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OPTIMISATION OF HEAT TREATMENT FOR STEEL STRESSED BY ABRASIVE EROSIVE DEGRADATION

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Abstract

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The aim of the present publication is the analysis of refined steels designed for conditions with increased abrasive stress (102Cr6, 54SiCr6, 25CrMo4 and 15 230 – does not have DIN equivalent). These include mainly mechanical components used as replaceable parts in machines for tillage, such as plough blades and chisels.
The experimental part is focused on the issue of heat treatment of steel materials, which are usually used for the production of machine parts intended for tools designed to withstand abrasive stress. The suitability of individual materials for the production of tools for tillage will be evaluated based on the results of mechanical tests. These include the analysis of the structure of the given material, its hardness (ČSN EN ISO 6508-1) and impact toughness (ČSN EN 10045-1). Microhardness of individual structural components was also measured. The analysis was processed on a metallographic microscope.
The individual tests of abrasive resistance are divided between interaction of two objects and a combination of abrasive erosive wear. Laboratory tests were performed on an abrasive cloth (ČSN 01 5084) and in Bond's drum apparatus (this experiment is not standardized).
Based on the results of the individual measurements it is possible to make recommendation of a suitable heat treatment of tested materials for environments with considerable abrasive stress.

Keywords: heat treatment, erosive degradation, abrasive wear, steel, fracture, microhardness, internal structure

INTRODUCTION

Heat treatment of steel components is one of the primary aspects of mechanical engineering. Based on the chemical composition of the given material, it is possible to achieve optimal mechanical properties and durability of replaceable parts (Stachowiak *et al.*, 2005). Depending on the variety and quantity of machinery in use in an agricultural enterprise, appropriate heat treatment can significantly reduce operating costs. A classic example is the preparation of edaphon.

Tillage is one of the basic operations in plant production. All machinery designed for individual procedures of tillage are subjected to significant abrasive wear. Degradation of the edge portion of a plough blade will be reflected not only in the tractive resistance of the whole ploughing unit, but mainly in the fuel consumption of the tractive device. The quality of tillage also decreases (Fielke, 1996; Natsis *et al.*, 1999). For this reason, it is necessary to find a compromise between timely replacement of a worn part and the increase in tractive resistance. From the economic perspective, however, the costs for tillage must also include the time required for the replacement of a worn component (Brožek, 2007).

Though classic ploughing is currently in decline and the new trend in soil preparation is mere soil loosening, it is necessary to note that post-harvest tillage significantly influences the yield in the next cycle.

The technology of deep loosening of the soil usually makes use of ploughshare cultivators. Similarly to plough blades, these cultivators are subjected to significant abrasive wear due to SiO_2 soil particles, whose hardness is up to 1,280 HV (Blaškovič, 1990). Since these machines require higher forward speeds than ploughing machines for proper functionality, the cultivating units are exposed to significant impact shocks. For this reason, it is necessary to pay due attention to the material used, for it must meet several criteria. These include mainly proper toughness of the material and increased resistance to abrasive wear. Since the weight losses in the cultivating unit are tied to its geometry, these units can be successfully renovated by weld depositing hard-surface metals (Müller *et al.*, 2011, Votava *et al.*, 2014, Ferguson *et al.*, 1998).

Renovation of worn-out parts is a commonly discussed issue. Naturally, financial demands of the renovation are the primary evaluation criteria. Currently, polymer particle composites are coming into widespread use. These composites are applied directly onto the most abrasively stressed parts of the ploughing unit (Valášek *et al.* 2014). A significant advantage of these materials is above all the possibility of combining them with other steel particles, thus creating a composite coating with excellent toughness and abrasive resistance (Nirmal *et al.*, 2011, Müller *et al.*, 2013). Tests to increase the durability of new components were performed also on ploughing units where the weld deposits of zig-zag strips were created directly on the plough blade diagonally to the direction of travel. The advantage of this arrangement is the creation of a sawtooth effect and thus reducing the tensive resistance of the machine as a whole (Müller *et al.*, 2014). However, long term use of these blades carries the risk of creating saw-like shapes also on the subsequent parts of the device, which would lead to their faster abrasive degradation. For this reason, it is necessary to choose a material that is homogenous in the entirety of the cross-section and optimise its heat treatment.

MATERIALS AND METHODS

Abrasive wear causes up to 80 % of damages of machine parts in technical praxis. The service life of plough blades or chisels of soil processing machines depends on the mentioned degradation process. This paper brings an entrance analysis of steels 102Cr6, 54SiCr6, 25CrMo4 and ČSN 15 230 with a different refinement and their usage in agricultural praxis. Heat treatment of the tested steels will be processed in a laboratory oven with the maximal deviation of ± 2 °C from the designed temperature.

There were processed the following laboratory tests:

- Impact toughness test (Charpy's hammer - ČSN EN 10045-1). Used sample – was of the size 10 × 10 × 55 mm with an indentation.
- Metallographic evaluation of phases structures, measurement of microhardness and HRC hardness in compliance with the ČSN EN ISO 6508-1 standard.
- Wear on an abrasive cloth in accordance with ČSN 01 5084 standard. Samples of 10 × 10 × 10 mm.

