BUDAPEST UNIVERSITY OF TECHNOLOGY AND ECONOMICS
FACULTY OF TRANSPORTATION ENGINEERING
Kálmán Kandó Multidisciplinary Technical Sciences PhD School

THE EFFECT OF LASER BEAM COATINGS ON THE TRIBOLOGICAL CHARACTERISTICS OF RAPID PROTOTYPING TOOL ELEMENTS

Summary of the PhD Thesis

By:
Tamás Sebestyén
Mechanical Engineer

Supervisor:
Dr. Gábor Buza
University Docent

Budapest
2007

[23] **Senthil Selvan, J. et al.** (1999): Laser boronising of Ti-6Al-4V as a result of laser alloying with pre-placed BN, Materials Science and Engineering A260 : 178-187

[24] **Wang, P. Z. et al.** (1996): Cemented carbide reinforced nickel-based alloy coating by laser cladding and the wear characteristics, Materials & Design, Volume 17, Issues 5-6 : 289-296

[25] **Zum Gahr, K.-H. et al.** (1995): Friction and wear reduction of Al_2O_3 ceramics by laser-induced surface alloying, Wear 181-183 : 118-128

[26] **Song, W. et al.** (1996): Effect of Ni content on cracking susceptibility and microstructure of laser-clad Fe-Cr-Ni-B-Si, Surface and Coatings Technology 80 : 279-282

[27] **Wang, K.L. et al.** (1997): Effect of laser surface cladding of seria on the wear and corrosion of nickel-based alloys, Surface and Coatings Technology 96 : 267-271

[28] **Mridha, S. et al.** (1997): Metal matrix composite layer formation with 3 □m SiCp powder on IMI318 titanium alloy surfaces through laser treatment, Journal of Materials Processing Technology 63 : 432-437

[29] **Chong, P.H. et al.** (2001): Microstructure and wear properties of laser surface-cladded Mo-WC MMC on AA6061 aluminium alloy, Surface and Coatings Technology 145 : 51-59

[30] **Pinkerton, A.J.- Li, L.** (2003)**:** The effect of laser pulse width on multiple-layer 316L steel clad microstructure and surface finish, Applied Surface Science, Volumes 208-209 : 411-416

[31] **Conde, A. et al.** (2002)**:** Cladding of Ni-Cr-B-Si coatings with a high power diode laser, Materials Science and Engineering A, v 334, n 1-2 : 233-238

[32] **Wu, X. - Hong, Y.** (2001): Fe-based thick amorphous-alloy coating by laser cladding, Surface and Coatings Technology 141 : 141-144

[33] **So, H. et al.** (1996): Wear behaviours of laser-clad stellite alloy 6, Wear192 : 78-84

[34] **Petrides, M. et al.** (2001)**:** Influence of Model Tests on the Selections of Lubricants for Gears in Dental Instruments, Plenary and Session Key Papers from the 2nd World Tribology Congress Vienna, Austria 3-7 September, Österreichische Tribologische Gesellschaft – ÖTG, ISBN 3-901657-07-X : 211–214

[35] **Lubbinge, H.** (1999): On The Lubrication of Mechanical Face Seals, FEBO druk B.V., Enschede, ISBN 90-3651240-9: 113

[36] Prüfung von Schmierstoffen, Prüfung im Mischreibungsgebiet mit dem Schmierstoffprüfgerät nach Brugger, Teil 2. Verfahren für Schmieröle, DIN 51347-2

[37] 1997 Reade Advanced Materials, http://www.reade.com/Prodducts/ Ferro_Alloys/ferro_boron.html (2004. május 27.)

[38] Ferroalloys & Alloying Additives Online Handbook – Boron, 2002, Shieldalloy Metallurgical Corporation, http://www.shieldalloy.com/boronpage.html (2004. szeptember 6.)

[39] Kureha Carbon Fiber – Kreca, Kureha Chemical Industry Co. Ltd., 94.9.30:1 M

[40] **Sebestyén T. et al.** (2001): Wear Resistance Improvement of Selected-Laser-Sintered Tools by Laser Surface Treatment, Laser Assisted Net Shape Engineering 3 – Proceedings of the 3rd LANE 2001 Erlangen, Germany, August 28–31, ISBN 3-87525-154-7 : 439-446

[41] **Sebestyén T. et al.** (2002): Formation of Highly Boron-Alloyed Surface Layer by Laser Beam, Gépészet 2002, Budapest, Hungary, May 30-31

9 LITERATURE IN THIS SUMMARY OF THE THESIS

[1] **Hague, R.** (2000)**:** Conference Report, The 8th International Conference on Rapid Prototyping, June 12 & 13, Japan, Japanese Society of Die and Mold Technology (Japan) & University of Dayton Research Institute (USA), http://www.lboro.ac.uk/departments/mm/research/rapid-manufacturing/consortium/confsyn/Japan2000.pdf (2004. június 12.)

[2] **Takács J. - Pap G.- Kálazi Z. - Bán T**. (1995): Rapid Prototyping of Laminated Structure with the Use of CO_2 Laser. Advanced Manufacturing and Repair Technologies in Vehicle Industry, 12. International Colloquium, BME, Balatonfüred : 92-95

[3] **den Ouden, A.** (2004): Homepage, Eindhoven – Nederland, http://www.denouden.demon.nl/capsel/rapprod4.htm (2004. június 12.)

[4] Helsinki University of Technology http://www.cs.hut.fi/~ado/rp/subsection3_6_3.html (2004. március 4.)

[5] **Wiesner, P. - Eckstein, M. - Son, T.** (1997)**:** Rapid Metal Prototyping Using Laser Radiation, Proceedings of the LANE '97, Meisenbach Bamberg : 555-559

[6] **Seitz, S. - van de Crommert, S. - Esser, K. J.** (1997)**:** New Materials for New Applications in SLS® Selective Laser Sintering, Proceedings of the LANE '97, Meisenbach Bamberg : 623-628

[7] **Coremans, A. - Groot, D.** (1997)**:** Residual Stresses and Thermal Stability of Laser Beam Sintered Metal Parts, Proceedings of the LANE '97, Meisenbach Bamberg : 577-588

[8] **Khaing, M.W. et al.** (2001)**:** Direct metal laser sintering for rapid tooling: processing and characterisation of EOS parts, Journal of Materials Processing Technology, Volume 113, Issues 1-3 : 269-272

[9] **Bertóti I.** (1997): Felületvizsgálat röntgen-fotoelektron spektroszkópiával (XPS – ESCA) Doktori tanfolyami jegyzet, MTA Szervetlenkémiai Kutatólaboratórium Bp. : 4-7

[10] **Beyer, E - Wissenbach, K.** (1998): Oberflächenbehandlung mit Laserstrahlung Springer-Verlag, Berlin Heidelberg, ISBN 3-540-63224-7.

[11] **Holzschuh, H.** (2004): Deposition of Ti-B-N (single and multilayer) and Zr-B-N coatings by chemical vapor deposition techniques on cutting tools, Thin Solid Films, 469-470 : 92-98

[12] **Kalss, W. et al.** (1998)**:** Deposition of B---C---N coatings from trisdimethylaminoboran by hot-filament and microwave plasma activation, International Journal of Refractory Metals and Hard Materials, Volume 16, Issue 3 : 233-241

[13] **Choy, K.L.** (2003)**:** Chemical vapour deposition of coatings, Progress in Materials Science, Volume 48, Issue 2 : 57-170

[14] **Harris, K.D. et al**. (2001): Porous thin films for thermal barrier coatings, Surface and Coatings Technology, Volume 138, Issues 2-3 : 185-191

[15] **Wolfe, D.E. et al.** (2003): Synthesis and characterization of multilayered TiC/TiB_2 coatings deposited by ion beam assisted, eelectron beam-physical vapor deposition (EB-PVD), Surface and Coatings Technology 165 : 8-25

[16] **Wang, J. et al.** (2001): Structure and tribological properties of MoSx coatings prepared by bipolar DC magnetron sputtering, Surface and Coatings Technology 139 : 143-152

