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DRY-SLIDING WEAR RESISTANCE OF AISI H11-TYPE HOT-WORK TOOL STEEL

OBRABNA ODPORNOST ORODNEGA JEKLA ZA DELO V VROČEM AISI H11 PRI SUHEM DRSNEM KONTAKTU

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This study focused on analyzing the tribological properties of AISI H11-type hot-work tool steel and how these properties depend on the heat-treatment parameters. The investigation focuses on the abrasive wear resistance under different contact conditions and correlations between the mechanical properties and the wear resistance. The results of the experiments show the importance of proper austenitizing- and tempering-temperature selection, thus providing the optimal combination of tool hardness, strength, and toughness. The coefficient of friction under dry-sliding-contact conditions and abrasive wear mode was found to be largely independent of the heat-treatment conditions and more determined by the contact conditions, especially the load. On the other hand, hardness and strength are the dominant mechanical properties controlling the abrasive wear resistance of the hot-work tool steel.

Keywords: hot-work tool steel, friction, sliding wear, mechanical properties

Študija predstavlja analizo triboloških lastnosti jekla za delo v vročem AISI H11 in kako so le-te odvisne od različnih parametrov toplotne obdelave. Predstavljena raziskava se osredotoča na abrazivno obrabno odpornost pri različnih kontaktnih pogojih ter na korelacije med mehanskimi in obrabnimi lastnostmi. Rezultati eksperimentov kažejo na pomembnost izbire pravilne temperature avstenitizacije in temperature popuščanja, ki zagotavlja optimalno kombinacijo trdote, trdnosti in žilavosti orodja. Ugotovljeno je bilo, da je koeficient trenja pri pogojih suhega drsnega kontakta in načinu abrazivne obrabe v veliki meri neodvisen od pogojev toplotne obdelave in veliko bolj odvisen od kontaktnih pogojev, zlasti obremenitve. Izkaže se, da sta trdota in trdnost prevladujoči mehanski veličini, ki nadzorujeta abrazivno odpornost orodnega jekla za delo v vročem.

Ključne besede: orodno jeklo, trenje, mehanske lastnosti materiala

1 INTRODUCTION

Forming tools are exposed to a combination of complex loads during operation in industrial processes, such as wear, plastic deformation and fatigue. These complex loads can result in tool damage and failure. To adequately address the loading and consequently the associated problems, a large set of material properties need to be known, as well as how these properties depend on heat-treatment processes and how they are interrelated. Although the main selection criterion in the tooling industry is hardness, there are also other mechanical properties being equally or often even more important when taking the final application into account. The properties required to successfully characterize tool performance and durability include toughness, strain-hardening exponent, compressive and bending strength.[1–3]

Contact surfaces between two bodies are not ideal, consisting of imperfections, such as surface roughness, inclusions, oxide layers, etc. The same is true for tools, where already very high contact loads and a large degree of plastic deformation lead to high stress concentrations and large amounts of wear. Consequently, a tool's contact surfaces are exposed to a complex loading situation during forming process, including chemical, thermal, mechanical and tribological loadings. These loads mainly come as a consequence of a sliding contact with a work material that undergoes a transformation process, high contact loads and temperatures, which finally result in tool wear. Thus, wear comes as a sum of different mechanisms, comprising crack initiation and propagation, thermal and mechanical fatigue, plastic deformation as well as failures in the form of erosion, corrosion, abrasive or adhesive wear.[4,5]

A very important aspect in the forming and tool industry is tool heat treatment and the selection of a proper heat-treatment procedure and parameters to obtain the best combination of mechanical, thermal, tribological and fatigue properties of the tool. Without proper heat treatment, the quality and functionality of the tool may be degraded to the point where it becomes defective and unusable. A correctly designed heat-treatment process, being dependent on the tool steel chemical composition, ensures that the tool functions according to the design and intent, and that it meets all the performance specifications.[6,7]

The aim of our investigation was to analyse the tribological properties of H11-type hot-work tool steel

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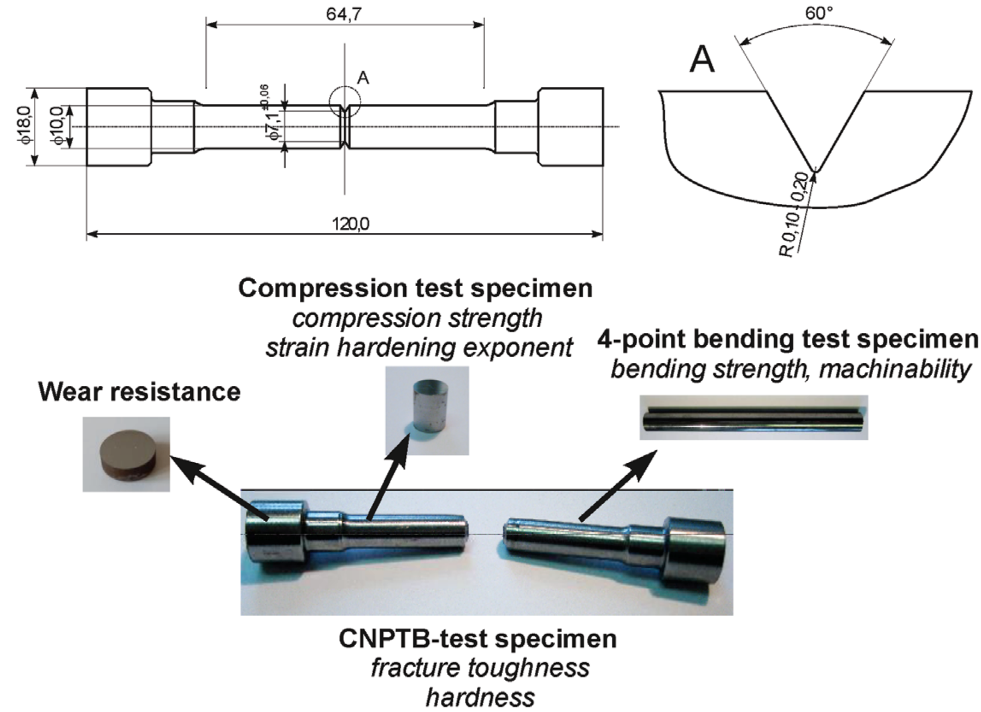

