effect of the WC coating, which can lead to a reduction in the tensile stress that occurs during the return stroke and thus to somewhat reduced cracking.

The overall low influence of the coatings on the tool wear can be explained by the fact that the cracks and chipping that occur are due to local overloading of the base material. This can only be prevented to a limited extent by the coating.

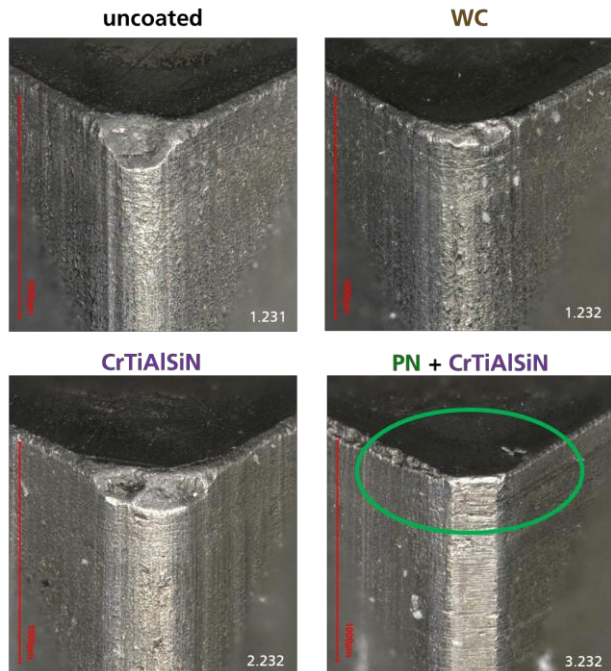
The positive effect of the additional plasma nitriding is remarkable. Cracking and chipping can be largely avoided, as will be confirmed by the cross sections shown later (see Section 4.5.4). On the basis of these results, additional tools were tested which had only been subjected to plasma nitriding treatment without additional coating (see Figure 58).

K110 / 1.2379 DCT cycl.

Tool wear after
100.000 strokes in
1.4301 / 0,6 mm:

Influence of the coatings

- Low effect of the coatings without additional plasma nitriding. (Failure of base material)
- Similar wear behavior as Caldie



K390 DCT cyclic

Tool wear after
100.000 strokes in
1.4301 / 0,6 mm:

Influence of the coatings

- Overall fewer cracks and breakouts than K110/1.2379
- Low effect of the coatings without additional plasma nitriding. (Failure of base material)
- Similar wear behavior as Vanadis 4E

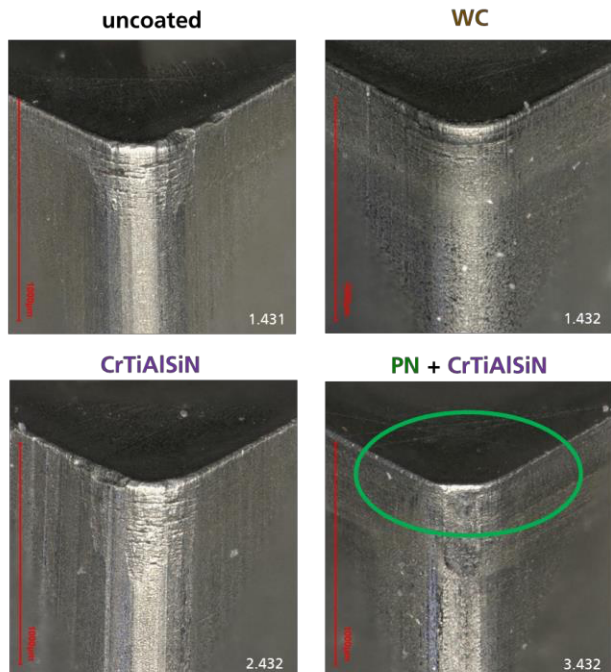


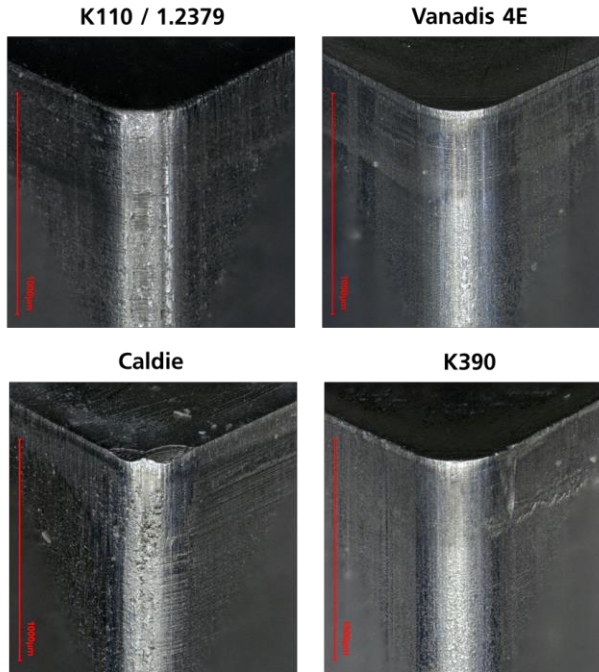
Figure 57: Tool wear "Dreieckgeometrie". Influence of the coatings (DCT cyclic, K110 and K390)

DCT
PN

Tool wear after
100.000 strokes in
1.4301 / 0,6 mm:

Influence of the tool material

- *Lowest wear with
additional
plasmanitriding*
- *Similar behavior of
all base materials*
- *Only minor
advantage due to
PM steel*



DCT
PN + CrTiAlSiN

Tool wear after
100.000 strokes in
1.4301 / 0,6 mm:

Influence of the tool material

- *Only minor
advantage due to
additional coating
of the plasma-
nitrided tools*
- *Slightly reduced
material buildup*

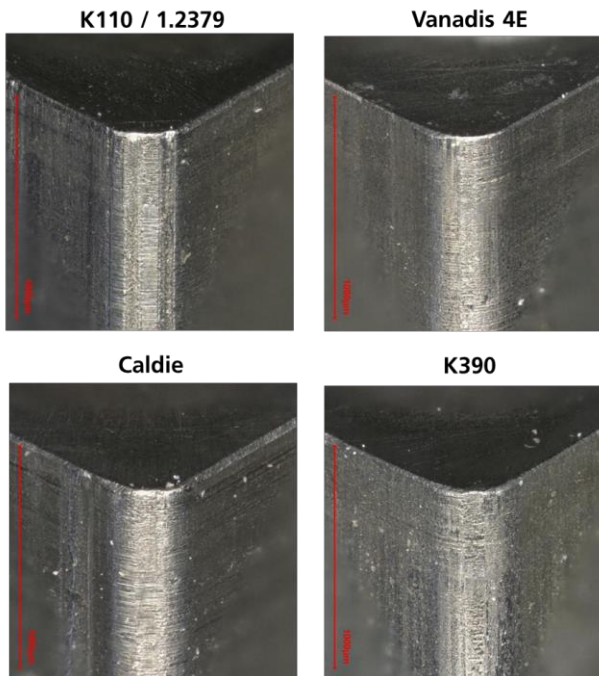


Figure 58: Tool wear "Dreieckgeometrie". Influence of the tool material (PN and PN + CrTiAlSiN)

The comparison in Figure 58 confirms the positive effect of plasma nitriding developed as part of the project for all four materials investigated. The additional coating does not result in any significant further improvement under the present tool load. Only the material adhesions seem to be slightly lower. This may have a beneficial effect on the cutting forces and the quality of the cutting surface.