[17] **Guruz, M.U. et al.** (2002): Synthesis and characterization of single and multilayer boron nitride and boron carbide thin films grown by magnetron sputtering of boron carbide, Thin Solid Films 414 : 129-135

[18] **Krannich, G. et al.** (1997): Formation of cubic boron nitride thin films by reactive cathodic arc evaporation, Diamond and Related Materials 6 : 1005-1009

[19] **Mitterer, C.** (1997)**:** Borides in Thin Film Technology, Journal of Solid State Chemistry, Volume 133, Issue 1 : 279-291

[20] **Jankowski, A.F.** (1995): Metallic multilayers at the nanoscale, Nanostructured Materials, Vol. 6 : 179-190

[21] **He, J.L. et al.** (2001): Improved anti-wear performance of nanostructured titanium boron nitride coatings, Wear 249 : 498-502

[22] **Cole, D. ta al.** (1997): Pulsed laser deposition of Fe thin film sin UHV, Journal of Magnetism and Magnetic Materials 165 : 246-249

CONTENTS

INTRODUCTION

In the last decades in the vehicle industry the application of composites and therefore also high performance fiber-reinforced plastics has continuously grown. It is probable, that according to the growing number of vehicles and parts application of injection molded parts will further grow. Nowadays it is usual, that designers and manufacturers use the tools of rapid prototyping for cost minimization and to improve the effectivity of production and product planning. This technology affords, that the product (part) is touchable, ergonomically and mechanically testable much before its debutation on the market (mass production) allowing an option to early modifications [1, 2]. For these tests a series of 2-300 pieces is needed to be produced.

According to today's technical knowledge, in case of a plastic part reinforced with glas or carbon fibers production of a model by rapid prototyping it is impossible or exteremely expensive to get a structure (fiber content, distribution, orientation) identical to the real one. In an indirect way [3], if first we produce the injection molding tool for example with selective laser sintering [4], then the part produced in the tool can have the wished structure, for example reinforced by fibers.

The most wide spread technology for a fast production of injection molding tools with a complex geometry is selective laser sintering. Of course, the model tool must have a proper strength and wear resistance to fulfill needs for injection molding. The accessible professional literature provides a few data about the mechanical characteristics of selective laser sintered pieces [5-8]. About friction and wear (generally tribological) behaviour of selective laser sintered pieces the only accessible publications were the ones, which arose from the cooperation of BUTE (Budapest University of Technology and Economics) and the TU-Wien (Vienna Technical University) coordinated by Professor János Takács and Professor Friedrich Franek.

Concerning production of fibre-reinforced plastic pieces there is a new industrial need arising, approaching rapid prototyping to the paradigm of rapid manufacturing which by growing badge size (even thousands of pieces). Of course, in this case it is important that the model tool, primarily from point of view of wear resistance, has a lifetime a magnitude higher. This is mainly needed where due to high pressure and flow rate of the streaming material results in high wear rate. The phenomenon occurs mainly at bottle necks of the tool, for example at the nozzle or the inlet.

There are several solutions for handling the problem [9-22]. The experience and knowledge I aquired during my previous works, and on grounds of the accessible possibilities for manufacturing I seeked my solution towards laser surface modification technologies [23-33]. Even coating of porous sintered surfaces seems to be possible with the so-called one step laser coating technology, which might be

[S10] **Takács J. - Tóth L. - Franek, F. - Pauschitz, A. - Sebestyén T.** (2001): Investigation of Tribological Properties of Laser-Sintered and Coated Parts, 2nd World Tribology Congress, Vienna, Austria, Sept. 3-7 ISBN 3-901657-08-8 (CD: ISBN 3-901657-09-6)

[S11] **Buza G. - Fábián R. - Kálazi Z. - Sebestyén T. - Somogyi R.** (2001): Lézeres mélyvarratos hegesztés hőhatásövezete. Bányászati és Kohászati Lapok. 134. 6 – 7. : 247 – 251

[S12] **Sebestyén T. - Franek, F. - Pauschitz, A. - Takács J. - Tóth L.** (2002): Increase of Wear Resistance of Laser-Sineterd Parts by Laser Coatings, Tribology and Lubricants Engineering, Esslingen, Germany, Jan. 15-17 ISBN 3-924813-48-5

[S13] **Buza G. - Molnár M. - Kálazi Z. - Sebestyén T.** (2002): Laser Beam Welding of Austenitic Stainless Steel, 19th International Colloquium – Advanced Manufacturing and Repair Technologies in Vehicle Industry, Pardubice, Czech Republic, May 26-28, ISBN 80-7194-449-1

[S14] **Tóth L. – Sebestyén T.** (2002): Plazmaszórt és lézeresen kezelt felületek, bevonatok alkalmazása és tribológiai vizsgálata, Géptervezők és Termékfejlesztők XVIII. Országos Szemináriuma, Miskolc (Gép. LIII. . 8-9. 51.)

[S15] **Takács J. - Tóth L. - Franek, F. - Pauschitz, A. - Sebestyén T.** (2003): Friction and Wear Measurement of Laser Sinetered and Coated Parts, Washington D.C., USA, March 31 – April 3 2003 (Wear 256 :. 1228-1231)

[S16] **Sebestyén T. - Buza G. - Kálazi Z. - Takács J. - Tóth L. - Franek, F. - Pauschitz, A.** (2003.): Tribological Investigations of Parts Sintered and Coated by Laser Beam (Lézersugárral szinterelt és bevonatolt darabok tribológiai vizsgálatai) IV. Országos Anyagtudományi, Anyagvizsgálati és Anyaginformatikai Konferencia és Kiállítás, Balatonfüred, október 12 - 14. Materials Science Forum Vol. 473-474, ISSN=0255-5476, ISBN=0-87849-957-1

[S17] **Polt, G. - Sebestyén T. - Franek, F. - Pauschitz, A.** (2003): Investigation of Stick-slip Effects in Wet Friction Drive Elements (poster), IV. Országos Anyagtudományi, Anyagvizsgálati és Anyaginformatikai Konferencia és Kiállítás, Balatonfüred,. október 12 - 14. Materials Science Forum Vol. 473-474, ISSN=0255-5476, ISBN=0-87849-957-1

[S18] **Sebestyén T. - Buza G. - Kálazi Z.** (2004): Formation of Highly Boron-Alloyed Surface Layer by Laser Beam, Gépészet 2002, Budapest, Hungary, May 30-31 2002

[S19] **Herczeg Sz. - Takács J. - Tóth L. - Franek, F. - Pauschitz, A. - Sebestyén T.** (2004): Tribological investigation of Fe-Ni-Cu based selective-laser-sintered rapid prototype tool models against fibre-reinforced polymer, Advanced Manufacturing and Repair Technologies in Vehicle Industry, Balatonfüred,. May 17-19., pp.:174-178, ISBN 963 420 796 0

[S20] **Herczeg Sz. - Takács J. - Tóth L. - Franek, F. - Pauschitz, A. - Sebestyén T.** (2004): The Effect of Sinter Parameters on Tribological Properties of Selective-Laser-Sintered Rapid Prototype Tool Elements, Procedings 8th International Conference on Tribology, Veszprém, Hungary, jun. 3-4.: 144-149

[S21] **Herczeg Sz. - Takács J. - Tóth L. - Franek, F. - Pauschitz, A. - Sebestyén T.** (2004): Investigation of Properties of Rapid Prototype Tool Elements Produced by Selective Laser Sintering, Proceedings of the 11th International Conference on Tools ICT-2004, Miskolc, Hungary, September 9-11., pp. 271-276, ISSN 1215-0851

[S22] **Herczeg Sz. - Takács J. - Tóth L. - Franek, F. - Pauschitz, A. - Sebestyén T.** (2004): Tribological analysis of Fe-Ni-Cu alloy produced by selective laser sintering, Laser Assisted Net Shape Engineering 4, Erlangen,. September 21-24., pp.:535-544 in Volume 1, ISBN 3-87525-202-0

[S23] **Sebestyén T.** (2004): Laser Surface Heat Treatment – An Overview, Symposium 2004 der Österreichischen Tribologischen Gesellschaft Wien, Reibung und Verschleiss im Spannungsfeld von Fahrzeugherstellern und deren Kunden, Nov. 4. pp 247-256, ISBN 3-901657-15-0

BAYATI and laser sintering experience of the BUTE. I am grateful to everyone, who helped and supported me in preparing this thesis.