- Test in Bond's drum device with a loose abrasives

Materials tested were selected due to their suitable chemical composition for abrasive degradation processes. At the same time these materials are convenient for production of soil processing tools.

During tillage, not only are the blades of the individual tools being abrasively worn down, but – depending on the skeleton content of the soil – the tools also exposed to considerable dynamic stress. For this reason, the toughness of the entire blade is of vital importance (Čičo *et al.*, 2012, Votava *et al.*, 2015a). The materials were thus chosen based on this parameter.

Steel 102Cr6 (14 100): A material with very hard surface resistant to wear. It finds use mainly in the production of pivots and cams, as well as piston rings or clamping jaws of machine tools. Depending on the amount of carbon, the material will be annealed at lower values. This procedure was chosen to increase toughness after heat treatment. The chemical composition is shown in Tab. I.

Steel 54SiCr6 (14 260): This material is used mainly for machine parts which come under large dynamic stress. These include flat and cylindrical springs for automotive industry. The material is also suitable for use in increased temperatures (300 °C). Suitable heat treatment endows the material with good abrasive resistance. The chemical composition is shown in Tab. I.

Steel 25CrMo4 (15 130): The material is suitable for moderately stressed machine components. It is mainly used for the production of connecting rods, crankshafts or strength-stressed screws. Based on the chemical composition (see Tab. I), a longer period of austenitisation may be recommended. The material is characterised by excellent hardenability and low susceptibility to surface decarbonisation.

Steel 15 230: This material is used for statically and dynamically stressed machine components. It can also be used for the manufacturing of shear pins and load-bearing elements. It is also used for valve and scale beam forgings. The chemical composition (see Tab. I) ensures low wear even in temperatures above 100 °C.

I: *Chemical composition of tested materials*

Marking based on DIN/ČSN	Chemical composition [%]									Transition points [°C]			
	C	Mn	Si	Cr	Mo	V	W	Ni	Other	Ac_1	Ac_3	Ar_1	Ar_3
102Cr6/ 14 100	0.95	0.60	0.40	1.25	-	-	-	-	-	750	780	625	705
54SiCr6/ 14 260	0.50	0.50	1.30	0.50	-	-	-	-	-	760	810	690	720
25CrMo4/ 15 130	0.32	0.70	0.17	0.90	0.15	-	-	-	-	740	790	660	770
–/ 15 230	0.24	0.80	0.40	2.50	-	0.20	-	-	-	750	840	650	750

II: *Heat treatment 102Cr6 and 54SiCr6 steels*

Marking based on DIN	Quenching			Tempering	
	Austenitisation [°C]	Hold [min.]	Quenching media	Heating [°C]	Cooling medium
102Cr6 steel Samples 1	840	20	Oil	450	Air
102Cr6 steel Samples 2	840	20	Oil	600	Air
54SiCr6 steel Samples 1	860	20	Oil	300	Air
54SiCr6 steel Samples 2	860	20	Oil	600	Air

III: *Heat treatment steels 25CrMo4 and 15 230*

Marking based on DIN/ ČSN	Quenching			Tempering	
	Austenitisation [°C]	Hold [min.]	Quenching media	Heating [°C]	Cooling medium
25CrMo4 steel Samples 1	Marking based on DIN/ČSN	Marking based on DIN/ČSN	Marking based on DIN/ČSN	Marking based on DIN/ČSN	Marking based on DIN/ČSN
25CrMo4 steel Samples 2					
15 230 steel Samples 1	25CrMo4 steel Samples 1	25CrMo4 steel Samples 1	25CrMo4 steel Samples 1	25CrMo4 steel Samples 1	25CrMo4 steel Samples 1
15 230 steel Samples 2	25CrMo4 steel Samples 2	25CrMo4 steel Samples 2	25CrMo4 steel Samples 2	25CrMo4 steel Samples 2	25CrMo4 steel Samples 2

IV: *Chemical composition of the original blade plates*

	Chemical composition [weight %]									
	C	Mn	Si	Cr	Mo	Al	Zn	W	Ni	Fe
Original blade I	0.38	2.18	1.41	1.98	0.40	0.15	0.02	0.14	0.24	the rest
Original blade II	0.34	1.20	0.90	2.15	0.75	-	-	0.09	0.49	the rest

Production of test samples

The procedure for heat treatment of the materials was determined based on chemical composition. Heat treatment is the most important operation during the preparation of samples. It affects all mechanical properties of the materials. Unsuitable temperatures can lead to the formation of a large number of internal defects which would significantly affect the resulting microstructure of the finished component.

The heat treatment parameters were chosen based on the technical standards for the given material. The initial analysis after heat treatment was focused on the toughness of the material. For this reason, two tempering temperatures were chosen for the tested samples.

Steels 102Cr6 and 54SiCr6 are designed for conditions with dynamic stress. The heat treatment of these materials (see Tab. II) is typical by a wide interval of tempering temperatures.

Due to faster heat conduction during the hardening process, a water bath was used for 25CrMo4 and 15 230 steel samples. The heat treatment process is described in Tab. III.