Figure 1: CNPTB master specimen and extracted specimens

and how these properties depend on the heat-treatment parameters. The investigation was focused on the abrasive wear resistance under different contact conditions as well as on the direct correlations between the mechanical properties and the wear resistance, obtained by using a multifunctional, circumferentially notched and fatigue pre-cracked tensile bar (CNPTB) specimen.[8,9]

2 EXPERIMENTAL PART

2.1 Material

The material, used in this research was AISI H11-type hot-work tool steel with a reduced content of silicon (< 0.3 %) and the chemical composition presented in **Table 1**. The material was produced by SIJ Metal Ravne, Slovenia and was delivered in the forged and soft-annealed state, which was then used to machine the CNPTB specimens (**Figure 1**). Ten specimens were prepared for each heat-treatment group and a fatigue pre-crack of about 0.5 mm was produced by rotating-bending loading in the V-notch root. More details are provided in Ref.[8]

Table 1: Hot-work tool steel's chemical composition in *w*/%

Element	C	Si	Mn	Cr	Mo	V
Content	0.36	0.22	0.25	5.02	1.25	0.43

2.2 Heat treatment

After fatigue pre-cracking the specimens were heat treated in an Ipsen VTTC-324-R horizontal vacuum furnace with high-pressure quenching in nitrogen gas at 1.05 bar. After two-step preheating to 850 °C at a heating speed of 10 °C/min, the specimens were finally heated to two different austenitizing temperatures of 990 °C and 1030 °C. After 20 min of holding time at the austenitizing temperature the specimens were rapidly cooled to 80 °C ($l_{800-500}$ = 0.9), followed by two-stage tempering.[8] All the specimens underwent primary 2h tempering at 540 °C, while secondary tempering was performed at 6 different temperatures (550 °C, 570 °C, 590 °C, 600 °C,

Table 2: Heat-treatment groups

	Group A T_A = 990 °C/20 min		Group B T_A = 1030 °C/20 min	
T_{T1} = 540 °C/2h	A1	T_{T2} = 550 °C/2h	B1	T_{T2} = 550 °C/2h
	A2	T_{T2} = 570 °C/2h	B2	T_{T2} = 570 °C/2h
	A3	T_{T2} = 590 °C/2h	B3	T_{T2} = 590 °C/2h
	A4	T_{T2} = 600 °C/2h	B4	T_{T2} = 600 °C/2h
	A5	T_{T2} = 610 °C/2h	B5	T_{T2} = 610 °C/2h
	A6	T_{T2} = 630 °C/2h	B6	T_{T2} = 630 °C/2h

610 °C and 630 °C), resulting in 12 different heat-treatment groups (**Table 2**).

2.3 Mechanical properties

For each heat-treatment group five different mechanical properties were measured, including the fracture toughness, hardness, compressive and bending strengths, and the strain-hardening exponent. Fracture toughness was determined by subjecting the CNPTB specimen to tensile loading at a cross-head speed of 1.0 mm/min until fracture. By measuring the load at fracture the size of the brittle fractured area fracture toughness can then be calculated using Equation 1.[6] After fracturing the CNPTB specimen according to ASTM E1820-18[10] the hardness was measured circumferentially on both fractured parts (2 × 3 measurements) using the Rockwell C method, according to the ISO 6508-1:2016 standard.[10] Afterwards, one part of the fractured CNPTB specimen was used to cut ϕ18 × 8 mm disc for wear testing and ϕ10 × 12 mm cylinder for compressive strength measurement, performed according to the ASTM E9 standard[11] and strain-hardening exponent determined from the slope of the logarithmic form of the true-stress vs. true-strain curve within the plastic region.[12] From another part ϕ5 × 60 mm rod was machined for a 4-point bending test, according to ASTM E290-14.[13]

2.4 Tribological testing

Tribological testing was focused on the abrasive wear resistance, simulated by a pin-on-disc reciprocating-sliding-contact configuration and an Al_2O_3 ball (1750 HV) used as an oscillating counter-body. Thus, all the wear (abrasive wear) was focused on the tool-steel disc specimen. Tests were performed at room temperature under dry-sliding conditions. For each heat-treatment group four different contact conditions were applied. First and second configurations, denoted K1 and K2, involved a frequency of 1 Hz (v_s = 0.01 m/s), a testing time of 7500 s (s = 60 m) and normal loads of 16 N and 40 N, corresponding to the nominal contact pressures of 800 MPa and 1100 MPa. For the third and fourth configurations (K3 and K4), the main difference is in the frequency and sliding speed applied. The frequency was increased to 15 Hz, corresponding to a sliding speed of 0.12 m/s and a testing time reduced to 830 seconds (s = 100 m). The test parameters are given in **Table 3**.