First of all, many thanks to university docent Dr. Gábor Buza, the vice president of BAYATI and university professor Dr. János Takács, head of department at BUTE-JJT for providing me the possibility to carry out my work and for the firm scientific background and supervision. Many thanks to the colleagues at BAYATI and BUTE-JJT - especially to Dr. Zoltán Kálazi, Dr. Lajos Tóth, Dr. Tamás Markovits and Ms. Enikő Réka Fábián - for the readiness for consultations, their help in the preparation and evaluation of the tests.

Very special thanks to professor Dr. Friedrich Franek and Dr. Andreas Pauschitz, and the colleagues of the TU-Wien IMFT for helping me solidifying my knowledge in the field of tribology and for the possibility carrying my tribological tests out.

Hereby, I would like to express my gratefulness to the company Mechroll for preparing my specimens.

Last, but not least, I am very grateful to my family and friends for the patience and spiritual support, which provided big help and strong background in my research work and writing of the thesis.

8 LITERATURE IN CORRESPONDENCE WITH THE THESIS

[S1] **Sebestyén T. - Kálazi Z. - Buza G. - Takács J**. (1999): Acélok felületi edzése rezgetett lézersugárral. Bányászati és kohászati lapok. 132. 8.

[S2] **Kálazi Z. – Sebestyén T**. (2000): Lézersugár diagnosztika a BAYATI-ban, ILAS – Ipari Lézer Alkalmazási Szeminárium, Balatonfüred,október 26-27.: 22-23. ISBN 963421554-8

[S3] **Sebestyén T. - Takács J. - Tóth L. - Franek, F. - Pauschitz, A.** (2000):. The Investigation of Tribological Properties of Laser-Sintered Parts, 17th International Colloquium on Advanced Manufacturing and Repair Technologies in Vehicle Industry, Zielona Góra - Lagów, Poland, June 7-9, ISBN 83-85911-51-0

[S4] **Sebestyén T. - Takács J. - Tóth L. - Franek, F. - Pauschitz, A.** (2000)**:** Tribological Aspects of Wear of Laser-Sintered Rapid Prototype Tools, NATO-Advanced Study Institute Course on Fundamentals of Tribology and Bridging the Gap Between Macro- and Micro/Nanoscale Tribology, Keszthely, Aug. 13-25 571 p. ISBN 0-7923-6837-1

[S5] **Sebestyén T. - Takács J. - Tóth L. - Franek, F. - Pauschitz, A.** (2000): Determination of Tribological Properties of Laser-Sintered Prototype Tools, VII. Tribológiai Konferencia, Budapest, szeptember 4–5: 314-317

[S6] **Sebestyén T. - Kálazi Z. - Takács J. - Tóth L. - Franek, F. - Pauschitz, A**. (2001): Improvement of Selected-Laser-Sintered Rapid Prototype Tools by Laser Surface Treatment, MATRIB '01, Vela Luka, Croatia 20-22. 06. 2001 ISBN 953-96038-7-0

[S7] **Buza G. - Kálazi Z. - Sebestyén T**. (2001): A szilárdtestlézerek új generációja, Bányászati és Kohászati Lapok. 134.. 3. .: 103 – 108

[S8] **Sebestyén T. - Takács J. - Tóth L. - Franek, F. - Pauschitz, A.** (2001): Laser Surface Coating for Improvement of Wear Resistance of Rapid Prototype Tools, 18th International Colloquium – Advanced Manufacturing and Repair Technologies in Vehicle Industry, Dresden 20-22. 05. 2001 ISSN 1433 – 4135

[S9] **Sebestyén T. - Kálazi Z. - Takács J. - Tóth L. - Franek, F. - Pauschitz A.** (2001): Wear Resistance Improvement of Selected-Laser-Sintered Tools by Laser Surface Treatment, 3rd LANE 2001, Erlangen, Germany, August 28-31, 439 p. ISBN 3-87525-154-7

an option for better local wear resistance. From among the standard coating materials, which are to be used on the temperature of injection molding, I chose a Co-based one reinforced with W- and Cr-carbides. During my investigations I considered the coating made of this alloy to be the basis for comparison. Searching for a new possibility based on material science and metallurgy I investigated the application of an alloy with high boron content (ferroboron). By investigating the new coating my aim was to substitute expensive coating alloys with materials cheaper but still suitable for the application.

With my measurements I intended to prove the theoretical ideas found in the professsional literature. The wear and friction tests were carried out with two different methods (pin-on-disk and Brugger test) on laser sintered phophorous bronze and low alloyed steel, and their versions coated by laser beam. My investigations included also study of the metallographic properties. Laser coating technology is not new, but neither laser coating of any sintered material, or coating with the applied ferroboron has been published, therefore it was reasonable to search the proper manufacturing parameters.

Such application of selective laser sintering has the potential to open new horizonts from rapid prototyping towards rapid manufacturing, where with a modern, flexible technology even the creation of a tool for the production of a few-thousand-piece series is possible.

Three research insitutions provided the scientific background. The sintered pieces were given by the BUTE-JJT (Department of Vehicle Manufacturing and Repairing), the laser coating was done at BAYATI (Bay Zoltán Institute for Materials Science and Technology), and the laboratory for the tribological tests were carried out at the TU-Wien IMFT (Institut für Mikro- und Feinwerktechnik). I carried out the metallographic investigations in the accredited Materialographic Laboratory of BAYATI to get more information about the structure of the base material and the coating, as well as their bound, furthermore hardness distribution was measured in the cross-section. For machining of the specimens I got help from the Mechroll company.

1 AIM OF THE RESEARCH

My research work presented hereby in my dissertation has two pillars: on the one hand the tribological investigations of a selective laser sintered material (prototype tool element), on the other hand production of a wear resistant layer on the same material and its wear and friction characterization via tribological testing. My basic aim was the extension of lifetime and applicability area of rapid prototyping tool elements by means of laser cladding.

After researching professional literature it was right to pose a question: which options do we have for application of selective laser sintered rapid prototype tools, how life time of such tools can be prolonged by wear resistant coatings and how these wear resistant coatings can be realized at all? For assessing this I created a wear resistant coating on laser sintered specimens and on steel reference materials. The coated pieces were exposed to extreme wear demand.

In my work I was seeking the answer for the following questions:

- Which tribological model investigation method provides practically applicable, comparable data concerning wear caused by fibre-reinforced plastics?
- How can wear resistance, and thus lifetime and production series size of laser sintered tools, be extended?
- Is it possible to create a bulk, wear resistant layer on the surface of a porous sintered metallic part by means of laser cladding?
- How can be the production costs of the wear resistant coating minimized?
- In which extent will the formed layer increase wear resistance of the porous sintered tool surface?

2 RESEARCH METHODS, TOOLS AND EQUIPMENTS

2.1 Applied Measuring Technique and Testing Equipments

2.1.1 The Pin-on-Disk Tribometer and Measurement

For determination of the friction and wear characteristics of laser sintered tool elements I used the high temperature pin-on-disk laboratory test rig (*Figure 1*) of TU-Wien. During my laboratory tests I tried to model the real load conditions by setting injection pressure, temperature and friction velocity [34].

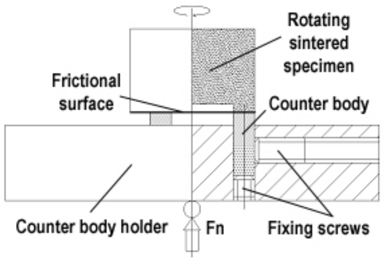

Figure 1. Arrangement of the specimen and counter body during the test

During my tests I measured friction force and common wear rate of the sintered ring and the fiber-reinforced pin. The friction force was measured via a calibrated strain gauge which was attached to the tribometer. The common wear of the sintered specimen and the counter part was measured by an induction sensor from Hottinger Baldwin Messtechnik (HBM).