Plasma nitriding significantly reduces the differences in the wear behavior between the base materials. The two PM steels Vanadis 4E and K390 have only a slight advantage over the two conventional cold work steels K110 / 1.2390 and Caldie in combination with plasma nitriding.

Conclusions from the wear analysis of the tools with "Dreickgeometrie"

The following conclusions can be drawn from the wear analysis:

- The wear is dominated by crack formation and breakage of the cutting edges
- Conventional heat treatment (CHT):
 - Lowest wear with Vanadis 4E and K390
- Effect of DCT:
 - Distinct wear reduction for K110/1.2379 and Caldie
 - Slight wear reduction for Vanadis 4E and K390
 - Only small differences between DCT and DCT cyclic
- Effect of the coatings:
 - Little effect of the coatings without additional plasmanitriding
 - Significant reduced crack formation and wear on all materials by adapted plasmanitriding procedure (5 % N₂, 4 h, 520°C)

4.5.4 Cross-sectional investigation of the wear mechanisms (IST)

In order to better understand the differences in wear behavior between the different treatment variants, cross sections were made of the tools with "triangular geometry" after the cutting tests. These were then examined using light microscopy techniques. The main objective was to identify cracks that are the starting points for material chipping in the cutting edge area.

The following comparative images show the effects of DCT treatment and plasma nitriding on the cracking in the highly loaded edge zone using the example of the material K110 / 1.2379 with an additional coating. The uncoated tools show a very similar behavior, therefore they are not shown.

Both the tools with conventional heat treatment (CHT) and DCT treatment show cracks in the edge zone of the lateral surface (Figure 59). Crack intensity tends to be somewhat lower with DCT treatment. The cracking can be explained by the cyclic compression and elongation of the edge zone as a result of the friction between the tool and the sheet material during the back and forth stroke of the cutting punch. The pronounced rounding of the cutting edges as a result of advanced tool wear is also clearly visible. In the area of the lateral surface, the coating is completely removed after the 100.000 cutting strokes. Other than at the highly loaded cutting edge corner (see Figure 53), no significant difference between the conventional and the DCT treatment can be seen. This can be attributed to the lower load on the cutting edge in the area of the cross section.

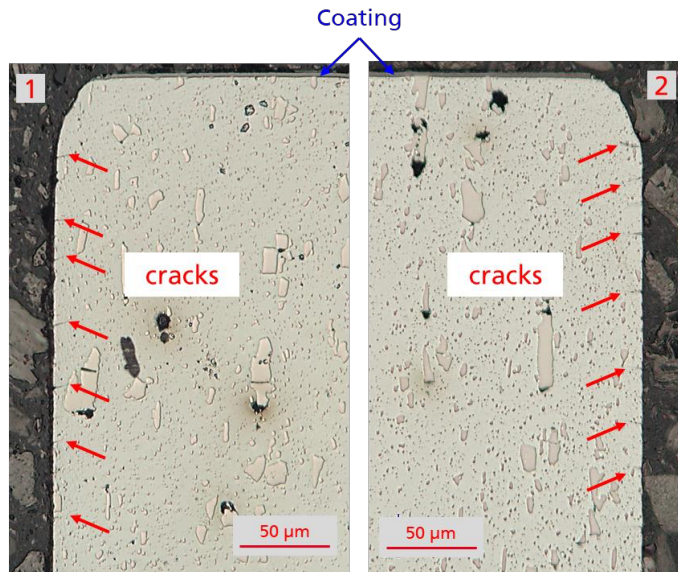
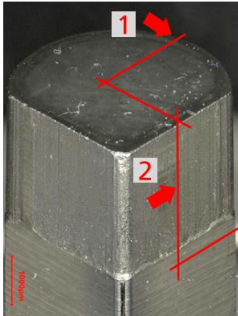
Figure 60 again shows the conventionally heat treated tool (CHT) and the DCT treated tool in comparison. The difference to the previous figure is the additional plasma nitriding treatment. The diffusion zone is faintly visible. Remarkable is the almost complete absence of cracks, both for the CHT and the DCT treatment. The cutting edge is largely intact, even the coating is still present in this area, unlike on the lateral surface.

K110 / 1.2379

CHT

CrTiAlSiN

Tool wear after
100.000 strokes in
1.4301 / 0,6 mm



K110 / 1.2379

DCT

CrTiAlSiN

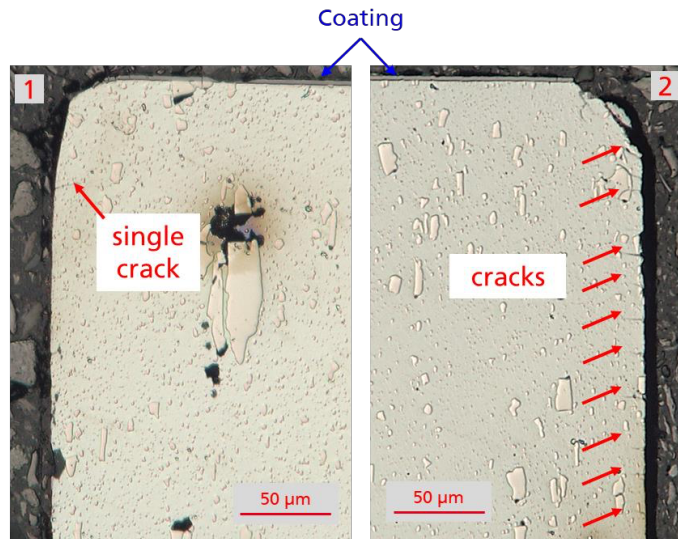


Figure 59: Cross section tool "Dreieckgeometrie". Influence of DCT (K110 / 1.2379 coated)