Table 3: Tribological test parameters

	K1	K2	K3	K4
Hertz contact pressure (MPa)	800	1100	800	1100
Normal load (N)	16	40	16	40
Sliding speed (m/s)	0.01	0.01	0.12	0.12
Frequency (Hz)	1	1	15	15
Test time (s)	7500	7500	830	830
Sliding distance (m)	60	60	100	100

3 RESULTS AND DISCUSSION

3.1 Mechanical properties

Table 4 lists all 5 main mechanical properties of the investigated AISI H11-type hot-work tool steel depending on the austenitizing and tempering temperatures applied. The hardness is decreasing with an increased tempering temperature and is increasing with an increased austenitizing temperature. The values range from 49.3 HRC to 39.8 HRC for the lower austenitizing temperature of 990 °C and from 51.8 HRC to 40.7 HRC for the higher austenitizing temperature of 1030 °C.

In terms of fracture toughness, the values are increasing with increased austenitizing and tempering temperatures. The fracture toughness values are in the range 30–87 MPa$\sqrt{m}$ for the lower austenitizing temperature of 990 °C and from 45 to 115 MPa$\sqrt{m}$ for the higher austenitizing temperature of 1030°C. The highest value of 114.9 MPa$\sqrt{m}$ is obtained at the austenitizing temperature of 1030 °C and tempering temperature of 630 °C.

Table 4: Mechanical properties at different heat-treatment conditions

Group	T_A (°C)	T_{T2} (°C)	Hardness HRC	Fracture toughness K_{Ic} (MPa$\sqrt{m}$)	Bending strength s_B (MPa)	Compressive strength s_C (MPa)	Strain-hardening exponent; n
A1	990	550	49.3 ± 1.0	29.9 ± 1.5	4547 ± 50	1967 ± 17	0.45 ± 0.10
A2		570	48.3 ± 1.8	33.6 ± 1.9	4372 ± 30	1916 ± 29	0.44 ± 0.11
A3		590	47.8 ± 0.5	36.0 ± 3.2	4156 ± 25	1791 ± 67	0.45 ± 0.14
A4		600	46.2 ± 0.8	38.1 ± 2.9	4000 ± 19	1740 ± 19	0.43 ± 0.13
A5		610	44.3 ± 0.7	48.0 ± 4.4	3790 ± 13	1652 ± 29	0.45 ± 0.13
A6		630	39.8 ± 0.6	86.9 ± 3.0	3259 ± 27	1450 ± 19	0.59 ± 0.05
B1	1030	550	51.8 ± 0.2	45.6 ± 4.3	4744 ± 36	2063 ± 15	0.42 ± 0.04
B2		570	49.7 ± 1.3	51.5 ± 6.0	4585 ± 14	2056 ± 13	0.49 ± 0.09
B3		590	47.9 ± 1.2	58.4 ± 5.9	4388 ± 16	1904 ± 18	0.49 ± 0.10
B4		600	47.8 ± 0.8	64.2 ± 9.3	4221 ± 18	1834 ± 19	0.45 ± 0.09
B5		610	46.3 ± 0.5	87.6 ± 11.0	3997 ± 20	1732 ± 14	0.44 ± 0.03
B6		630	40.7 ± 1.4	114.9 ± 2.1	3518 ± 96	1562 ± 24	0.55 ± 0.08

Table 5: Tribological parameters under different heat-treatment conditions

Group	T_A (°C)	T_{T2} (°C)	Coefficient of friction; μ (/)				Wear rate; k ($\times 10^{-5}$ mm^3/Nm)			
			K1	K2	K3	K4	K1	K2	K3	K4
A1	990	550	0.78	0.73	0.75	0.67	3.30 ± 0.38	2.59 ± 0.87	2.81 ± 0.31	2.97 ± 0.70
A2		570	0.78	0.73	0.80	0.73	3.60 ± 0.16	2.84 ± 0.25	2.27 ± 0.34	1.70 ± 0.26
A3		590	0.79	0.72	0.79	0.70	3.61 ± 0.27	3.02 ± 0.14	2.18 ± 0.26	2.04 ± 0.31
A4		600	0.78	0.72	0.80	0.71	4.11 ± 0.31	3.40 ± 0.27	2.65 ± 0.28	2.98 ± 0.03
A5		610	0.77	0.73	0.84	0.68	3.80 ± 0.96	3.76 ± 0.11	3.17 ± 0.22	2.86 ± 0.82
A6		630	0.78	0.78	0.81	0.69	4.19 ± 0.33	3.53 ± 0.72	3.44 ± 0.39	4.19 ± 0.34
B1	1030	550	0.82	0.78	0.82	0.69	3.45 ± 0.05	2.97 ± 0.04	1.76 ± 0.35	1.75 ± 0.27
B2		570	0.79	0.73	0.85	0.71	4.40 ± 0.36	2.83 ± 0.15	2.48 ± 0.39	1.59 ± 0.27
B3		590	0.79	0.71	0.76	0.71	3.53 ± 0.51	4.28 ± 0.61	1.26 ± 0.11	1.51 ± 0.34
B4		600	0.82	0.74	0.80	0.70	4.61 ± 0.56	4.78 ± 0.97	3.09 ± 0.28	2.12 ± 0.27
B5		610	0.80	0.70	0.80	0.68	5.19 ± 0.27	4.26 ± 0.69	2.33 ± 0.74	3.49 ± 0.05
B6		630	0.80	0.74	0.87	0.71	4.90 ± 0.43	4.34 ± 0.36	3.94 ± 0.41	3.85 ± 0.11