6 NEW SCIENTIFIC RESULTS

1. **THESIS**: **By laser coating technology I created** a homogeneous, hard, **wear resistant ferroboron** multilayer **coating** the **first time** ever on a **porous**, selective laser sintered **phosphorous bronze** (EOSINT M Cu 3201) surface [40].
2. **THESIS**: **I determined the values of the most important processing parameters** (specific amount of powder, sweeping speed, specific laser power, inert gas quality and quantity) for the production **of wear resistant ferroboron layers by means of one-step laser coating.** By tests **I verified the** rightness of the **technological data** to create a compact layer. With identical geometrical situation on the surfaces bulk low-alloy steel can be coated in one step (750 W laser power, 500 mm/min speed, 9.75 g/min powder amount), the surface of selective laser sintered phosphorous bronze (EOSINT M Cu 3201) in two steps (500 mm/min speed, 9.75 g/min powder amount, 1st layer: 750 W, 2nd layer: 1000 W laser power) [40].
3. **THESIS**: **The ferroboron** surface **layers created** under identical geometrical circumstances, produced with right (optimal) laser coating technology in the given parameter field (pv = 4…17 (N/mm^2)*(m/s)) in case of bulk low alloy steel substrate already at the first, in case of selective laser sintered phosphorous bronze from the second layer have **independent metallographic and tribological properties from the substarte** [41].
4. **THESIS**: According to the measured data by the modified Brugger tester **wear rate of the ferroboron coatings created by laser beam processing** tested in the given load range (pv = 4…17 (N/mm^2)*(m/s)) against fiber-reinforced PPS and PEEK plastics **is one fifth of that of the phosphorous bronze substrate's** [41].
5. **THESIS**: **Wear resistance of the Co-based coating alloy** (C 0.76 / Mn 0.31 / Fe 3.13 / Si 2.48 / Ni 13.13 / Cr 19.23 / W 7.75 / B 1.79 / Co Bal.) **is at most 50 % more than that of the ferroboron's** (B 19 / Si 2.11 / C 0.44 / Fe Bal.), **but its price is at least a magnitude higher** – under identical geometrical conditions and optimal laser coating technology, in the same field of test parameters (pv = 4…17 (N/mm^2)*(m/s)). Application of the FeB coating makes substitution of more expensive coating alloys (f.e. cobalt-based) possible [41].

7 ACKNOWLEDGEMENTS

My research work was carried out with the support of the BUTE-JJT, the BAYATI and the TU-Wien IMFT. I had the possibility to join an Austrian-Hungarian research project (TéT) which was based on the CO$_2$ laser coating experiences of

- Usually the value of the friction coefficient changed between 0.2 and 0.3. It is observable, that in case of higher normal force, above 50 N there is a higher deviation of the measured friction coefficient values above a velocity of 0,6 m/s in case of both coatings. The higher deviation is probably a consequence of an uncertain run due to the common effect of higher speed and normal load. This means, that slightly above 2500 J friction energy temperature change causes also changing friction conditions. The starting dry friction changes partly or completely into sliding friction, which results an uncertain run between the specimen and the counter part. If we look only at the normal force, it is clear that the dry friction coefficient of the investigated coatings under observed load conditions (pv = 4…17 $(N/mm^2)*(m/s)$) is independent from the applied normal load.

5 CONCLUSIONS

By laser cladding, I modified the surface of the selective laser sintered tool material created for injection molding of fibre-reinforced plastic and therefore exposed to extreme wear. My aim with the rapid prototyping tools reinforced by laser surface modification for a better wear resistance was to be able to produce a bigger series of injection molded parts. The parts produced with these tools should have the same structure as the planned ones and are going to be applicable for zero-series tests. This makes the planning process faster and more effective, helping the work of product and tool designers.

1., I used ferroboron metallurgical prealloy and cobalt-based alloy, which had similar tribological properties. From a financial point of view substitution of the expensive cobalt based alloy by using a cheaper, easily accessable ferroboron is considerable. The wear properties of the coatings produced with optimal technological parameter were independent from the substrate.

2., The modified Brugger wear tests seemed to be a proper way for the investigation and comparison of wear resistance of the selective laser sintered and the coated parts. The cylinder-on-cylinder setup and the chosen high performance fibre-reinforced automotive polymer counter part with the applied normal force caused a wear big enough to characterize the coatings on grounds of their tribological properties.

3., Laser sintered phosphorous bronze tool material lifetime could be prolonged with the help of local coating. Surface treatment resulting a longer lifetime resists not only local wear better, but also enables the production of a bigger series. This might make an utopistical tendency real, by approaching rapid manufacturing from the direction of rapid prototyping, where the tool produced by rapid manufacturing could produce a full value teljes értékű injection molded parts.

After the tests I measured the height of the specimens and the length of the pins with a micrometer screw (accuracy 0.005 mm). Wear rate of the ring was measured as an average value of four measuring points distributed 4 x 90 ° on the periphery. Wear of the pins has been determined as an average of the wear values on the three pins used simultaneously in the same test. With one set of parameters I carried out three tests according to the possibilities. The wear rate measured by the induction sensor during the tests and the data measured by micrometer screw after the tests were not comparable due to the plastic deformation of the polymer matrix. Therefore, in the evaluation I took only the data measured by the micrometer screw into consideration.

2.1.2 Modified Brugger-Test and Measuerement

The tests carried out by the pin-on-disk tribometer in the first test series were not very successful. The problems which occured can be summarized as follows:

- It was not possible to get well defined and measurable wear tracks with the applied pin-on-disk layout in case of the selected material couples and parameter sets.
- It took very long time to heat up the furnace reaching test temperature, and during high temperature tests the number of uncertain factors has grown, primarily by softening and plastic deformation of the matrix material on the counter body.
- It was not favorable to use three pins, because the resulting contact surface was uncertain. This became extremely critical, as under high load circumstances the plastic counter bodies started to soften. The advantage in case of pin-on-disk tests is that the contact surface of the pins theoretically does not change. In practice the pins did not have a complete overlapping with the specimen, and so due to the propagation of the wear process sooner or later an extra shoulder occurred, which touching the mantle of the specimen grew continuously.

The experiences of the pin-on-disk tests suggested an other type of application, where specimen and counter part are in a different set-up. A tribometer specialized for testing sliding bearings seemed to provide the solution, as slight modification gave the opportunity to carry Brugger tests out [34]. This system suited my needs, which were the following:

- A more exact measurement of the wear rate is possible. The effect of resonance is smaller (lower noise level), so the measured friction coefficient is also more precise.
- A higher speed can be set, as in the case of pin-on-disk, so the time needed for an accelerated test is also less. Nevertheless, wear rate will also be bigger on room temperature.

- Corresponding to the layout of the machine (point-like contact surface, measured by a pressure sensitive foil) the contact surface area grows continuously during the wear process, so the specific pressure decreases along a quadratic function. In spite of this test results are comparable, since friction energy is well definable. In tribology loadability of polyamids used mainly in sliding bearings is characterized by the so-called pv value. The pv value is a multiplication of the specific pressure (p) and the velocity (v) [35]. By using the modified Brugger-test it is unavoidable, that the pv value changes during the wear process, because the contact surface continuously changes (grows). Therefore, in the beginning of the test the pv value, depending on the load, starts from approximately 10-17 N/mm^2*(m/s), and during the wear process reaches a value between 4 and 6 N/mm^2*m/s continuously decreasing (*Figure 2*).
- As the fiber-reinforced polymer counter part rotates against the fix specimen, the polymer has possibility for a short relaxation (regeneration), because due to the rotation there is no constant contact between the two bodies. Therefore, the metallic surface will always be worn by a relatively new, cooled plastic surface.