Chemical analysis of plough blades for soils with increased skeleton content

The tested materials are compared with original chisels designed for soils with higher skeleton content. Since the manufacturer only lists the basic chemical composition of the tested material, a chemical analysis was performed on a scanning electron microscope VEGA II XMU (Tescan) along with an energy dispersion microanalyser QANTAX 800.

Measurement of the elemental composition of the sample was performed in three surfaces at 100× instrumental magnification. The voltage on the measuring probe was set to 15 kV. This value was set in order to eliminate outside influences. The measured values are at 100 % mass concentration. The chemical composition of the individual samples is listed in Tab. IV. The results listed are an average from the three measurement.

The analysis of the chemical composition of the tested material revealed a higher percentage representation of carbide-forming elements. It also revealed the presence of nickel and tungsten, which leads to the formation of a tough matrix in the individual structural phases.

The individual peaks of elemental compositions are listed in Fig. 1. The characteristics reveal that the material contains zinc, which may be caused by impurities present in the hardening furnace during heat treatment. Due to the mechanical properties of the material, the presence of zinc is undesirable.

ČSN EN 10045-1 impact test at bend point

The impact test serves to determine the properties of the material under impact stress. These values are key, since they allow, to an extent, a prediction of the behaviour of technical materials in real conditions. The samples were produced based on the dimensions provided by ČSN EN 10045-1.

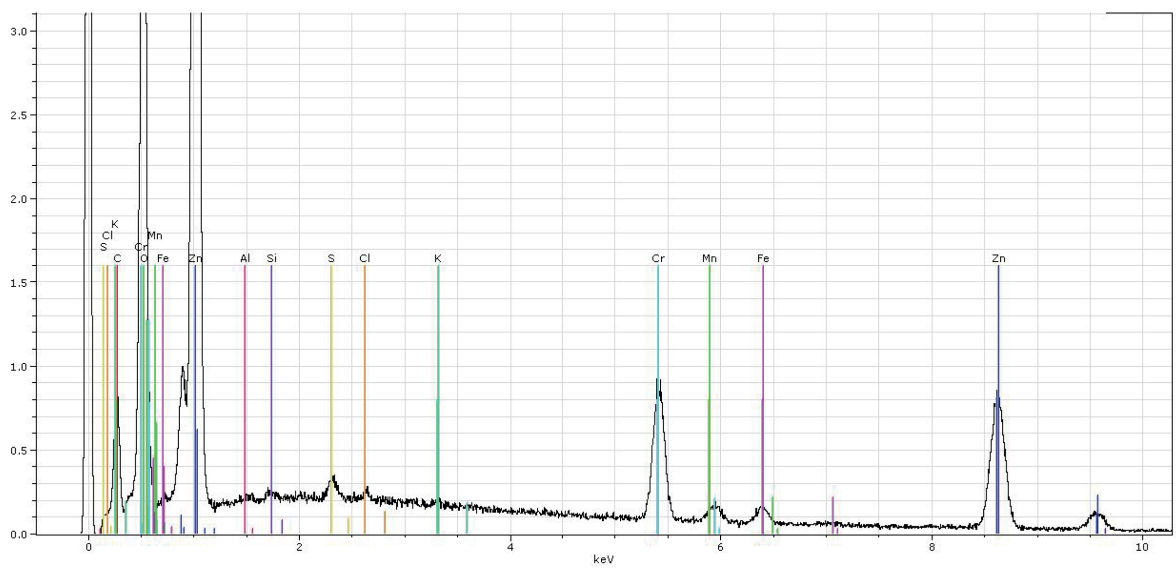
A simple mathematical relation can be used to determine the toughness of technical materials. Fracture toughness *Kc* is the work required to fracture the test object, relative to the initial section S_0 of the test object at the point of cracking.

$$Kc = \frac{K}{S_0} \; (\mathrm{J/cm^2})$$

The required work *K* is determined by the difference between the potential energies of the hammer before and after impact.

$$K = G \times (H - h) \; (\mathrm{J})$$

The result of the test establishes the susceptibility of the tested material to brittle or ductile fracture.



1: *EDS spectrum of the plough blade I (results of chemical analysis listed in Tab. IV)*

V: *Toughness test results after heat treatment*

Tested material	Number of measurements			Average [J/cm2]	Standard deviation [J/cm2]	Variation coefficient [%]
	1 [J/cm2]	2 [J/cm2]	3 [J/cm2]			
102Cr6 tempered at 450 °C	12.5	11.9	13.5	12.63	0.66	5.25
102Cr6 tempered at 600 °C	18.3	21.6	19.4	19.77	1.37	7.12
54SiCr6 tempered at 300 °C	19.6	22.1	22.9	21.53	1.41	6.59
54SiCr6 tempered at 600 °C	25.9	27.1	26.3	26.43	0.50	1.89
25CrMo4 tempered at 530 °C	29.5	28.3	28.7	28.83	0.50	1.74
25CrMo4 tempered at 690 °C	33.2	34.0	33.1	33.43	0.40	1.21
15 230 tempered at 550 °C	30.4	29.7	28.9	29.67	0.61	2.04
15 230 tempered at 650 °C	36.2	37.8	35.2	36.40	1.07	2.93
Original material I	45.3	45.9	44.9	45.37	0.41	0.91
Original material II	24.9	21.2	26.8	24.30	2.33	9.38

As is evident from Tab. V, heat treatment and above all the carbon content in the material has a major effect on the toughness of the created structure. Brittle fracture was detected mainly in materials with lower tempering temperature.