Both the bending and compressive strengths are increasing in accordance with increased hardness, with higher austenitizing and lower tempering temperatures resulting in higher strengths. The bending strength is in the range 3260–4750 MPa and the compressive strength in the range 1450–2060 MPa (**Table 3**). From the mechanical properties measured only the strain-hardening exponent (n) is almost independent on the of the heat-treatment conditions. For both austenitizing temperatures and tempering temperatures up to 610 °C it shows a constant value of about 0.45. Only at the highest tempering temperature of 630 °C is the value increased over 0.55 (0.55–0.59), as shown in **Table 4**.

3.2 Tribological properties

Tribological properties for each heat treatment group, comprising the average steady-state coefficient of friction and wear rate (wear volume divided by normal load and sliding distance; mm^3/Nm) analysed under four different contact conditions are listed in **Table 5**.

3.2.1 Coefficient of friction

Figure 2 shows the steady-state coefficient of friction for the investigated H11-type hot-work tool steel as a function of tempering temperature and contact conditions for the two applied austenitizing temperatures of 990 °C and 1030 °C. In both cases the coefficient of friction is more determined by the contact conditions, especially the load, than the tempering temperature. For low-load conditions (16 N, 800 MPa; K1 & K3) the steady-state coefficient of friction is in the range 0.77–0.82 and for high-load conditions (40 N, 1100 MPa; K2 & K4) in the range 0.67–0.78, with a higher sliding speed (K4) provoking a further drop in friction. However, in terms of heat-treatment conditions, the investigated tool steel in general shows a negligible increasing trend in the coefficient of friction under dry-sliding abrasive wear conditions with increased austenitizing and tempering temperatures, with the difference being less than 5 %.

3.2.2 Wear rate

Wear rates for the investigated H11-type hot-work tool steel austenitized at two different temperatures are

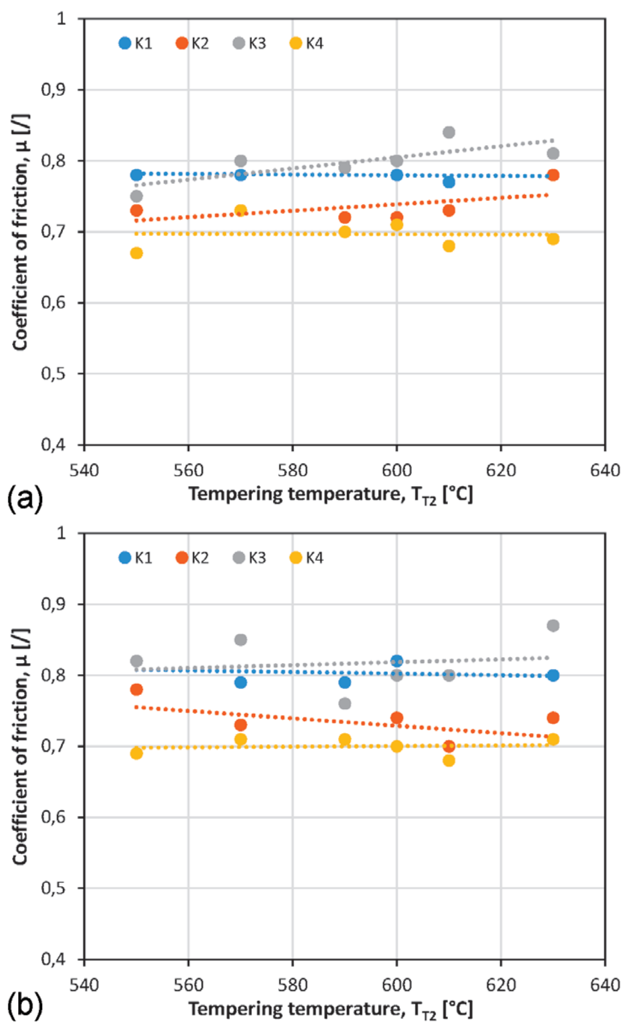

Figure 2: Influence of tempering temperature and contact conditions on steady-state coefficient of friction for: a) austenitizing temperatures of 990 °C and b) 1030 °C