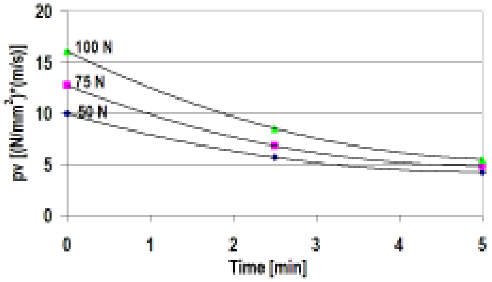

Figure 2. Characteristic changing of the pv value as a function of time

I investigated the wear and friction properties of the coated specimens on the modified Brugger tester, a tribometer of the the TU-Wien IMFT, basically built for sliding bearing tests. I needed a special clamping unit to be able to apply my specimens on the tribometer. This unit was built in a way, that it kept the cylindrical specimen fix, having free access by the counter part to its mantle surface. With perpendicular axis, opposite to the specimen rotates the counter part (also cylindrical), in my case the fiber reinforced polymer. The way of the clamping is to be seen in *Figure 3*.

serves as lubricating third body between specimen and counter body, causing a lower friction coefficient.

4 EVALUATION OF THE RESULTS OF THE TRIBOLOGICAL INVESTIGATIONS, GENERAL STATEMENTS

After evaluation of the pin-on-disk tests with the given load circumstances the following statements can be made:

- The characteristic wear mechanism is, as expected, abrasive, mainly due to the "ploughing" effect of the glas fibers. Pitting or cavities on the worn surface were not detectable. On grounds of my observations, taking each and every pin-on-disk test into consideration, wear rate on the laser sintered specimens was small, maximal 0.26 mm.
- The tightest tolerance of injection molded plastic work pieces calculated according to the relevant size (geometry) allows the production of 664 pieces and 984 pieces at sizes above 250 mm and between 6 and 18 mm respectively.
- My measurements provided a friction coefficient between 0.1 és 0.2. Between room temperature and 80°C the coefficient increases slightly with growing normal force, above 80°C the rate of growing is less or even constant. On higher temperature around 150–180°C the value of the friction coefficient, probably due to partial melting of the matrix, is less at bigger normal forces. According to my measurements, velocity did not have an effect on the friction coefficient.
- The surface roughness of the laser sintered specimens – as long as their surface was prepared – did not change significantly. This means, that the Ra value was between 1 and 2 µm. Without preparation change in the surface properties was significant: the Ra sank from 10–14 µm below 10 µm. If the specimens were not prepared, there was a tendence that during the wear processes the plastic matrix material sticked onto the sintered surface.

The results of the modified Brugger tests lead to the following statements:

- Looking at the diagramms it is obvious, that the cobalt-based, as well as the iron-based coatings improve significantly the wear resistance of the specimens. Under my test conditions wear resistance of the surfaces applying the coating became approximately 4-5 times higher independently from the substrate (sintered phosphorous bronze and steel).
- The wear rate grew with growing friction energy. At constant normal load the cobalt based coating had approximately 25% better wear resistance as the iron-based coating. A difference in the rate of increment is to see above a friction energy level of 2500 J: the increment of wear rate as a function of friction energy in case of the iron-based coating is at least 50 % higher than in case of the cobalt-based coating.

By wearing of the FeB coating the friction coefficient was also around 0.25 (*Figure 21*). Maximum of the value was 0.30, its minimum was a bit below 0.20.

At higher speed levels the same phenomenon is valid as before concerning dependency on normal force. It can be also clearly seen, that friction coefficient values change in a discrete band, independently from the normal force. Curves of the iron-based alloy show the same type of break down at 0.45 m/s as in the case of the Co-based coating, but the curves do not differ from each other that significantly as above mentioned. *Figure 210 and 21* show this behavior independent of velocity and of normal force.

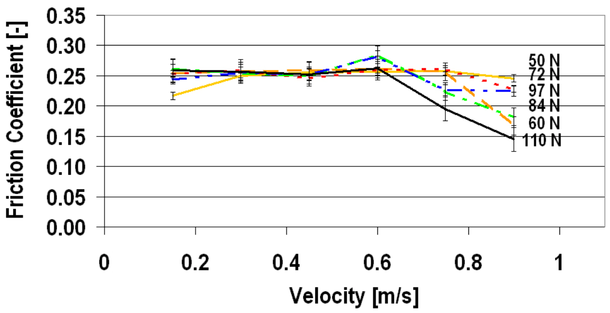

Figure 20. Wear rate of steel specimens coated with cobalt based alloy as a function of normal force and friction velocity, the counter body is fiber reinforced PPS

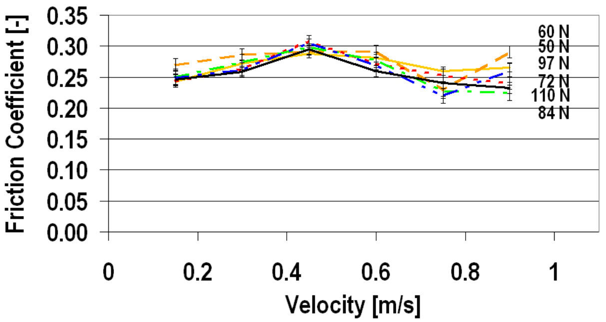

Figure 21. Wear rate of steel specimens coated with iron based alloy as a function of normal force and friction velocity, the counter body is fiber reinforced PPS

At the evaluation of the curves it is important, that the friction coefficient axis scaling is the same on each diagram, therefore it is difficult to see the tendencial behavior of the curves, as values change in a very narrow band. The difference in friction circumstances is also visible embodied in the measured data levels (bands). The standard deviation of the values is presented also here.

Above 0.4 and 0.6 m/s there is a tendencial sinking of the friction coefficient to observ. This can be the conclusion of the fact that contact surface became larger due to higher local temperature softening the plastic surface. The softened material

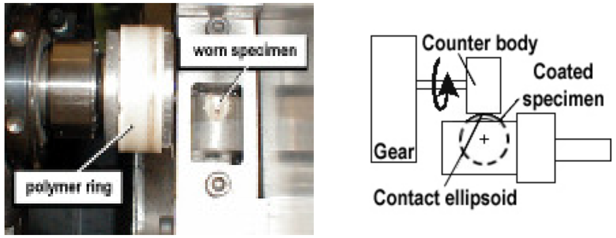

Figure 3. Fixing of the specimen

The variables for the tests (normal force, velocity, ambient temperature) were chosen according to the previous series of tests, the test rig parameters and the requirements of the model. I measured wear optically with a microscope and I determined the approximate area of the contact ellipsoid calculating it on grounds of the Brugger test standard [36].

2.2 The Testing Material

2.2.1 Properties of the Selective Laser Sintered Rings

In the first half of my tests I used specimens made of Ni-alloyed phosphorous bronze powder (EOSINT M Cu 3201) by CO_2 selective laser sintering. The powder material is widely used by rapid prototype producers, therefore I chose this material, too. The selective laser sintered pieces were provided by the BUTE-JJT.

2.2.2 Properties of the Specimens made by Laser Cladding

As a result of the literature research and the first test series local reinforcement of the sintered material seemed just. So coating by laser beam seemed to be the best solution, as laser is a flexible, easily handable and applicable technology. I gained experience from professional literature [10] and earlier works on using cobalt-based alloy on bulk steel substrate, but I haven't found any applications concerning wear resistant coatings on sintered surfaces. To find a cheap and relatively easily accessible competing material to the consumable and already applied Co-based alloy seemed to be the righteous. For this purpose I chose the high boron-content FeB prealloy, which is well known from iron metallurgy. I had the possibility to compare the uncoated specimens with the coated ones, and to qualify the two coatings on two different substrates. Ferroboron is known as a 2-component alloy, with a boron-content between 17.5 and 20%. This prealloy is a cheap addditive of steel and other iron-based alloys, and usually used for a better hardenability of low-alloy steel [37, 38].

During the screening tests of the next test series I investigated all together five different specimens. These were on the one hand the previously tested sintered uncoated ones, and on the other hand the laser coated specimens. I investigated the following coated specimens:

- sintered substrate with cobalt based laser clad coating,

- sintered substrate with iron based coating based laser clad coating (FeB),
- steel substrate with cobalt based laser clad coating,
- steel substrate with iron based coating based laser clad coating (FeB).

The substrate of the coated specimens was a low alloy steel 9SMn28 (DIN 1651-88) and the earlier applied sintered phosphorous bronze.

