Piotr KOSTENCKI*, Piotr BOROWIAK*

TEMPERATURE OF PLOUGHSHARE MATERIAL IN THE COURSE OF PLOUGHING

TEMPERATURA MATERIAŁU LEMIESZA PŁUŻNEGO W CZASIE ORKI

Key words:

ploughshare, friction, temperature

Słowa kluczowe:

lemiesz płużny, tarcie, temperatura

Abstract

The change of temperature of subsurface layer material of ploughshare, occurring in the course of fine sandy loam (8% moisture and temperature 15.3°C) cultivation, done with bed making plough, was determined. Measuring system with 10 temperature sensors built in the ploughshare material was used in the research. Temperature value was registered with frequency of 1 Hz. The increase of temperature of subsurface layer of ploughshare blade material used in soil was fast – time of temperature stabilization was, depending on location the place of measuring from 17 to 43 s. In the course of ploughing the most

* West Pomeranian University of Technology Szczecin, Faculty of Environmental Management and Agriculture, Department of Agriculture Engineering Systems, ul. Papieża Pawła VI nr 1, 71-459 Szczecin, Poland, e-mail: piotr.kostencki@zut.edu.pl, piotr.borowiak@zut.edu.pl.

heated was the initial area of the attack of landslide part of ploughshare blade and area adjacent to field edge – from 42.6 to 47.3°C. The temperature of material of trapezoid part of ploughshare blade was 26.6 to 29.7°C. In the conditions of the conducted measurements the rate of cooling of the subsurface layer of ploughshare blade material as the result of its cooling was 0.007 to 0.028$°C \cdot s^{-1}$ while plough was not working, however while making U-turns was from 3 to 7 times higher. In the places where the material of ploughshare blade was more heated the rate of cooling was of course higher. Faster cooling of ploughshare blade during U-turns was probably the result of intensified cooling induced by plough movement in the air.

INTRODUCTION

The wear and tear of working elements of tools cultivating soil, usually produced from various types of steel, is the consequence of abrasive wear during the course of their movement in abrasive mass containing hard particles, mainly quartz. In the process these elementary methods of wear, caused by interaction of abrasive grain on material surface layer of the element are micro cuttings, scribing, ridging and micro fatigue **[L. 1, 2]**. The wear and tear process usually takes place in a mixed way, containing all forms of the mechanical reaction of abrasive grains on element material. It is caused by various shapes and dimensions of soil grains **[L. 3]**, different values of their pressure on the surface of the element and different force systems restraining soil grains by adjoining particles. Of course, this process is also determined by the properties of steel, which the elements are made from **[L. 4]**, the state of soil in which they are being used, and exploitation factors such as speed and work depth. The result of wear, however, is the change of the geometry of elements leading to loss of the useful functions that they are supposed to fulfil.

The process of the wearing of the elements working in soil is characterized by large complexity, because it is determined by number of mechanisms **[L. 5]**, which might be supported by additional factors connected to elements work environment. Such factors are the presence of substances taking part in adsorption or chemisorption (influencing the decrease of mechanical strength of surface layer of material), substances corrosively active (affecting the material chemically or electrochemically), and the presence of hydrogen, which is absorbed into steel causes lowering of its mechanical strength **[L. 6, 7]**. In the research conducted in laboratory conditions on influence of hydrogen in steel on lowering its resistance to abrasive wear was confirmed **[L. 8, 9]**.

In the research concerning the wear and tear of elements of agricultural machines working in soil, the increase of their temperature caused by friction in soil taking place on working surfaces is not included. The general increase of the temperature of the material of elements is the result of friction and wear occurring in micro areas of soil grains' contact with material of elements, in which the value of temperature might be high (it was ascertained that in case of boundary friction occurring in typical kinematic pair of machine, that is, in slide bearings and gear wheels, where the temperature of vertexes of irregularity being in contact might be even higher than 1000°C **[L. 10, 11]**). Thanks to the high thermal conductivity of steel, part of the heat emitted in the zones of mechanical influence of soil grains is rapidly spread in the volume of material causing a general increase in the temperature of elements **[L. 12, 13, 14]**. The presence of high temperature in the areas of friction and the wearing of element materials, structural changes in steel **[L. 15]** used for their production could occur, and the local temperature and pressure and the reaction of the soil components would create a complex tribological layout.

The aim of this research was the determination of the temperature of subsurface layer of ploughshare material induced by friction in soil in the course of ploughing.