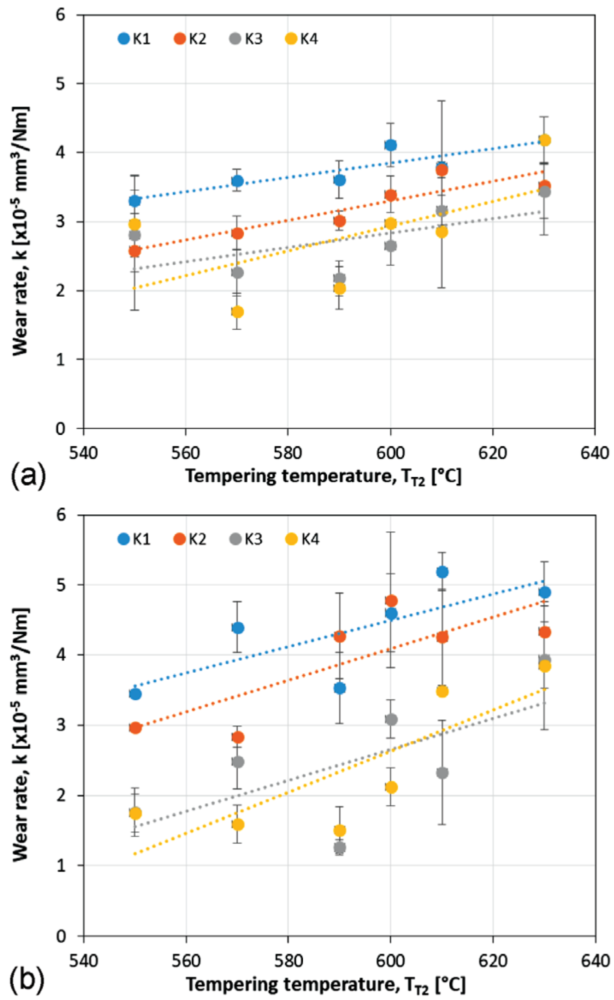

Figure 3: Influence of tempering temperature and contact conditions on wear rate for: a) austenitizing temperatures of 990 °C and b) 1030 °C

shown in **Figure 3**. In all cases abrasive wear was the prevailing wear mechanism, accompanied by minor adhesive wear, as exemplified in **Figure 4**. Furthermore, for both austenitizing temperatures and all four contact conditions the wear rate increases with tempering temperature. However, the rate of increase intensifies with higher austenitizing temperature, which also results in higher wear rates, especially for low-sliding-speed conditions, as shown in **Figure 3**. For a lower austenitizing temperature of 990 °C (**Figure 3a**) the wear rate under low-sliding-speed conditions (v_s = 0.01 m/s; K1 & K2) ranges between 2.6 and 4.2 × 10^{-5} mm^3/Nm and between 2.0 and 3.5 × 10^{-5} mm^3/Nm under high-sliding-speed conditions (v_s = 0.12 m/s; K3 & K4). For a higher austenitizing temperature of 1030 °C (Figure 3b) the wear rate under low-sliding-speed conditions (K1 & K2) is 3.0–5.0 × 10^{-5} mm^3/Nm and under high-sliding-speed conditions (K3 & K4) 1.2–3.5 × 10^{-5} mm^3/Nm.

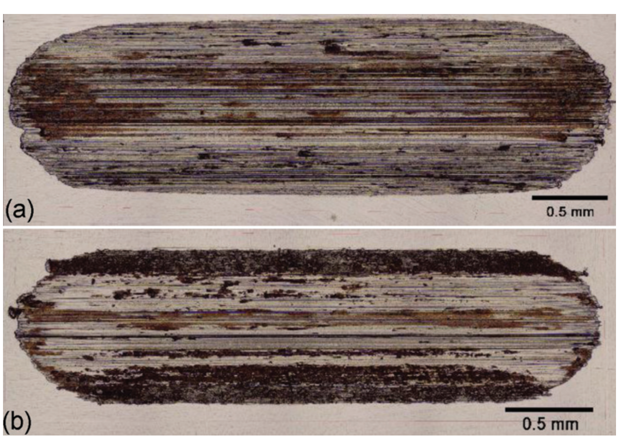

Figure 4: Typical wear scars; a) A6, p_H = 1100 MPa, v_s = 0.01 m/s; b) A6, p_H = 800 MPa, v_s = 0.12 m/s

3.3. Correlations – coefficient of friction

3.3.1 Friction vs. hardness

The dependence of the coefficient of friction of the investigated H11-type hot-work tool steel on the hardness obtained by different heat-treatment regimes (**Table 2**) is shown in **Figure 5**. In general, under dry-sliding conditions and dominant abrasive wear coefficient of friction of the investigated tool steel is more-or-less independent of the hardness. Only for low-load and high-sliding-speed conditions (K3), with intensified adhesive wear component (**Figure 4b**), is the coefficient of friction reduced with hardness, although the drop is in the range of just 5–10 % over the hardness range 39–52 HRC.

3.3.2 Friction vs. fracture toughness

Similarly, as for hardness, the coefficient of friction of the investigated hot-work tool steel is in general independent of the fracture toughness (**Figure 6**). Again, the exception is low-load and high-sliding-speed conditions

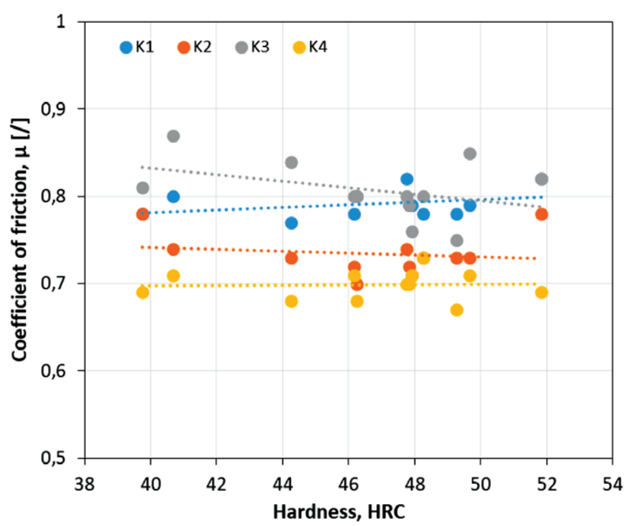

Figure 5: Dependence of the investigated hot-work tool steel coefficient of friction on hardness under dry-sliding contact and different contact conditions