The fragmented section of test samples was examined using a Meopta binocular microscope with standard ten-fold magnification. The individual fracture surfaces are shown in Fig. 2–3.

As is evident from Fig. 7(a), the fracture surface of 54SiCr6 shows clear signs of crystalline fracture. The considerable amount of differently oriented glossy facets points to transcrystalline fragmentation of the base metal material. In Fig. 2(b), there is clear evidence of brittle fracture with destruction of the base material.

The fracture surface in Fig. 3(a) of 25CrMo4 steel is formed in the central section via crystalline fracture, which gradually transitions into a fracture surface of a ductile nature. The amount of glossy facets also points to brittle rupture of the central section. Fig. 3(b) shows ductile fracture of 15 230 steel.

Fig. 4(a) shows partial ductile fractography of fracture surface caused by partial separation of shear planes in the material. Fig. 4(b) shows a typical brittle fracture throughout the cross-section of the tested sample.

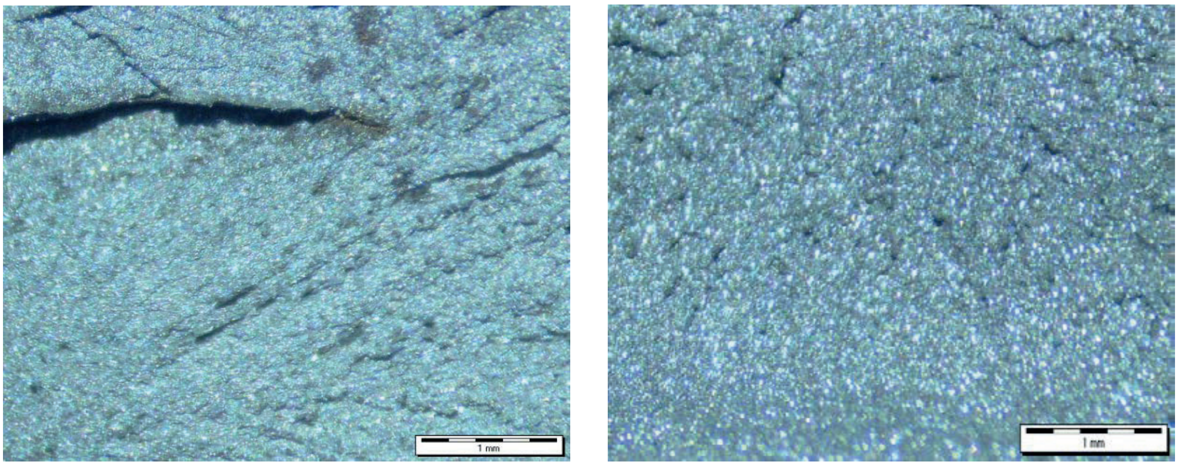
As is evident from the results of dynamic testing, fragmentation of the entire tool can easily occur in homogenous steel material. To eliminate brittle fracture, a heat treatment with higher coefficient of dynamic toughness can be chosen; an increase in abrasive resistance can be achieved by hard-surface metal weld deposits (Kotus *et al.*, 2013a). Again, the technology used and the internal microstructure of the weld metal plays a significant role (Pauliček et al., 2013, Kotus *et al.*, 2013b).

Metallographic evaluation of materials used

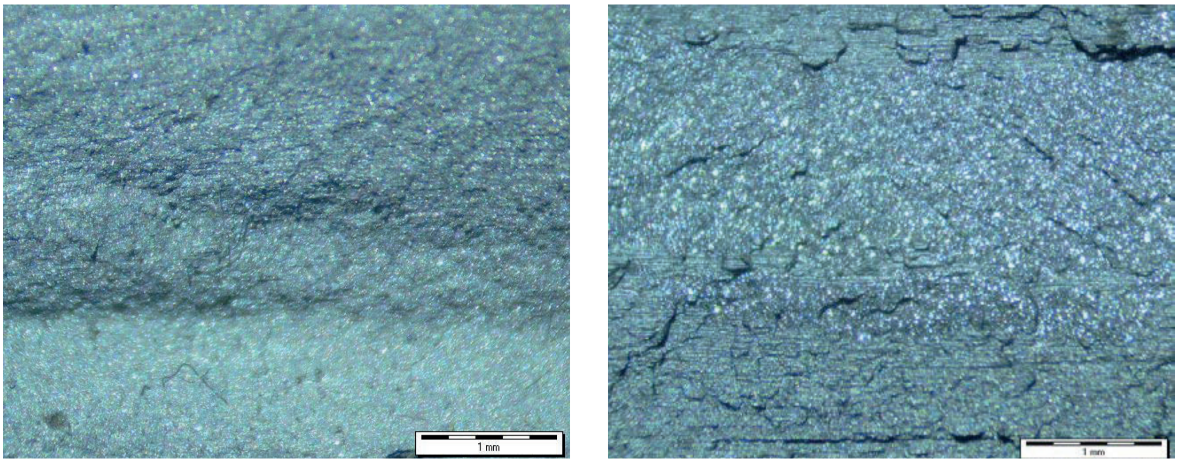
The prepared samples were subjected to metallographic analysis of the individual structural phases created after heat treatment. The production of metallographic preparations can be summarised into the following steps: splitting the preparation by an accurate metallographic saw, grinding, polishing, corrosion and photographic documentation on a Neophot 21 metallographic microscope. As is evident from Fig. 5, chemical composition of the given material plays a pivotal role in the structural phases of the individual samples. This is particularly the case with carbon content and alloying elements Cr, Mn or Si. In steels 102Cr6 and 54SiCr6, carbides distributed across the metal matrix as well as predominantly tempered martensitic structure supplemented by bainite are present. These bainite needles are oriented in accordance with basic martensitic structure. Steels 25CrMo4 and 15 230 consist mainly of sorbitic structure. It is a tough structural phase characteristic by significant elimination of internal tension. This phenomenon manifests itself by impact absorption and gradual ductile fracture. In abrasion-resistant commercially supplied plough blades, the structural component consists mainly of a combination of sorbitic and bainitic structure. In the case of original chisel II, frequent defects were also detected in the form of pores in the base material. The internal structure is also made up of very hard needles of martensite and residual austenite.