For my tests I chose the so-called one step laser coating technology. In this case the powder is blown into the melt pool, which is created simultaneously by the laser beam. The gas stream transports and protects the powder against oxidation. By setting the laser power and the powder amount I got a surface which bounded with a strong cohesion to the substrate. For cladding of the specimens, I used the modular 5-axis 5 kW TRUMPF TLC 105 CO_2 laser at BAYATI mounted with flying optics.

The parameter settings for the production of the specimens, which were found on grounds of my previous experiences in the field and on basis of optical evaluation and metallographical investigation, are summarized in *Table 1*.

Table 1. Parameters of the laser cladding

	Parameter sets	Remarks
1.	**Iron-based coating on steel substrate** Laser power: P = 30 % (1500 W) Powder amount: m = 14.13 g/min Axial velocity: v = 6 mm/min	**Not applicable, defective layer**
2.	**Iron-based coating on steel substrate** Laser power: P = 15 % (750 W) Powder amount: m = 4.88 g/min Axial velocity: v = 12 mm/min	**Not applicable, defective layer**
3.	**Iron-based coating on steel substrate** Laser power: P = 15 % (750 W) Powder amount: m = 7.8 g/min Axial velocity: v = 10 mm/min	**Not applicable, defective layer**
4.	**Cobalt-based coating on steel substrate** Laser power: P = 15 % (750 W) Powder amount: m = 7.8 g/min Axial velocity: v = 10 mm/min	**Not applicable, defective layer**
5.	**Iron-based coating on steel substrate** Laser power: P = 15 % (750 W) Powder amount: m = 9.75 g/min Axial velocity: v = 8mm/min	**Proper coating**
6.	**Cobalt-based coating on steel substrate** Laser power: P = 15 % (750 W) Powder amount: m = 9.75 g/min Axial velocity: v = 8 mm/min	**Proper coating**
7.	**Cobalt-based coating on sintered substrate** Laser power: P = 15 % (750 W)	**Not applicable, defective layer**

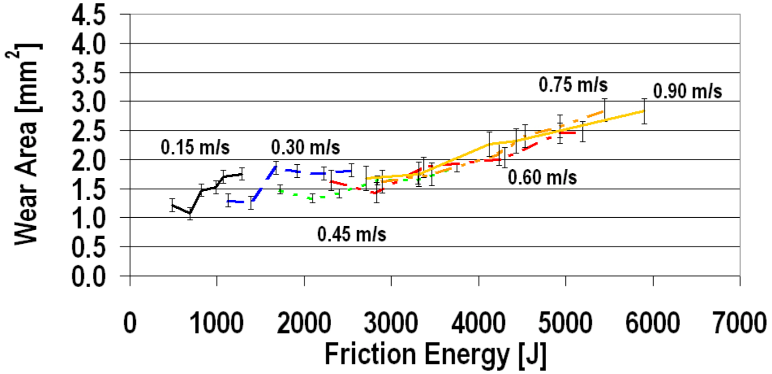

Figure 18. Wear rates of steel specimens coated with cobalt based alloy as function of friction energy, the counter body is fiber reinforced PPS

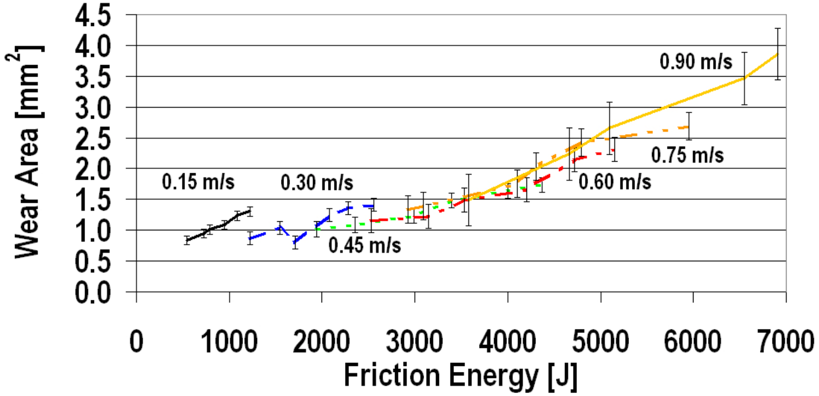

Figure 19. Wear rates of steel specimens coated with iron based alloy as function of friction energy, the counter body is fiber reinforced PPS

3.2.2 Friction Properties Measured in Case of the Modified Brugger Tests

According to *Figure 20* cobalt-based coating on steel specimens provided a relatively constant friction coefficient of 0.25 until 0.6 m/s. Exceeding this velocity value friction coefficient starts to sink, seemingly independently from the normal force. It is also mentionable, that at low normal force (50 N) the friction coefficient is almost constant.

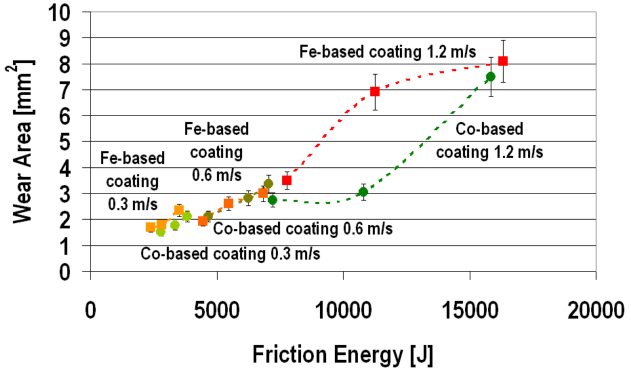

Figure 16. Wear rate of steel specimens as a function of friction energy. Specimens are variously coated, counter part is fiber reinforced PPS

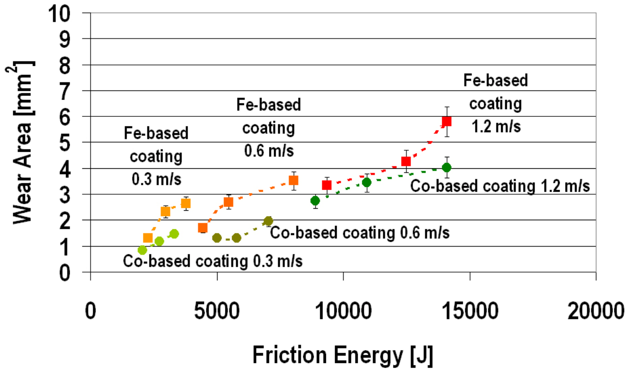

Figure 17. Wear rate of steel specimens as a function of friction energy. Specimens are variously coated, counter part is fiber reinforced PEEK

Figure 18 shows wear rate of the Co-based coating as a function of the friction energy. With growing friction energy also wear rate grows. The same tendence is to be observed in case of iron-based coatings (*Figure 19*). It is noticeable, that in my tests the Co-based alloy resisted more against wear. On lower normal load level this difference is not significant. In the diagramms the standard deviation of the test values is also marked.

	Parameter sets	Remarks
	Powder amount: m = 9.75 g/min Axial velocity: v = 8 mm/min	
8.	**Iron-based coating on sintered substrate** Laser power: P = 15 % (750 W) Powder amount: m = 9.75 g/min Axial velocity: v = 8 mm/min	**Not applicable, defective layer**
9.	**Cobalt-based coating on sintered substrate** 1. layer: Laser power: P = 15 % (750 W) Powder amount: m = 9.75 g/min Axial velocity: v = 8 mm/min 2. layer: Laser power: P = 20% (1000 W)	**Proper coating**
10.	**Iron-based coating on sintered substrate** 1. layer: Laser power: P = 15 % (750 W) Powder amount: m = 9.75 g/min Axial velocity: v = 8 mm/min 2. layer: Laser power: P = 20 % (1000 W)	**Proper coating**

The aim was to get a continuous, smooth and homogeneous surface. I coated the specimens, which were fixed onto a rotating axis, in a length of 8 mm. The revolution of the axis was 5.55 RPM which gave a 500 mm/min tangential velocity. The laser head moved above the substrate surface parallel to the rotation axis with a constant 8 mm/min speed in a distance from the surface, which ensured a 2 mm diameter laser spot on the surface. The powder was transported by 2 l/min gas and the amount of shield gas reaching the surface was 8 l/min. After coating, the specimens were grinded to ensure equal test conditions during the tribological tests.