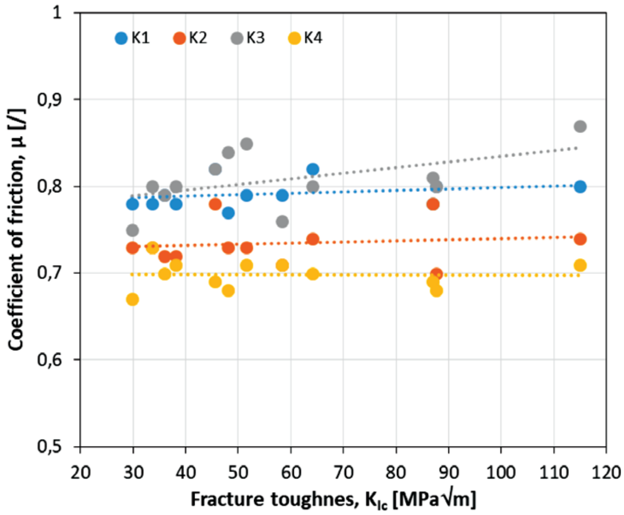

Figure 6: Dependence of the investigated hot-work tool steel coefficient of friction on fracture toughness under dry-sliding contact and different contact conditions

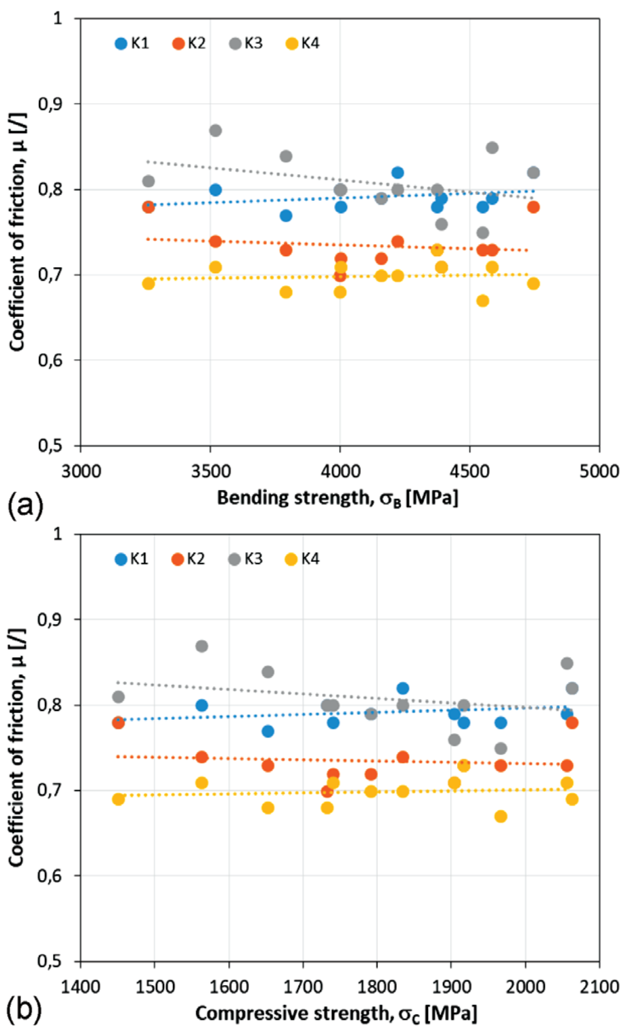

Figure 7: Dependence of the investigated hot-work tool steel coefficient of friction on bending and compressive strength under dry-sliding contact and different contact conditions

(K3), with the coefficient of friction showing an increasing trend with a higher fracture toughness.

3.3.3 Friction vs. strength

As expected, the coefficient of friction follows the same dependency on bending and compressive strength (**Figure 7**) as observed for hardness, being independent of the dry-sliding-contact conditions, promoting abrasive wear and showing a decreasing trend with increased strength as the adhesive-wear component starts to dominate.

3.3.4 Friction vs. strain-hardening exponent

In terms of the strain-hardening exponent *n* (**Figure 8**) the coefficient of friction is independent for very mild, low-load, low-sliding-speed (K1) and very harsh, high-load, high-sliding-speed (K4) conditions. However, it increases with *n* when mixed contact conditions are applied (high/low; K2 & K3). For low-load, low-siding-speed conditions (K1) the material is in pure elastic regime and for high-load, high-sliding-speed conditions (K4) in the severe plastic regime. On the other hand, in the K2 and K3 case the elasto-plastic regime takes place with effective strain-hardening behaviour of the material in the tribological contact.