Analysis of the hardness of the tested materials and microhardness of structural phases

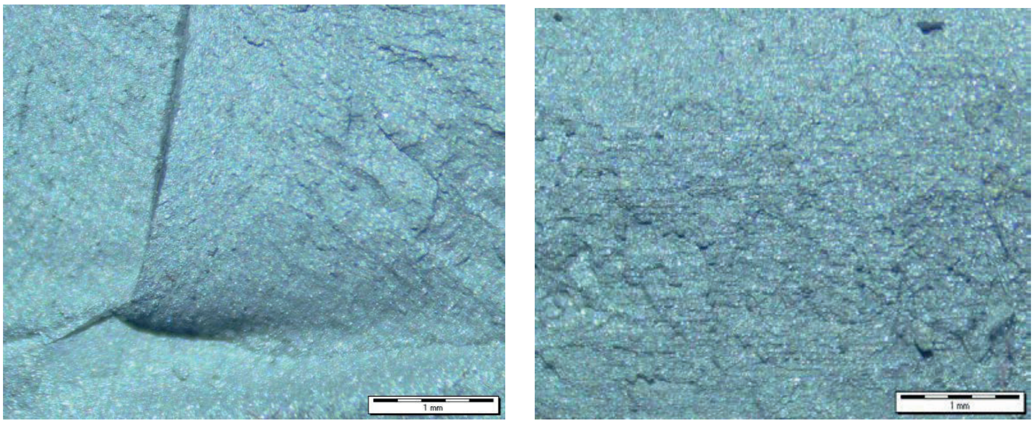
The resulting hardness of the steel component provides significant data on its durability and overall wear (Dillinger, 2007). In tillage, however, the ability of the material to absorb impact during contact with soil fractions (skelet) plays a significant role



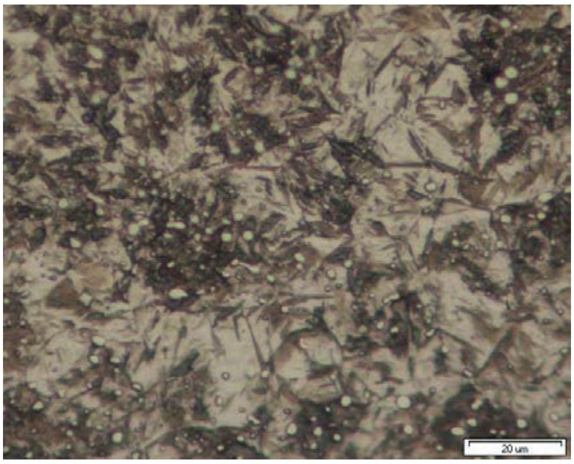
2: *a – Fracture surface of steel 54SiCr6 tempered at 600 °C, b – Fracture surface of 102Cr6 steel tempered at 450 °C*



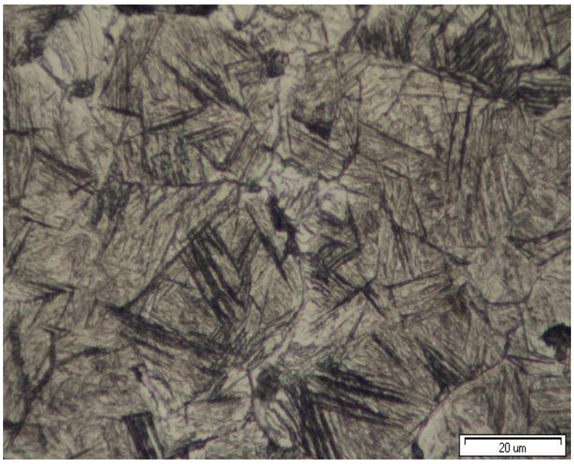
3: *a – Fracture surface of 25CrMo4 steel tempered at 690 °C, b – Fracture surface of 15 230 steel tempered at 530 °C*