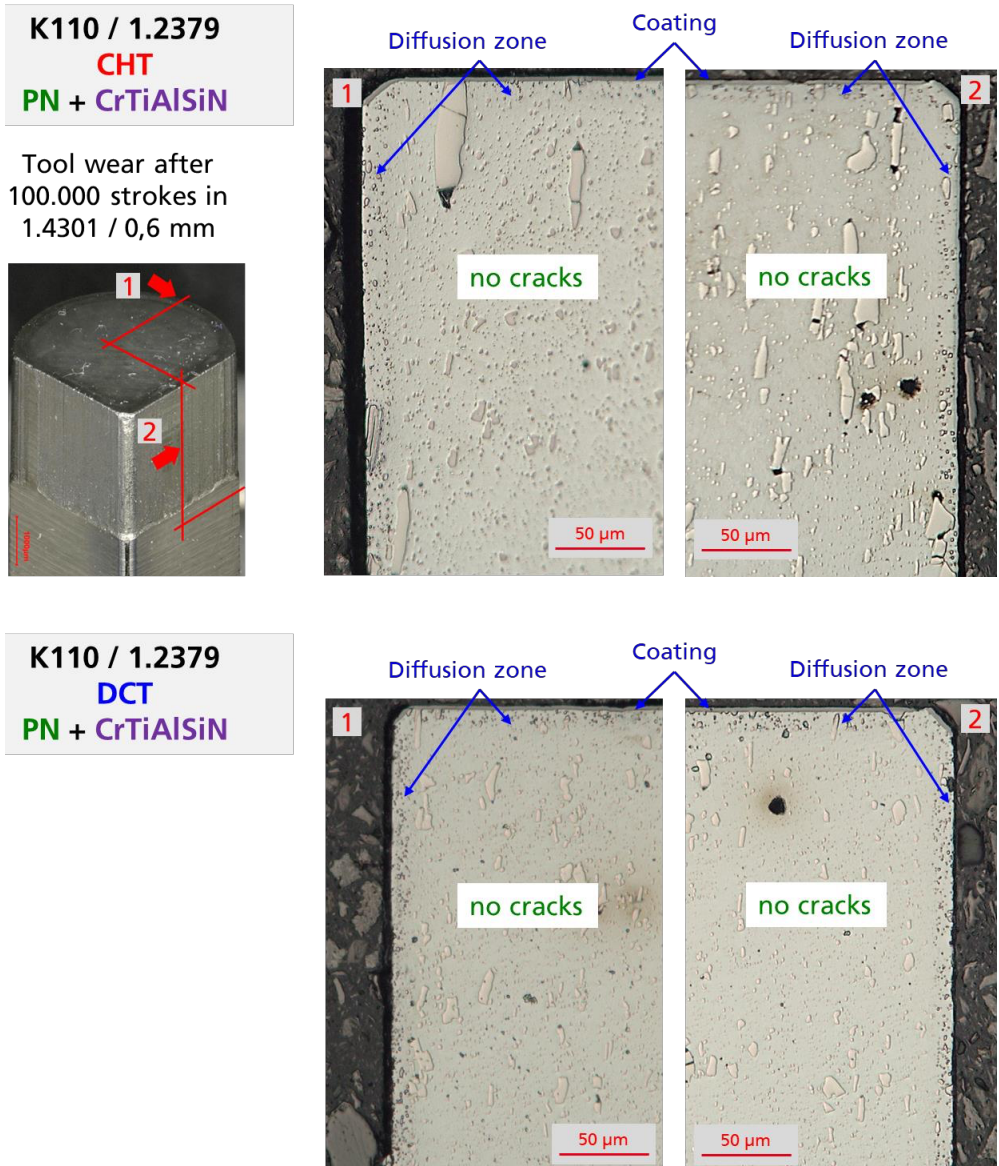


Figure 60: Cross section tool "Dreieckgeometrie". Influence of DCT and PN (K110 / 1.2379 coated)

4.5.5 Additional wear tests (IWU)

Additional wear tests were carried out with a 3-roller test rig at IMP Warschau (details see chapter 4.1.2 Figure 13). The wear volume was determined in dependency on the heat and DCT treatment for different contact pressures.

Four different treatment options were compared:

- Q+T: Quenching + Tempering
- Q+DCT+T: Quenching + Deep Cryogenic Treatment (-180°C) + Tempering
- Q+MCT-100+T: Quenching + Multicycle Cryogenic Treatment (-180...-100°C) + Tempering
- Q+MCT 20+T: Quenching + Multicycle Cryogenic Treatment (-180...+20°C) + Tempering

Details of the used cryogenic treatments see Figure 61.

3-Roll-Test:

Used cryogenic treatments

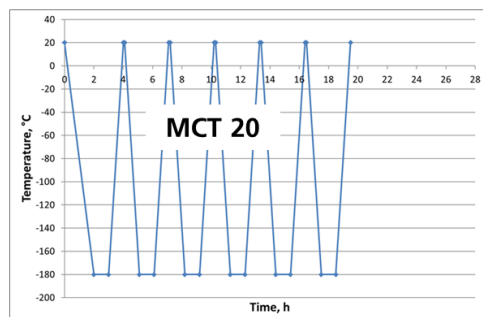
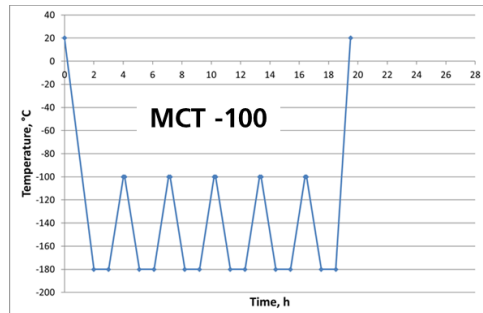
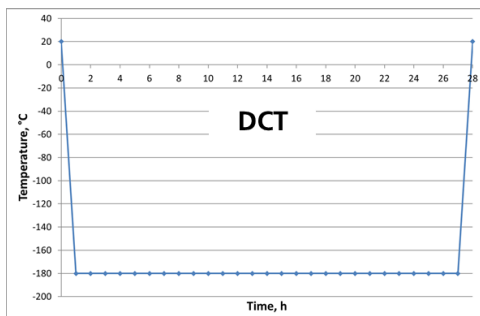


Figure 61: 3-Roll-Wear-Test at IMP Warschau. Used cryogenic treatments.

The results for the materials K110 (1.2379) and K390 at a load of 400 MPa are shown in Figure 62 and Figure 63.

In the case of the material K110 / 1.2379, regardless of the type of treatment, the wear initially increases slowly in a linear manner and then changes almost seamlessly into a steep increase (Figure 62). This indicates a failure of the material due to fatigue effects leading to a sudden increase in wear.

Wear is significantly lower on the K390 and increases evenly over the entire test period (Figure 63). This correlates with the more favorable wear behavior of this material observed on the punches with "Dreieckgeometrie" (see chapter 4.5.3).