3.4 Correlations – Wear rate

3.4.1 Wear rate vs. hardness

Figure 9 represents the correlation between the investigated AISI H11-type hot-work tool steel dry-sliding-wear resistance and hardness for 4 different contact conditions. For all contact conditions the abrasive wear resistance improves with hardness. However, the effect of hardness on the wear-resistance improvement is more pronounced for the high sliding speed conditions (K3 & K4), with the wear rate being reduced by up to 60 % within the investigated working hardness range

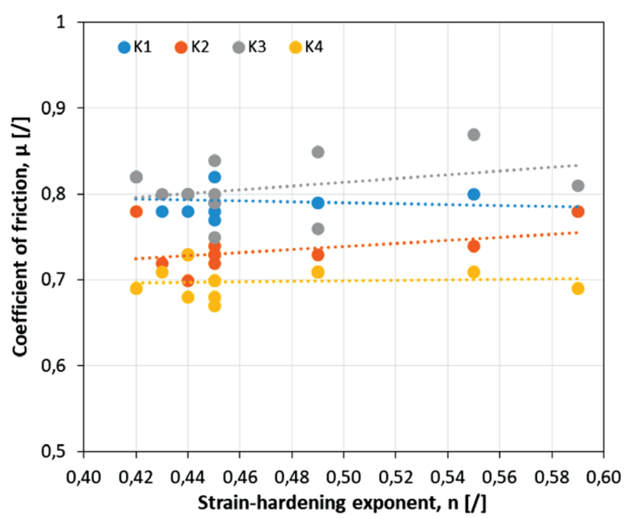

Figure 8: Dependence of the investigated hot-work tool steel's coefficient of friction on strain-hardening exponent under dry-sliding contact and different contact conditions

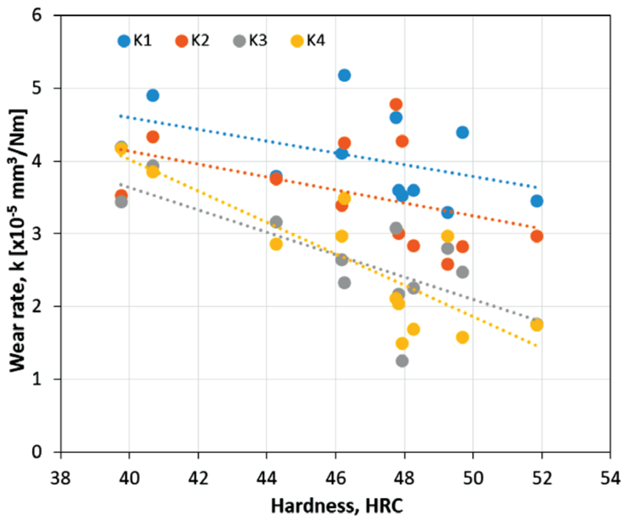

Figure 9: Dependence of the investigated hot-work tool steel's wear rate on the hardness under dry-sliding contact and different contact conditions

(38–52 HRC), as compared to only about 20 % under low-sliding-speed conditions (K1 & K2).

3.4.2 Wear rate vs. fracture toughness

The dependence of the investigated hot-work tool steel's dry-sliding wear resistance on the fracture toughness is shown in **Figure 10**. In contrast to the hardness, the increased fracture toughness results in a similar dry-sliding wear-rate increase, regardless of the sliding speed and load applied. The increase in the fracture toughness from 30 MPa√m to 115 MPa√m resulted in 60–70 % higher wear rates, as shown in **Figure 10**.

3.4.3 Wear rate vs. fracture toughness

Figure 11 shows the dependence of the investigated hot-work tool steel's dry-sliding wear rate on the bending and compressive strengths. In accordance with the

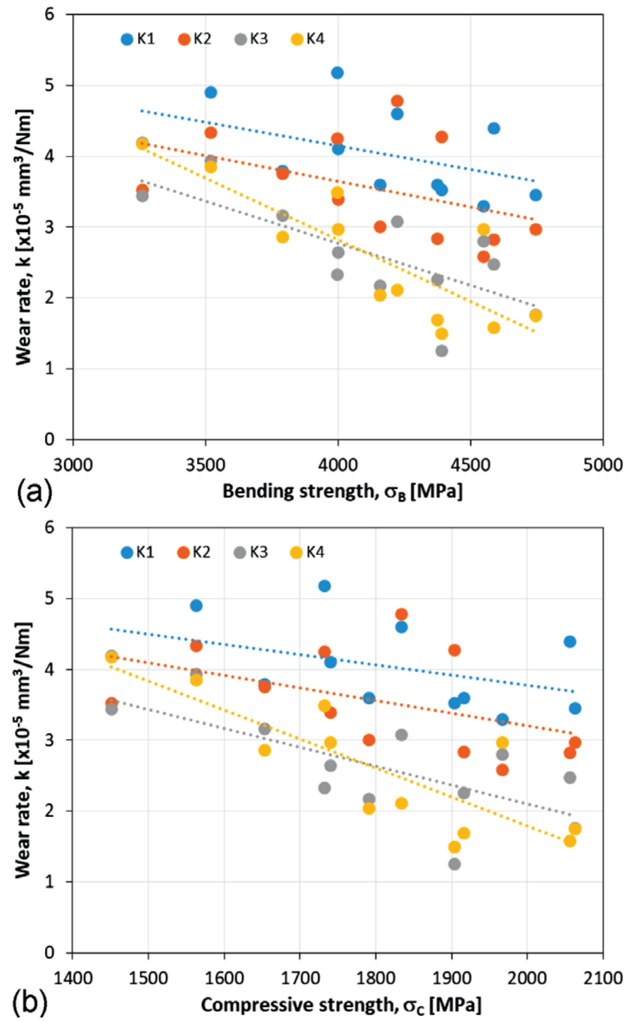

Figure 11: Dependence of the investigated hot-work tool steel's wear rate on bending and compressive strength under dry sliding contact and different contact conditions