METHODS OF RESEARCH

To measure the temperature of subsurface layer of the material of a ploughshare, a sensor system mounted in the element material was used. The sensor arrangement is presented in **Figure 1**. In this figure the arrangement

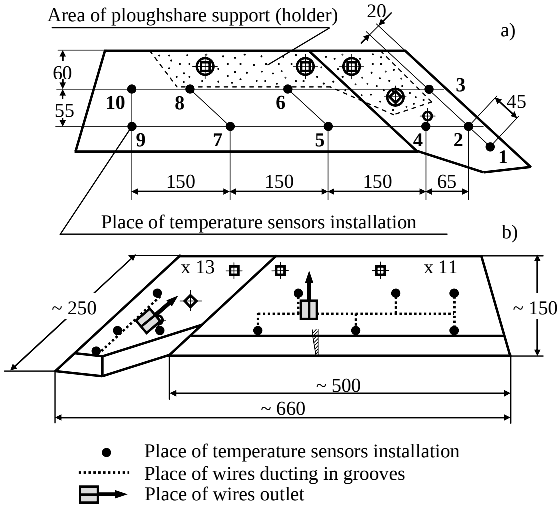

Fig. 1. Arrangement of temperature sensors, places of wire routing and their outlets and overall dimensions of ploughshare: a – ploughshare presented from the side of working surface, b – ploughshare presented from the opposite side of the working surface

Rys. 1. Rozmieszczenie czujników temperatury, miejsca prowadzenia przewodów i miejsca ich wyprowadzenia oraz gabarytowe wymiary lemiesza: a – lemiesz przedstawiony od strony powierzchni roboczej, b – lemiesz przedstawiony od strony przeciwnej do powierzchni roboczej of grooves leading wires connecting sensors with power and measuring system, the place of wires' outlet, and the overall dimensions of ploughshare are presented. In the conducted research, a ploughshare with divided construction was used consisting of an independent share point and trapezoidal part designed for ploughshares of Lemken Company, which was mounted on the fourth body of eight-furrow field ploughshare Vari-Turmalin 9 produced by Lemken Company, which was equipped in the body of Dural BS 42 with openwork moldboards. Both elements of the plough were made from the same steel containing a micro additive of boron.

A single temperature sensor built-in ploughshare is presented in **Figure 2**. Temperature sensors LM35DZ, which have the shape of a flattened cylinder, and the dimensions of ø5 x 3.8 mm and 5 mm height, were used in the measuring system. According to producer, their measuring range is from 0 to 100^{o}C, accuracy typical error ± 0.6^{o}C, supply voltage - from 4 to 30 V.

The sensors have linear calibration characteristics for Celsius degrees – 10 mV/°C.

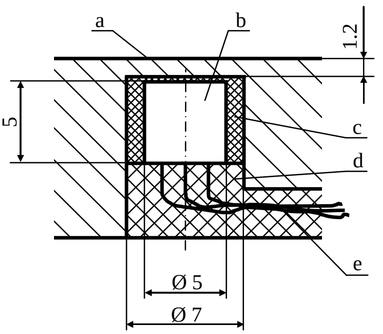

Fig. 2. Temperature sensor built in ploughshare: a – working surface of ploughshare, b – temperature sensor, c – thermal conductive adhesive, d – two-component epoxy adhesive, e – temperature sensor connection with power supply and meter circuit

Rys. 2. Czujnik temperatury wbudowany w lemiesz płużny: a – powierzchnia robocza lemiesza, b – czujniki temperatury, c – klej termoprzewodzący, d – dwuskładnikowy klej epoksydowy, e – połączenie czujnika temperatury z zasilaniem i układem pomiarowym

Temperature sensors were mounted with thermal conductive adhesive in a blind hole with flat bottom made in the ploughshare on the opposite side of the working surface. Between the working surface of ploughshare and bottom of the hole there is a 1.2 mm thick wall. Arctic Alumnia Thermal Adhesive with a thermal conductivity of 7.5 W·mK^{-1} and a working range from –40 to +150^{o}C was used to mount the sensors. The rest of holes were filled with a two-component epoxy adhesive, which was supposed to protect the sensors from moisture and mechanical damage. The wires connecting the sensors with the measuring circuit and power supply were laid at the bottom of the 3 × 3 mm grooves, which were made in ploughshare also on the side opposite to working surface. The wires were protected from eventual mechanical damage by falling out of the grooves with two-component epoxy adhesive. The place of the outlet of wires were picked in such a way that they would be in the area of "air hollow," which forms just behind the ploughshare in the course of its movement in soil. In the places of the wires' outlet, connectors were screwed into ploughshare in blind, threaded holes. The task of the connectors was to enable the mounting covers (in the form of pipe made from helically wounded wire) in which the wires were led out over the soil surface. The covered wires were mounted with band clips to the plough's standard body. Then, they were guided (without cover) along the frame of the plough to the cabin of tractor in which the rest of elements of meter circuit (**Fig. 3**) were installed. The meter circuit consisted, among others, of Personal Daq/56 converter to convert analogue voltage signals generated by temperature sensors into digital signals for the mobile computer with Personal Daq View Plus program, registering the results of measurements with 1 Hz frequency. The length of the wires applied in the measurement circuit was 14 m. A voltage measuring system was used in the research in which current intensity was so small that the length of the used wires had no influence on the value of the voltage signal (it was verified experimentally). The measuring circuit enabled the determination of ploughshare material temperature with an accuracy of 0.1°C.