For both materials, wear is lower with all used cryogenic treatments than with conventional heat treatment (Q+T). The multicycle cryogenic treatment between -180°C and -100°C (MCT-100) seems to be less effective than the other cryogenic treatments for the material K110 (1.2379). This may be due to the smaller temperature amplitude than the multicycle cryogenic treatment between -180°C and $+20^{\circ}\text{C}$ (MCT 20) and the shorter residence time at low temperatures for the deep cryogenic treatment at constant -180°C (DCT).

K110 (1.2379)

3-Roll-Test

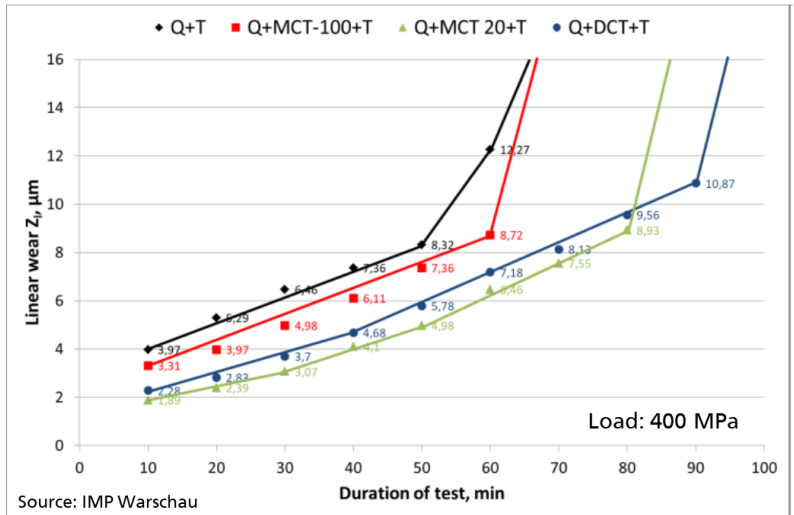
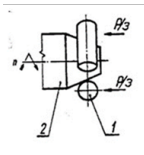


Figure 62: 3-Roll-Wear-Test at IMP Warschau. Influence of DCT on linear wear (K110 / 1.2379)

K390

3-Roll-Test

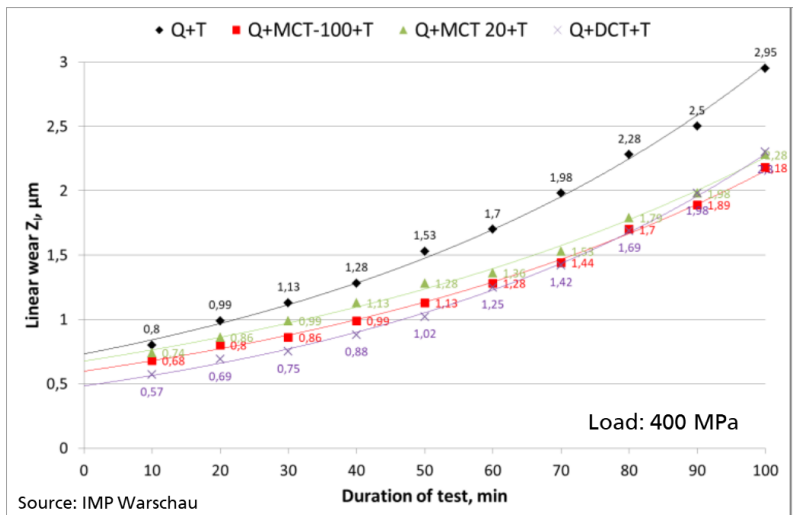
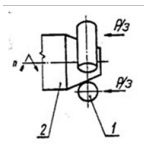


Figure 63: 3-Roll-Wear-Test at IMP Warschau. Influence of DCT on linear wear (K390)

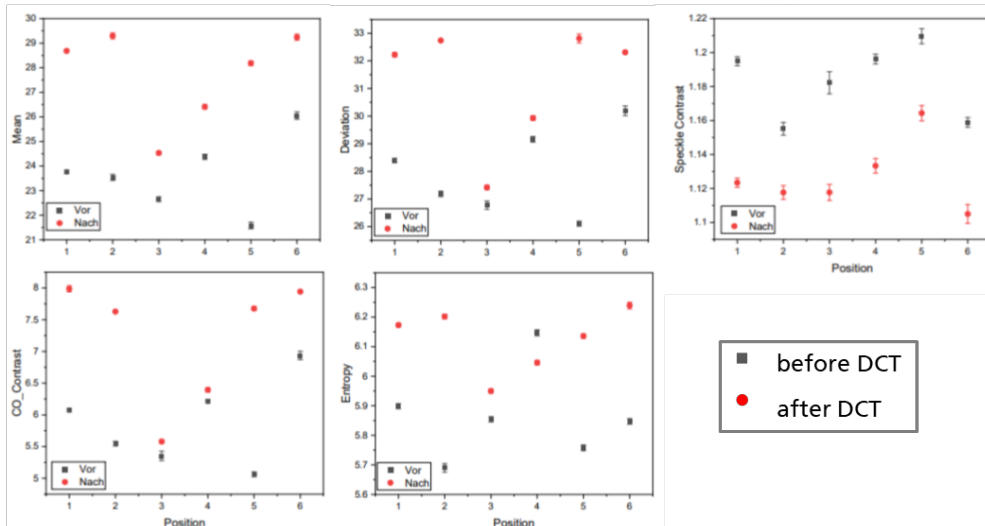
4.6 Cutting tests under production conditions

4.6.1 Cutting of steel and high strength steel

Industrial cutting test “Fuelcells” with complex phase steels (Germany)

Industrial cutting tests with high strength sheet material in Germany were carried out at company Bernd Flach Präzisionstechnik. The complex-phase steel CR900Y1180T-CH with a tensile strength >1.100 MPa is used for Fuelcells. Punch material was cold working steel 1.2379. Punch diameter was 10 mm. Different cutting gaps were tested. Details of the press used, the dies, the sheet material and the varied test parameters are given in chapter 4.1.1 Figure 11. Cutting punches made of 1.2379 with conventional heat treatment (CHT) and DCT treatment were compared.

Before and after the DCT treatment, a speckle analysis was performed on the piercing punches at Fraunhofer IKTS. Details of the speckle analysis used are shown in Figure 15. The analysis revealed significant changes in the speckle pattern as a result of the DCT treatment (see Figure 64). However, a correlation of the changes in the speckle pattern with the microstructural changes caused by the DCT treatment is still pending and requires further research.



- Significant change in speckle parameters before and after Cryo treatment
- Standard deviations come from 60 speckle recordings
- Slight changes in position influence the accuracy of the measurements

Figure 64: Industrial cutting test “Fuelcells” with complex phase steel. Speckle analysis of the punch before and after DCT treatment

On the cutting punch with conventional heat treatment, a massive breakout of the cutting edge occurred, which led to the breakage of the punch head after 1,300 cutting strokes (Figure 65). With DCT treatment, the wear of the cutting edge was considerably lower and the breakage of the punch head occurred after 1,500 strokes.