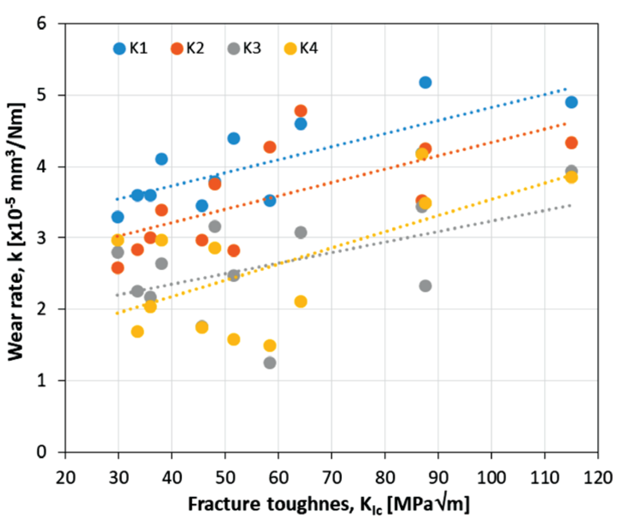

Figure 10: Dependence of the investigated hot-work tool steel's wear rate on the fracture toughness under dry-sliding contact and different contact conditions

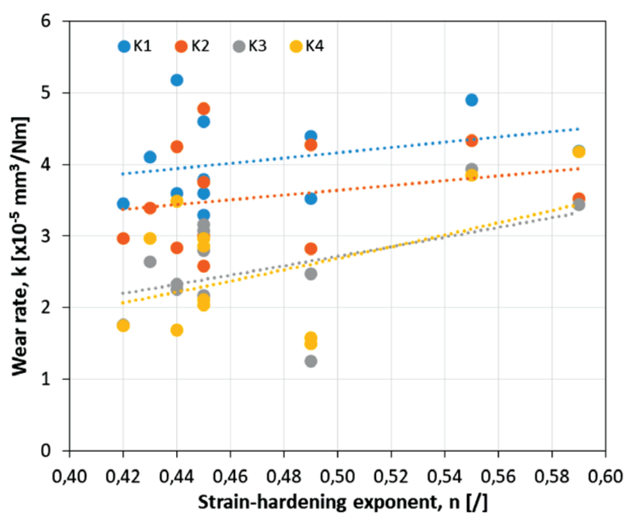

Figure 12: Dependence of the investigated hot-work tool steel's wear rate on strain-hardening exponent under dry-sliding contact and different contact conditions

hardness-strength relationship the wear resistance improves with the bending and compressive strengths in the same manner as with hardness (see **Figure 9**). An increase in the bending and compressive strengths of about 50 % provides 20–25 % better dry-sliding wear resistance of the investigated AISI H11-type hot-work tool steel when operating under low-sliding-speed conditions and almost 50 % under more severe, high-sliding-speed conditions, as shown in **Figure 11**. Those results reveal the hardness as the dominant property when it comes to the abrasive wear resistance of hot-work tool steels.

3.4.4 Wear rate vs. strain-hardening exponent

In terms of strain-hardening exponent (**Figure 12**) the wear rate under dry-sliding contact conditions increases with its increase, again high sliding speed conditions resulting in stronger increase rate (60 % vs. 10 %).

4 CONCLUSIONS

Aim of this study was to analyse the tribological properties of AISI H11-type hot-work tool steel under different dry-sliding contact conditions with prevailing abrasive wear and to correlate its friction and wear performance with the mechanical properties, varied by applying different heat treatments (i.e., austenitizing and tempering temperature). The main results of the investigation can be summarized in the following conclusions. By increasing the austenitizing temperature an increase in all mechanical properties, including hardness, toughness and strength, is obtained. A higher tempering temperature, on the other hand, increases the toughness while it results in drop in hardness and strength. Therefore, choosing the proper austenitizing and tempering temperatures provides optimal combination of tool hardness, strength and toughness. In terms of tribological properties the coefficient of friction under dry-sliding contact conditions and abrasive wear was found to be largely independent of the heat-treatment conditions. It is more determined by the contact conditions, especially the load than the austenitizing and tempering temperature. However, the wear rate increases with higher tempering temperature, while a higher austenitizing temperature intensifies this dependency, especially for high-sliding-speed conditions. A mechanical-tribological properties correlation analysis revealed the coefficient of friction as being more-or-less independent of the mechanical properties within the working hardness range and dominant abrasive wear. However, under low-load, high-sliding-speed conditions and intensified adhesive wear component coefficient of friction is reduced by hardness and strength. Also, the contact conditions promoting material elasto-plastic behaviour in the contact (low load, high sliding speed, and high load, low sliding speed) will result in a reduced coefficient of friction with higher hardness and strength and thus lower toughness and strain-hardening exponent. An increase in the hardness and strength leads to increased abrasive wear resistance under dry-sliding contact conditions, with improvement being more pronounced for high sliding speed and thus higher contact-temperature conditions. Fracture toughness has the opposite effect, reducing the abrasive wear resistance at a similar rate, regardless of the contact conditions. Therefore, hardness and strength of the material are the dominant mechanical properties controlling abrasive wear resistance of the hot-work tool steel.

5 REFERENCES

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