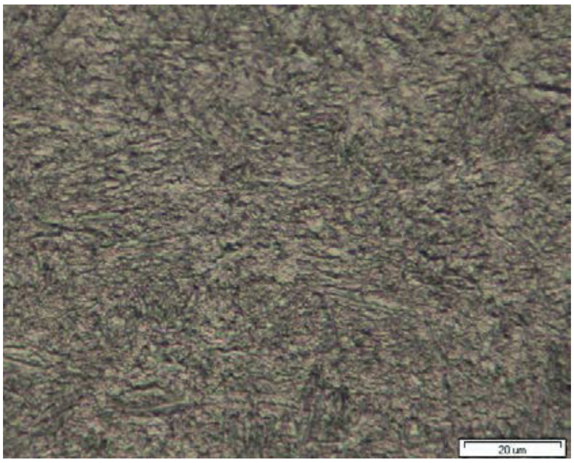
4: *a – Fracture surface of a commercially supplied blade from original material I, b – Fracture surface of a commercially supplied blades from original material II*



102Cr6 steel tempered at 450 °C

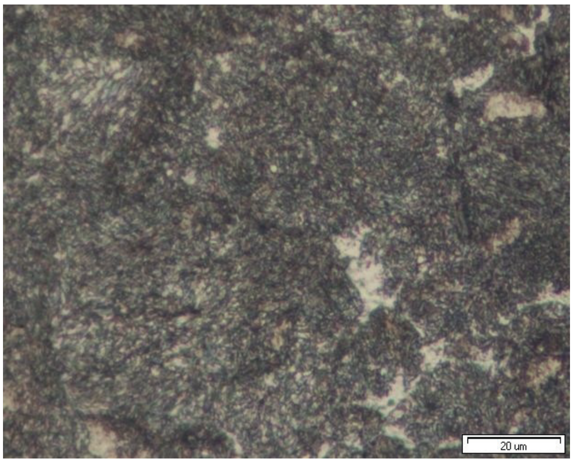


54SiCr6 steel tempered at 600 °C

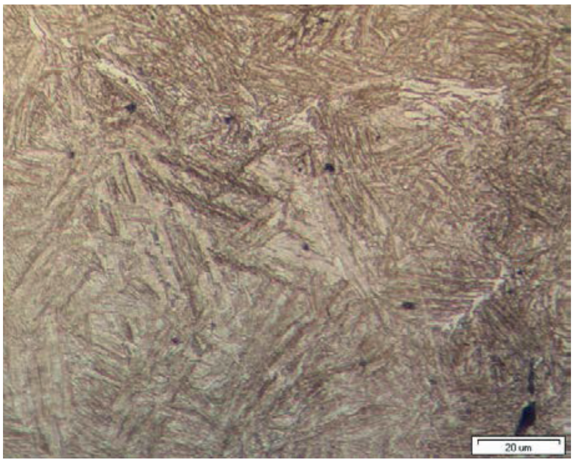


25CrMo4 steel tempered at 690 °C

15 230 steel tempered at 650 °C



Original material



Original material II

5: *Metallographic scratch pattern: structural phases of the tested materials*

(Votava *et al.*, 2015b). The hardness measurement was performed on five samples of each material via the HRC method (penetration of the sample with a diamond cone with apical angle of 120° at 1470 N of force). It is evident from the arithmetic average (see Tab. VI) that the resulting hardness is determined mainly by the chemical composition and the heat treatment of the material.

Microhardness measurement was performed using Hannemann microhardness tester which is a part of the Neophot 21 metallographic microscope. It is a classic method based on Vickers. A diamond cone with apical angle of 136° is indented into the material at a force of 0.1 kp. Based on the length of the diagonals, the HV microhardness is then deduced. Only samples with higher tempering temperature were measured due to the toughness requirements.

Since the Hannemann microhardness tester is fitted with an injector with lower resolution, the measured values are partially distorted by the size of the individual structural components.

ČSN 01 5084 Wear on the abrasive cloth

The initial analysis of the suitability of the tested materials for application in tillage tools was performed on an abrasive cloth. The principle of abrasive wear is the interaction of two bodies (objects). The test can also be counted among analyses with solid abrasive particles. The rotating movement of the disc and radial displacement of the sample ensures constant contact of the tested material with sharp corundum particles. The weight loss was measured on digital scales with accuracy to 0.01 g. Three measurements for each material were performed to statistically calculate average values. See Fig. 6.

In addition, the relative volumetric resistance against abrasive wear ψ_{abr} was calculated according to the relation:

$$\psi_{\text{abr}} = \frac{m_{et} * \rho_{vzo}}{m_{vzo} * \rho_{et}}$$

where:
m_{et} – etalon (original material II) weight loss [mg]
m_{vzo} – weight loss of the sample [mg]
ρ_{et} – etalon (original material II) density [g·cm^{-3}]
ρ_{vzo} – sample density [g·cm^{-3}]

Abrasive resistance in Bond's apparatus

The analysis of resistance against wear in free abrasive was performed using Bond's drum apparatus. It is a device with free abrasive particles. A significant advantage of this device lies in the simulation of abrasive erosive wear which occurs in technical praxis.