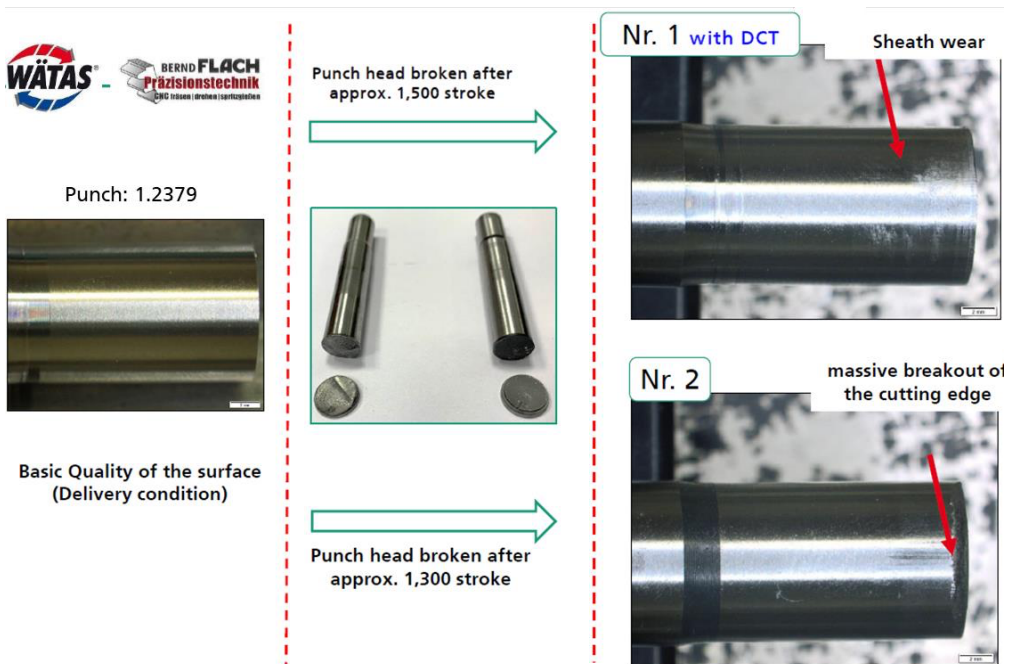


Figure 65: Industrial cutting test "Fuelcells" with complex phase steel. Comparison of tool wear (punch 1.2379 CHT and DCT)

Production of stainless steel rivets (Belgium)

The production of stainless steel rivets was done at the company Dejong in Antwerp. The punch used for this operation (see Figure 66) has a diameter of 5 mm and a length of 88 mm and is commercially available from the company Sala Punzoni. The punches are made of PM steel ASP23 with a hardness of 65,5 HRC. Since the punches were hardened they were treated according to the variant method 4 (post DCT with constant temperature). After DCT the hardness was measured and 66.5 HRC was found. Three test runs were made: without DCT about 76000 rivets in stainless steel 316 and 1.6 mm thickness were made before wear occurred. Two other runs were made with DCT treated punches: the first run ended at 75000 parts and the second at 88000 parts (see Figure 67). It shows that in this particular case the post DCT had a minor influence on the lifetime.

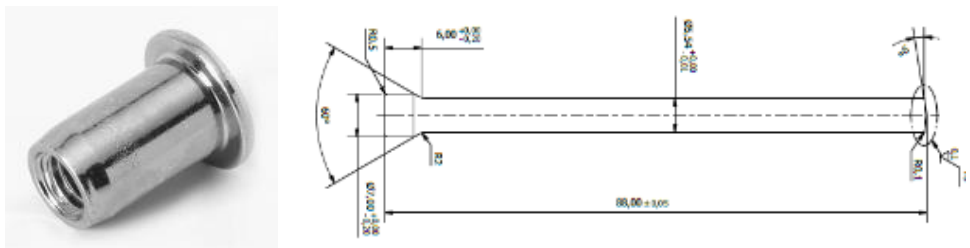


Figure 66: Rivet (left) and commercial punch (right) for making rivets

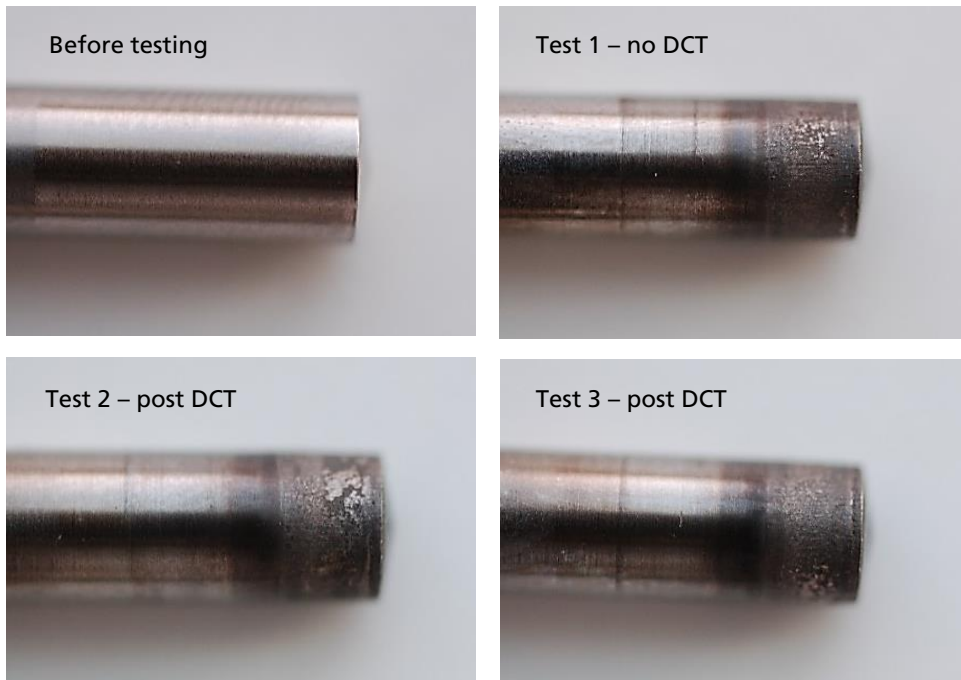


Figure 67: Punches from the industrial cutting test at Dejong before and after testing

Side cutters for steel plates (Belgium)

Another industrial test was done with side cutters for steel plate. Figure 68 shows two side cutters as well as the punching press used for the tests.

Two massive blocks in 1.2379 steel were hardened at 1050°C followed by three tempering steps at 510°C to obtain a hardness of 58+1 HRC. The side cutters for the tests were machined from this blocks by EDM.