The next figures show cross-sections of bulk steel specimens coated by the Fe-based alloy.

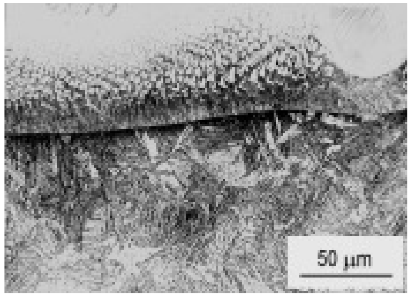

Figure 4. Cross-section of bulk steel specimen coated by the Fe-based alloy

Figure 4 shows the boundary of bulk steel base material and the iron-based coating. Due to laser beam processing, steel had an α–γ–α phase transition below the melt zone. Due to its low carbon content traditional martensite texture is not expectable, but there is a needlelike structure to observ, which is typical for rapid cooling.

Close to its boundary, the layer, which partially melted during the laser processing, became richer in Fe from the substrate. So the Fe-content decreases gradually and the boron content grows in the layer as a function of the distance from the boundary. Therefore, close to the boundary there are Fe_2B phase, and a eutektikum of α-Fe and Fe_2B. Further away from the boundary the FeB phase is to be observed.

In *Figure 5* we can see a similar texture phenomenon with the difference, that the areas with different Fe and B content are more separated form each other due to the formed structural circumstances. The 40-50 µm thick transition zone is characterized by α-Fe and Fe_2B phases. *Figure 6* gives an impression of the hardness distribution across the layer showing a series of Vickers prints.

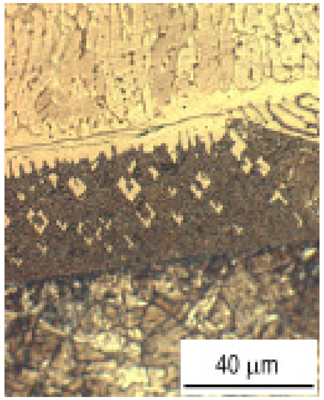

Figure 5. Cross-section of bulk steel specimen coated by the Fe-based alloy (transition zone)

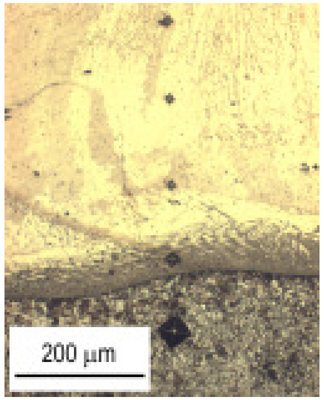

Figure 6. Cross-section of bulk steel specimen coated by the Fe-based alloy (transition zone)

Figure 7 shows the cross-section of a Co-based layer on bulk steel substrate. The type of the layer created by the laser beam is a solid solution.

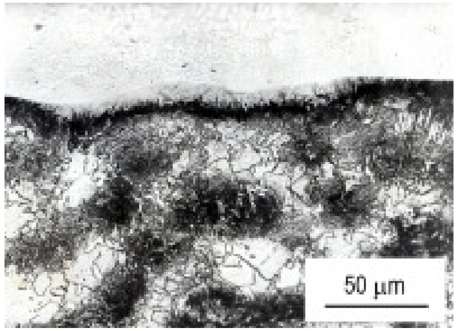

Figure 7. Cross-section of bulk steel specimen coated by the Co-based alloy (transition zone)

Partial melting of the substrate and a consequently formed thin transition zone is observable also here. According to the contents of the coating, there is a fine network of intermetallic phases (carbide, boride and silicid) with a fine grain size in the solid solution matrix.

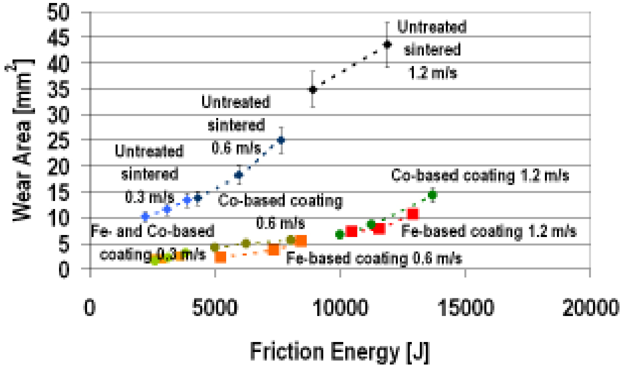

Figure 14. Wear rate of sintered specimens as a function of friction energy. Specimens are uncoated and variously coated, counter part is fiber reinforced PPS

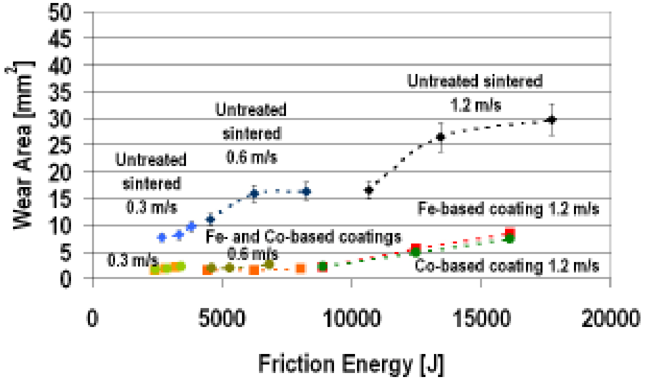

Figure 15. Wear rate of sintered specimens as a function of friction energy. Specimens are uncoated and variously coated, counter part is fiber reinforced PEEK

In case of equal friction energy level, wear occurring on the untreated specimens is approximately four times as big as on the coated ones (*Figure 14*). The curves of the coated specimens can not be differed from each other, because of the scaling of the axis, nevertheless, the curve series shows the tendencial behaviour of the material couples. It is also observable, that on the same friction energy level PPS causes approximately 25% more wear as PEEK.

Figure 166 and 17 represent the previous tendence of the sintered specimens also in the case of the steel substrate. The wear rate of the coated steel and laser sintered specimens has the same order of magnitude.

(Ra values) with a Hommelwerke LV 50 (TKL 300/155 Tastn.-R.-5 µm) tactile surface roughness device. Surface roughness of the specimens was measured on a 2.5 mm long track.

The surface roughness of the original sintered surface was Ra=10…15 µm, with further application of P 40 W emery paper this value decreased to 1…2 µm, which due to wear hasn't decreased significantly any more (0.5…1 µm).

The surface roughness measurements show it clearly, that in the fiber-reinforced polymer and sintered phosphorous bronze relation the abrasive wear mechanism was characteristical. Grinding of the sintered phosphorous bronze decreased the surface roughness a lot and enhanced measurement accuracy, because the process resulted an identical starting condition, which was also proven by the deviation of the measurements. Due to wearing effect of the fiber-reinforced polymer the surface of the specimens became even smoother.

3.2 Results of the Measurements Carried Out by the Modified Brugger Test

3.2.1 Obsereved Wear Properties at the Modified Brugger Tests

In the next phase of the tests wear rate was determined, following the evaluation method of the Brugger tests, by the area of the wear track on the specimen surface. *Figures 14 to 17* show the different wear rates in case of various specimens, coatings and counter bodies. These figures represent tendencial similarities of steel and sintered specimens. For this similarity and for economical reasons I used steel substrates to compare tool material and coating properties. In addition, these diagrams also show, that the brand KRECA CHOP M-107T carbon fiber-reinforced polyphenilene-sulphide counter body caused higher wear rate on the specimens under identical test conditions. So I chose this counter material for the further tests, nevertheless to enhance effectivity and to decrease uncertainities in the measurements.

I characterized the wear rate measured in the tests with various material couples and test conditions as a function of the friction energy. Representation of friction energy as a multiplication of friction force and the distance run enables the comparison of tests run with different speeds in different time intervals.