The test objects numbering two, four or eight pieces are attached in the rotor ($\omega_2 = 64.4$ s^{-1}). The rotor is placed in a testing drum which rotates in the same direction ($\omega_1 = 7.3$ s^{-1}). The wear was evaluated at the interval of 30, 45, 60, 120 and 240 minutes. After each interval, the abrasive was replaced. An abrasive with higher rate of wear was chosen for the test: a stone fraction with 8 to 16 mm grain size. The sharp edges of this agent guarantee considerable abrasive stress.

The resulting weight loss values from Bond's apparatus are shown in Fig. 7. As is evident from the measured values, the highest abrasive wear was recorded at the introduction of a new fraction in the abrasive. This can be explained by the sharpness of the new fraction.

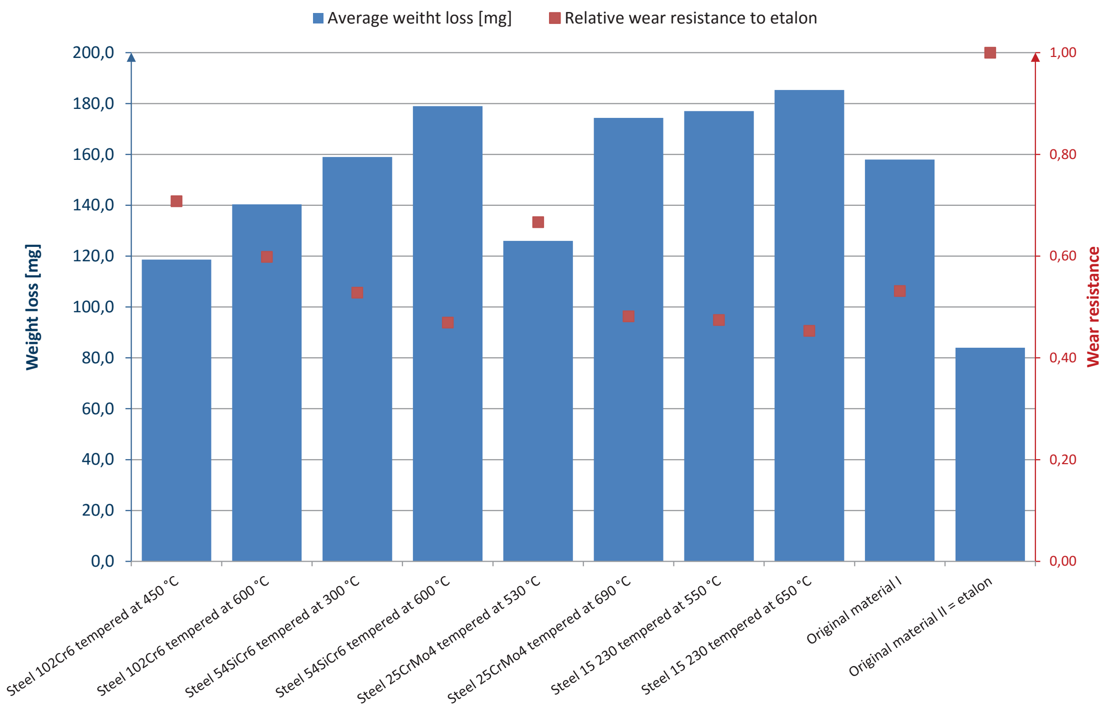
DISCUSSION

Heat treatment has a profound effect on the hardness, toughness and other mechanical properties of steel materials. The present publication is focused on the analysis and possibilities of heat treating steel for the production of machine components which come into direct contact with the soil profile. Abrasive wear is also the main cause of malfunctions in technical praxis (Doubek *et al.*, 2011, Suchánek *et al.*, 2007, Čičo *et al.* 2012)

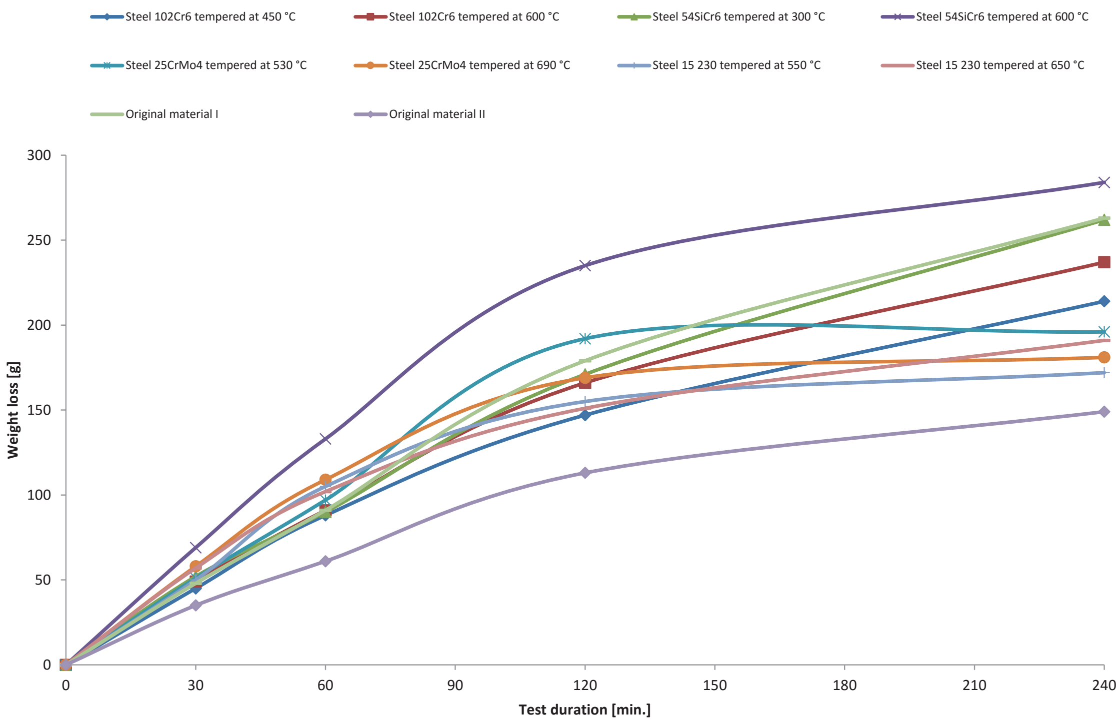
Laboratory tests of abrasive wear have a considerable explanatory power when comparing wear within a certain group of tested materials. Since the conditions are precisely defined, there is only ever one specific stress (wear) environment present. Authors Filípek and Březina primarily recommend analysis of abrasive wear in laboratory conditions, secondarily to choose an appropriate microstructure of the material for field experiments. In practice, however, a combination of different types of wear at the same time occurs. This concerns mostly a combination of abrasive and erosive wear. For this reason, tests in Bond's apparatus were