Figure 68: Side cutters from the industrial cutting test at Haemers NV (left: XS=DCT), right punching dies with side cutters

After 30000 strokes in steel S235 with thickness 8 mm, no difference in wear behaviour could be revealed between the two punches. The test was followed by an additional run with a high strength steel S700 MC and 1.5 mm thickness. After ca 70000 strokes the DCT treated side cutter showed almost no wear whereas the conventional treated side cutter showed flaking at its cutting edge (see arrow in Figure 68).

Punchung of industrial steel storage racks (Belgium)

The last application was organized at the company Stow. This company is a known-producer of large steel racks for storing. The punches (see Figure 69) were made by a Flemish die maker namely Denoo Matrijzen in CPM4V steel and coated afterwards with a Variantic duplex TiAlN/TiCN coating by the company Eifeler in Germany. Two series of punches were made: one series with DCT and one without DCT, both had the mentioned duplex coating on the surface to reduce the adhesive wear.

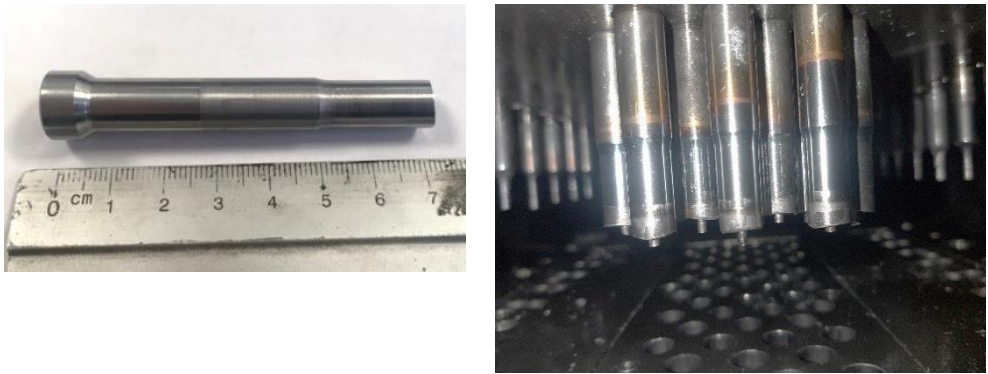


Figure 69: Punch for industrial test at Stow (left), mounted punches in the die (right)

The first die without DCT punches could make 2.182.288 holes with diameter 9 mm in steel S355 with a thickness of 4 mm and the second die with conventional treated punches could make 2.091.400 holes. During punching the punches were grinded to maintain the correct shape of the holes. The die without DCT punches had to be grinded from 70.5 mm to 67.5 mm thus became 3 mm shorter whereas the other die was grinded from 71.7 mm to 70.8 mm which is only 0.9 mm shorter.

The test clearly demonstrates the performance of the DCT treatment in combination with a PVD coating.

4.6.2 High speed cutting

Industrial HSIC cutting test of solid copper

Precision forging requires blanks with very small volume deviations. High-Speed Impact Cutting with its very flat cutting surfaces is ideal for this. Wear on the cutting tools causes deviations in the volume of the cut parts. Low tool wear is a requirement for using the advantages of the cutting process. Industrial HSIC tests were carried out at the MSA company when cutting round bars of solid copper with a diameter of 15 mm. The tools were made from tool steel K105 (X165CrMoV12). Further details of the cutting process see Figure 12.

The wear on conventionally heat-treated tools (CHT) and DCT-treated tools was compared after 220.000 cutting operations (Figure 70). While the CHT treated tool showed significant signs of wear leading to unacceptable volume deviations on the copper blanks, the DCT treated tools showed no significant wear and could continue to be used.

Industrial HSIC cutting test:

Material:

- Bar: solid copper Ø 15 mm
- Tool: K105 (X165CrMoV12)

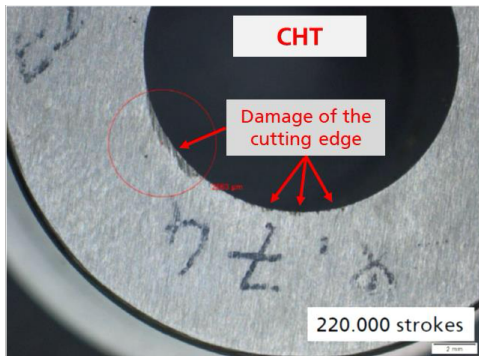
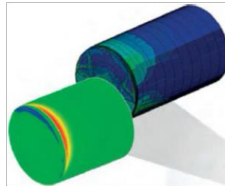


Figure 70: Industrial HSIC cutting test of solid copper. Tool wear after 220.000 strokes (CHT and DCT)

4.7 Systematization, Evaluation, Guidelines, Final report

The results of the above mentioned cutting tests were compared and evaluated in order to determine the performance of the examined combination of substrate and coating for cutting of high strength materials and for HSIC.

From the results within DCT4Cut it can be concluded that:

Effect of the tool steels on the wear behavior:

In the laboratory-scale cutting tests, the wear behavior of two conventionally produced cold-work steels (K110/1.2379 and Caldie) was compared with two PM steels (Vanadis 4E and K390). In the highly loaded areas of the cutting edges, the two PM steels showed, as expected, a significantly lower tendency to chipping than the two conventionally produced cold-work steels. This has a particular effect when cutting high-strength steels.

Effect of DCT treatment on materials and tool life:

The positive effect of DCT treatment on the wear behavior and service life of cutting tools has been confirmed for various applications. However, the economic benefit for the different cutting processes depends on the type of tool load and the resulting wear mechanisms limiting

the tool life. Positive effects can be achieved especially when cutting edge chipping due to fatigue effects and cracking in the tool material are the limiting wear mechanisms. In this case, a DCT treatment can significantly increase the tool life and can extend its application limits.

The positive effects were particularly evident with conventional cold-work steels such as K110 (1.2379) and Caldie. DCT treatment of these materials may therefore be a more cost-effective alternative to the use of higher-grade PM steels.

The project also demonstrated effects of DCT treatment on the properties of tool coatings and plasma-nitrided surfaces. In particular, some multicomponent nanocrystalline coatings reacted with a hardness increase of more than 15 % to the cryogenic treatment. On the plasma-nitrided surfaces, partly opposite effects could be observed after cryogenic treatment. Depending on the nitriding parameters used, both an increased and a decreased crack sensitivity in combination with a slight hardness decrease in the edge zone could be observed. The effects of DCT treatments on plasma nitrided and coated surfaces should be further investigated in terms of their technical and economic usefulness. This was not part of DCT4Cut.