Figures 14 and 15 show the wearing effect of the fiber-reinforced PPS and the fiber-reinforced PEEK. The curves prove that both coatings improved a lot the wear resistance of the sintered specimens.

The next pictures (*FiguresFigure* 8 *to 11*) represent the cross-sections of sintered phosphorous bronze specimens with iron- and with cobalt-based coatings. The solid solution type coating is packed with bubbles of the phosphorous bronze substrate. The microhardness measurement prints show that hardness in the layer is much different from that of the substrate's (*Figure 9*). Melting situation is the same as above mentioned.

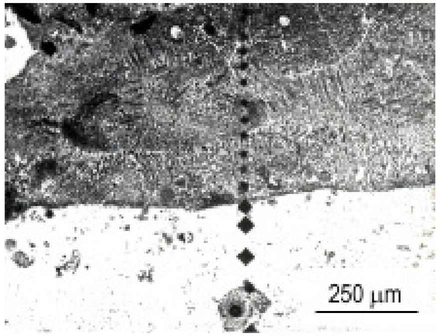

Figure 8. Cross-section of sintered phosphorous bronze specimen coated by the Fe-based alloy (layer)

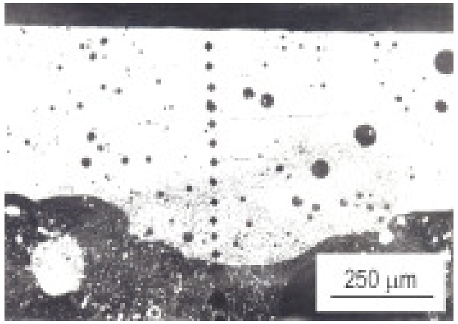

Figure 9. Cross-section of sintered phosphorous bronze specimen coated by the Co-based alloy (layer)

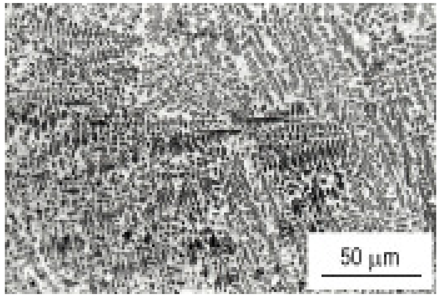

Figure 10. Cross-section of sintered phosphorous bronze specimen coated by the Fe-based alloy (layer)

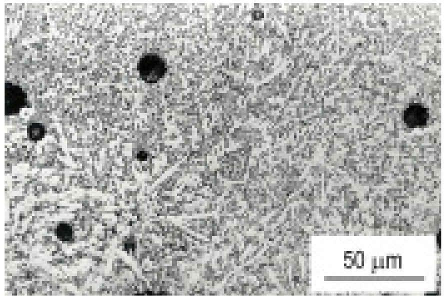

Figure 11. Cross-section of sintered phosphorous bronze specimen coated by the Co-based alloy (layer)

Cross-sectional disribution of the hardness shows clear boundaries of the layers and the transition zones. It has been also shown, that the hardness of the Co-based coating is 700–800 $\mathrm{HV}_{0.2}$, but the FeB-coating had values over 1200 $\mathrm{HV}_{0.2}$ in the case of sintered substrate. The hardness of the Co-based coating on steel substrate is not significantly different, the measured hardness in case of FeB-coating approached 1500 $\mathrm{HV}_{0.2}$. In the case of steel substrates the average hardness in the transition zone is approximately 850 $\mathrm{HV}_{0.2}$ probably due to the presence of boron-carbide particles which formed because of the high melting point of boron.

Below the transition zone, the strength of the substrate is not directly affected by the hardened and relaxed substrate, which has a rough needlelike martensitic structure. Deeper in the substrate a finer bainitic needlelike structure is detectable, below this the original ferrite-perlite grains of the substrate are to be seen (*Figure 4*). In case of sintered specimens there is a higher grade of mixing with the substrate in the transition zone, which is represented by the gradual transition of the hardness. The higher grade of mixing is most probably due to the lower melting point of the phosphorous bronze.

2.2.3 The Structure and Characteristics of the Fiber-Reinforced Plastic Counter Body

For my tests I chose carbon fibre-reinforced plastic, as ploughing and abrasive wearing effect of the hard fibres is strong. In the beginning I used glass-fibre reinforced polyamid-Imid, later Polyether-Etherketone (PEEK) and Polyfenilene-Sulphid (PPS), so-called high performance plastics with various types of reinforcing fibres.

In the pin-on-disk tests the counter body was glass-fibre reinforced polyamid-Imid, in the modified Brugger tests I used three different types of high performance fibre-reinforced plastics. From these, according to the screening tests, the most tests ran with the brand KRECA CHOP M-107T with PPS matrix. The PPS matrix is reinforced by Kreka Chop fibres, which have high strength and good wear, thermal and corrosion resistance [16].

3 RESULTS OF THE TRIBOLOGICAL TESTS

3.1 Results of the Tribological Tests by the Pin-On-Disk Method

3.1.1 Wear Characteristics During the Pin-On-Disk Tests

During the pin-on-disk tests I investigated the wear of untreated selectiv laser sintered against glass fibre reinforced polyamid-imid. I measured the wear rate in two different ways. With an induction sensor I measured the common wear of the specimen and the counter body, which gave me an impression of the wear propagation as a function of the time. Specimen geometry, wear rate on the sintered specimens and on the fiber reinforced counter parts, was measured by a micrometer screw before and after the tests. Since wear on the plastic counter parts was much bigger, than on the sintered phosphorous bronze pieces, in addition changes in geometry were strongly affected by the plastic deformation of the plastic counter parts, measurement of the common wear rate did not help me to understand better the wearing process of the phosphorous bronze. Of course, single measurements on the specimens by a micrometer screw brought more results, but evaluation of the wear rate was not easy because of its small value. It was impossible to discover any correlation between the measured data and the examined materials or test circumstances using the pin-on-disk tribometer: the method is not applicable for the task in its present layout (*Figure 12*).

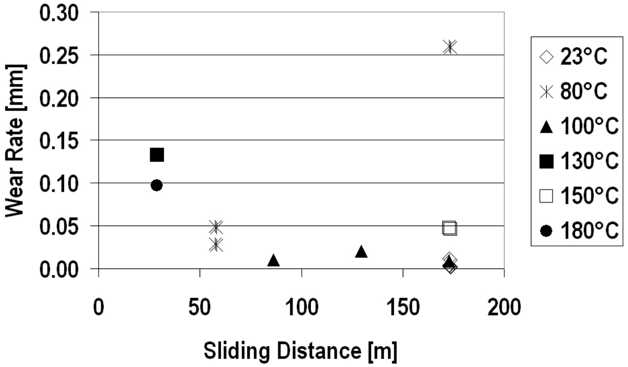

Figure 12. Wear rate of the untreated phosphorous bronze specimens

3.1.2 Friction Properties Measured in Oin-On-Disk Tests

I determined friction coefficient as a function of specific pressure, temperature and the relative velocity of the two bodies (*Figure 13*).

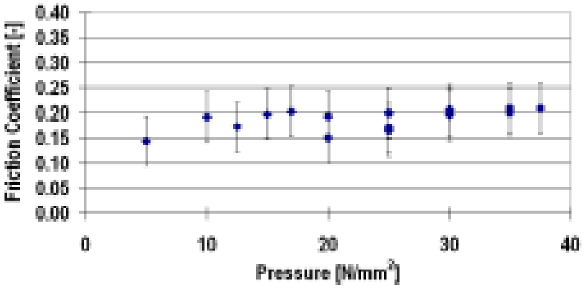

Figure 13. Friction coefficient values as function of the specific pressure, at 0.016 m/s friction velocity and 23 °C room temperature in case of an untreated phosphorous bronze specimen worn by a glas fiber reinforced polyiamid-imid counter body

3.1.3 Changing of the Surface Roughness during the Pin-on-Disk Tests

On grounds of the examination results, I tried to get quantitative information on how the working (forming) surface of the sintered phosphorous bronze injection molding tool changes under the operation conditions. I evaluated the changes in the surface properties by optical evaluation, after that I measured surface roughness