VI: *Microhardness values of individual structural phases of the tested materials*

Steel used	Martensite[HV]	Sorbite[HV]	Bainite[HV]	Carbides[HV]	HRC hardness
102Cr6 tempered at 600 °C	942	–	–	1187	48
54SiCr6 tempered at 600 °C	886	–	620	–	42
25CrMo4 tempered at 690 °C	852	562	–	–	47
15 230 tempered at 650 °C	–	511	–	–	39
Original blade I	–	493	635	–	37
Original blade II	915	–	641	–	44



6: *Wear on abrasive cloth*



7: *Representation of weight losses during the Bond's apparatus test* also performed, where a combination of multiple abrasive influences takes place.

The initial indicator of a material's resistance against abrasive wear is its hardness. However, it is important to note that the chemical composition of the steel and its heat treatment are also important. The results from the experiments on Charpy's hammer have shown that 102Cr6 steel possesses very low toughness. The material has shown the lowest values of energy required to break the test object (ca 14 J/cm^2).

Low toughness is caused by inner microstructure, which is formed by carbides extracted in a metal matrix. Also authors Liška and Filípek (2012) state that these materials are not suitable for soil processing machine parts. However, it is a material with the same microstructure in the whole profile, not for example a hard-metal weldment. Geometry of soil processing tools (blades or chisels) are also important.

The highest toughness value was recorded on the original material I (ca 45 J/cm^2) which is correlated by total hardness of 37 HRC units, as well as by the sorbitic-baintic structure itself. The commercially supplied material of original blade II, however, shows an entirely different consistency. The predominantly martensitic structure achieves higher hardness (44 HRC) but the material itself requires only 25 J/cm^2 for the test rod to be broken. This alone is enough to make the material unsuitable for tilling of soil with higher skeleton content. However, based on the analysis on the abrasive cloth, the material possesses excellent abrasive resistance, which is ca 2× higher than in original blade I. In the tested steel grade 102Cr6, 54SiCr6 and 25CrMo4, ČSN 15 230 steel materials, similar weight losses occurred as in the original blade I. Based on the values measured, tempering temperatures of above 500 °C are recommended.

During tests in Bond's apparatus, these materials even showed lower weight losses than the original material from plough blade I. From the practical perspective, the analysis has considerable explanatory power, since the test consists of a combination of abrasive and erosive stress, which is typical for machines used in tilling. The lowest weight losses were recorded on the material from the original blade II. This result was achieved due to the internal microstructure.

The test results speak favourably of grade 54SiCr6 and 15 230 steel for the production of replaceable parts for tilling. However, heat treatment must be chosen based on the soil edaphon the tools will be used in.

CONCLUSION

Tilling machines are irreplaceable for agriculture. The largest share in the degradation of these machines is held by abrasive wear and the combination of abrasive wear with impacts. For this reason, it is necessary to choose materials which have considerable resistance against abrasive wear while also having good toughness, since tillage leads to excessive impact shocks.

Since the economic demands of replaceable parts in tillage continue to grow, the suitability of the chosen material is the main factor for the production of these components. When using homogenous steel materials, it is vital to always find a compromise between the intensity of abrasive wear and the price demands of the material.

Based on processed laboratory tests, it can be stated the possibility of using tested materials in conditions with an increased abrasive wear. An appropriate heat treatment was also recommended. It is necessary to process this heat treatment on a machine part (plough blade and chisels) and process field tests under real conditions.

It must be further noted, however, that the intensity of abrasive wear is determined by the nature of the soil particles which affect the machinery. For this reason, it is advisable to choose materials which resist not only silica sand particles, but are above all capable of resisting softer, multi-edged soil fractions.

Acknowledgement

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