Effect of tool coating on the tool performance:

The effect of tool coatings on the wear behavior of the tools depends strongly on the tool load and the wear mechanisms limiting the tool life. When cutting high-strength steels, where cracking in the tool material and chipping of the cutting edge are the limiting factors, tool coatings can only bring a very limited improvement. In the best case, a low-friction coating can reduce the load on the lateral surface and thus crack formation.

The situation is different for continuous abrasive wear below the load limit of the tool material and for adhesive wear as a result of material adhesion of the workpiece material. However, this case was not the focus of the DCT4Cut project. Here, tool coatings can make a significant contribution to wear reduction.

Effect of plasma nitriding on the tool performance:

The plasma nitriding had the greatest influence on the tool properties, in particular the wear resistance of the cutting edges. This had not been expected to this extent before. For example, the adaptation of the nitriding parameters carried out as part of the DCT4Cut project almost completely prevented the formation of cracks on the highly loaded cutting punch with "triangular geometry" for all four materials. This could not be achieved with any of the other measures investigated. Thus, plasma nitriding adapted to the tool material and the load situation is a highly effective and comparatively inexpensive variant for optimizing the cutting tools. However, it should be noted that the process window for achieving optimum results is relatively small and the selection of unsuitable nitriding parameters can lead to premature tool failure. To identify suitable process parameters (nitrogen content in the process gas, nitriding duration, process temperature) and to pre-evaluate the crack sensitivity for the nitrided materials, the Rockwell indentation test used in the project has proven its worth.

Use of analytical techniques to evaluate DCT treatments:

Three analysis techniques were used in DCT4Cut to evaluate the DCT treatments. The scratch test was suitable to show the effects of the DCT treatment on the crack sensitivity of the material K110 (1.2379). The results from the 3-roll wear test allowed conclusions concerning the wear behavior of the DCT-treated materials, which correspond with the results from the laboratory-scale cutting tests. Non-destructive Speckle analysis was used to detect changes in the material as a result of the cryogenic treatment. However, the changes in the Speckle pattern still need to be correlated with the microstructural changes in the course of further work in order to be able to use the method for quality control in DCT treatment.

5 Use of the grant

For the achievement of the project objectives the procedures and appropriations for personnel costs were necessary and appropriate. There were no funds for equipment and services of third parties spent. In addition to the grant by the grantor, the research project was supported richly by the user committee in the form of plan based expenses, which documents the practical relevance and necessity of the research project.

The grant was used in the following way from the Fraunhofer Institute of Machine Tools and Forming Technology (IWU):

- scientific and technical personnel (individual approach A.1 of the financing plan)
 - *employees university degree: 19,83 MM*
(2019: 7,89 MM; 2020: 7,41 MM; 2021: 4,53 MM)
- other qualified personnel (individual approach A.2 of the financing plan)
 - *technician similar: x MM*
(2019: 4,98 MM; 2020: 6,07 MM; 2021: 11,05 MM)
- devices (single approach B of the financing plan)
 - *none*
- third party services (single approach C of the financing plan)
 - *none*

The grant was used in the following way from the Fraunhofer Institute for Surface Engineering and Thin Films (IST):

- scientific and technical personnel (individual approach A.1 of the financing plan)
 - *employees university degree: 18,31 MM*
(2019: 7,7 MM; 2020: 6,61 MM; 2021: 4 MM)
- other qualified personnel (individual approach A.2 of the financing plan)
 - *technician similar: 6,85 MM*
(2019: 3,87 MM; 2020: 1,62 MM; 2021: 1,36 MM)
- devices (single approach B of the financing plan)
 - *none*
- third party services (single approach C of the financing plan)
 - *none*

6 Explanation of the necessity and appropriateness of the work done

The work carried out as well as the resources spent on it were necessary and appropriate as they corresponded to the detailed planning given in the project application and all the tasks formulated in the work plan have been successfully processed. In addition, no additional resources had to be spent on the implementation of the project.

7 Presentation of the scientific-technical and economic benefits for SME

The scientific, technical and economic benefits of the results achieved, especially for SMEs, as well as their innovative contribution and their industrial applications are shown in Table 21.

Table 21: Scientific-technical and economic benefits for SMEs

Result	Relevance for SME, innovative add-on, industrial application
30-100 % increasing of tool life time comparison to conventional heat treated tool materials	- Substitution of previous heat treatment process chains for tool steels - Saving of tool costs or production costs/component and reduction of CO₂ emissions - Opening up of new fields of application - Excellent performance in cutting and forming operations
Design of the heat treatment in alignment with the manufacturing process chain of the tool	- Improved material properties of the tool materials with regard to abrasive wear behaviour, settlement behaviour, torsional stress and increased resistance to plastic deformation. - Use of innovative cryogenically treated tool materials for manufacturing processes with increased loads - Realisation of very good PVD layer bond for special applications in cutting and forming
Expansion of the field of application of conventional tool materials	- Application of cryogenic treatment for the realization of industry-compatible economic tool life for the special manufacturing process of high-speed shearing with extreme stress on the tool material . - Use in the field of highly abrasive cutting regimes for various composites of different composition and thickness with high cutting surface quality at extreme cutting parameters
Transfer of the findings from the substrate (plant tensile material) to coating systems (PVD)	- Significant increase in the hardness and abrasive wear resistance of the PVD coating systems - Optimisation of the residual surface stresses of the substrates (tool materials) - Avoidance of coating delamination and thus increase in service life even in highly stressed load regimes
Concept for new abrasive wear testing and surface analytics	- The qualitative evaluation of the tool materials and different heat treatment process routes with regard to abrasion wear and plastic deformation could be carried out for the first time in a way that could be evaluated and classified in a highly quantitative manner. - Furthermore, with the integration of speckle analysis, a test methodology of the safely changing residual stress after heat treatment was successfully applied in feedback of the tribological system with different mechanical processing technologies.
Demonstrator parts in different industrial branches	- In order to demonstrate the feasibility of cryogenic treatment of tool steels using the example of a complex manufactured 3D tool active part geometry, the industrial user can use the present use case to precisely select the required heat treatment process parameters, tool materials considering the mechanical machining strategy for stamping and forming processes and apply the appropriate procedure. - It could be shown that the integration of an additional low-temperature treatment step leads to very advantageous material and coating properties with regard to abrasive welding, material setting and plastic deformation or the fracture behaviour and fracture energy of hybrid metal composites in comparison to non-structured bonded joints.

8 Adjusted plan for transfer of the results

The transfer measures were fulfilled according to Table 22, Table 23 and Table 24.

Table 22: Dissemination activities during project phase (Germany)

Dissemination	Responsible	2019	2020	2021
User committee meeting				
User committee: - Germany (D) - Germany+Belgium (D+B)	IST, IWU, Sirris	05/2019 (D)	05/2020 (D)	03/2021 (D+B) 06/2021 (D) 09/2021 (D+B) 11/2021 (D)
Exhibitions / Trade Fairs				
Intec Leipzig	IWU, IST	02/2019		
Hannover Messe	IWU, IST		06/2020	
EuroBLECH	IWU, IST			03/2021
Blechexpo	IWU, IST			11/2021
Conferences and seminars, publications				
Materials Science and Engineering: A, Volume 824, 8 September 2021, 141846: "Analyzing the influence of a deep cryogenic treatment on the mechanical properties of blanking tools"	IWU, IST		09/2021	
Innovationstag Mittelstand, Berlin	IWU, IST		05/2021	
Materials+Eurofinish+Surface Brabanthallen, 's-Hertogenbosch (NL)	IWU, IST, Sirris			09/2021
Demonstrations				
Manufacturing with optimized tools	IWU, IST, Sirris			02/2021: IT Ingenieurtechnik GmbH, Erdmannsdorf 10-11/2021: MSA Maschinenbau, Chemnitz 10/2021 Schmutzler Werkzeugbau, Aue 12/2021: ADZ Lüftungsbau, Leipzig

Table 23: Dissemination activities during project phase (Belgium)

Date	Activity	Responsible	Reached companies
28-02-2019	Publication: DCT4Cut onderzoekt optimalisatie van gereedschappen voor high demanding materialen	VOM/SIRRIS	1900
22-03-2019	Kick-off meeting with Belgian users group	VOM/SIRRIS	6
22-03-2019	www.vom.be/nl/nieuws/1259/vom-is-projectpartner-van-verschillende-onderzoeksprojecten	VOM	1900
22/03/2019	https://www.vom.be/nl/technische-artikels/1211/dct4cut-project-onderzoekt-optimalisatie-van-gereedschappen	VOM	3500
20-06-2019	Publication: Nieuwe materialen bij de groep Voest Alpine	SIRRIS	1200
02-09-2019	Publication: Klaar voor de toekomst met nieuwe staalnuances	Metallerie	1500
05-12-2019	Meeting with Belgian user group	VOM/SIRRIS	8
03/03-2020	Survey about use of DCT and coatings	VOM	1900
11-03-2020	Folder: Wilt u slijtvastheid van uw componenten verhogen ?	SIRRIS	50
03-07-2020	Meeting with Belgian user group	VOM/SIRRIS	8
11-09-2020	Publication: Slijtageweerstand verhogen door cryobehandeling en coatings op staal	SIRRIS	1200
30-11-2020	Training course heat treatment for FAM en Stumabo	SIRRIS	2
18-03-2021	Meeting with Belgian and German user group	VOM/SIRRIS /FOSTA	10
24-03-2021	Blog: Gebruikers uit Vlaanderen en Duitsland ingelicht rond het project DCT4Cut	SIRRIS	1200
31-03-2021	Publication: Ontwikkelingen in het gebruik van koudwerkstalen voor ponstoeepassingen	SIRRIS	1200
16-09-2021	Presentation tijdens Materials+Eurofinish+Surface 2021: Cryogenic treatment for wear resistant tools https://materials-eurofinish-surface.com/programma/programma-dag-2/	VOM	25
30-09-2021	Meeting with Belgian and German user group	VOM/SIRRIS /FOSTA	10
21-10-2021	Training course heat treatment (part Massive hardening and tempering)	VWT - SIRRIS	19
28-10-2022	Final meeting with Belgian user group	VOM/SIRRIS	8
31-01-2022	Publication: Finale stand van zaken en resultaten van het project	SIRRIS	1200

Table 24: Dissemination plan after project phase

Dissemination	Responsible	2022	2023	2024
Internet				
Publication of the final report on the website of FOSTA Website: www. tieftempera- turbehandlung.de	IWU, IST, Sirris, FOSTA	06/2022 12/2022		
Poster				
Final poster	IWU, IST, Sirris	05/2022		
Annual Report Fraunhofer IWU, IST, Sirris	IWU, IST, Sirris	03/2022		
Conferences and seminars				
4. Fachtagung zum Stanzen und Umformen	IWU, IST	06/2022		
Sächs. Fachtagung für Umform- technik (SFU 2022 in Chemnitz, Freiberg, Dresden)	IWU, IST, Sirris	11/2022	11/2023	11/2024
Consulting				
Werkzeugbau Hartmann	IWU, IST	whole 2022		
DMB Metallverarbeitung	IWU, IST	whole 2022		
Metallbauverband Sachsen e.V.	IWU, IST	whole 2022	whole 2023	
Publications in journals and periodicals				
UMFORMtechnik	IWU, IST	09/2022		
Techniline	SIRRIS	11/2022		
VOM Info	SIRRIS	05/2022		
Exhibitions / Trade Fairs				
Hannover Messe	IST, IWU		04/2023	04/2024
Euroblech	IST, IWU	10/2022		10/2024
Blechexpo			11/2023	
Intec Leipzig	IWU		02/2023	02/2018
Demonstrations				
Karl Naumann GmbH	IWU	04/2021		
Werkzeugbau Ullmann (HGSS)	IWU, IST		03/2023	
Bilateral projects:				
Werkzeugbau Winkelmühle GmbH	IWU, IST	10/2021-09/2023 (ZIM-project)		
ADZ Lütec Markkleeberg	IWU, IST	11/21-02/22	011/21-02/22	
KLÄDTKE Metallverarbeitung GmbH		01/2022	04/2023	

9 Assessment of the feasibility of the proposed and updated transfer concept

During the project, a total of 6 meetings of the UC project took place. The intermediate results as well as the final result were presented to a wide circle of users at 2x FOSTA and 2x working group meetings. In addition, the interim results were presented at specific conferences (Blechexpo, Hannover-Messe, TRAKO (Warsaw), EuroBLECH) and on the internet on both institutional websites (www.iwu.fraunhofer.de, www.ist.fraunhofer.de) and discussed with the expert audience. A final thesis dealt with the contents of the project. In addition, future activities of the participating research centres and associations such as website, seminars, congresses, newsletter, publication of the final report are planned as next steps. In this way, a broad distribution of the results was achieved and an intensive exchange with the relevant industry representatives (in particular also SMEs from the areas of toolmaking, heat treatment and coating as well as component supply industry) was initiated.

10 Funding information

Supported by:



Federal Ministry
for Economic Affairs
and Climate Action

on the basis of a decision
by the German Bundestag

The CORNET project “Optimizing of cutting tools for high strength materials by means of deep cryogenic treatments and coatings” (No. 240 EGB) of the Forschungsvereinigung Stahlanwendung e. V. (FOSTA) has been funded by the German Federation of Industrial Research Associations (AiF) within the programme for sponsorship by Industrial Joint Research (IGF) of the German Federal Ministry for Economic Affairs and Climate Action based on an enactment of the German Bundestag.