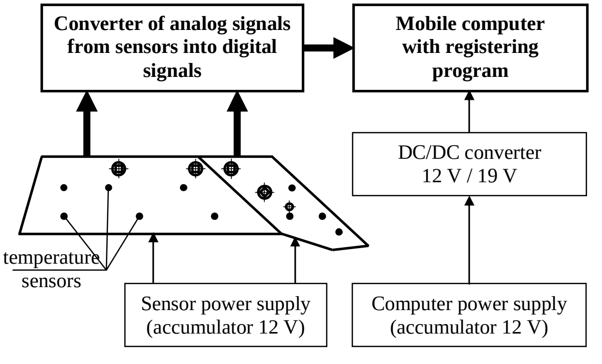

Fig. 3. Block diagram of measuring circuit
Rys. 3. Schemat blokowy układu pomiarowego

The research was conducted in 2015 in the course of soil cultivation works in the agricultural farm Texas Ranch Company located in West Pomeranian Voivodeship. Parameter values characterizing conditions of ploughing conducted during the measurements are presented in **Table 1**. Soil graining was determined for cumulative trial by the Casagrande hydrometer method with Prószyński modification; the participation of gravel and humus content were also determined for cumulative soil trial, respectively, with the sieve method and based on the content of organic carbon determined with the use of Costech CHNS analyzer; the moisture and density of soil was determined by the dry – weight method applying Kopecky cylinders, volume 100 cm^3; firmness of soil was measured with firmness spring meter produced by Instytut Agrofizyki PAN with the use of taper - base diameter 16.6 mm and apex angle 30^o; the value of shearing stress of soil was measured with Geonor, type Vane Tester H – 60 rotational shearer finished with a cross having a width was 20 mm and height 40 mm.

Table 1. Characteristics of operating conditions of the elements
Tabela 1. Charakterystyka warunków pracy elementów

<table>
<tr><th colspan="2">Quantity</th><th>Soil layer</th><th colspan="2">Working conditions of elements</th></tr>
<tr><td colspan="2">Soil type**</td><td rowspan="12">ploughing layer</td><td colspan="2">silt (Si)</td></tr>
<tr><td rowspan="9">Soil graining and grain size group*</td><td>fraction, mm</td><td>part, %</td><td rowspan="9">fine sandy loam (FSL)</td></tr>
<tr><td>2 ≥ d > 1</td><td>1.5</td></tr>
<tr><td>1 ≥ d > 0.5</td><td>5.9</td></tr>
<tr><td>0.5 ≥ d > 0.25</td><td>10.1</td></tr>
<tr><td>0.25 ≥ d >0.1</td><td>12.7</td></tr>
<tr><td>0.1 ≥ d > 0.05</td><td>24.5</td></tr>
<tr><td>0.05 ≥ d > 0.02</td><td>17.7</td></tr>
<tr><td>0.02 ≥ d > 0.002</td><td>21.7</td></tr>
<tr><td>d ≤ 0.002</td><td>5.9</td></tr>
<tr><td colspan="2">Participation of gravel in soil, %</td><td colspan="2">1.6* (3.1)**</td></tr>
<tr><td colspan="2">Participation of humus, %</td><td colspan="2">2,15</td></tr>
<tr><td colspan="2">Current soil moisture,
% of weight</td><td>5–15 cm
15–30 cm</td><td>9.1
7.3</td><td>s = 1.6
s = 0.6</td></tr>
<tr><td colspan="2">Volume density
of soil, g·cm^{-3}</td><td>5–15 cm
15–30 cm</td><td>1.56
1.43</td><td>s = 0.08
s = 0.07</td></tr>
<tr><td colspan="2">Firmness of soil, kPa</td><td>5–15 cm
15–30 cm</td><td>4282
5297</td><td>s = 1616
s = 1800</td></tr>
<tr><td colspan="2">Shearing stress
of soil, kPa</td><td>5–15 cm
15–30 cm</td><td>92
118</td><td>s = 28
s = 19</td></tr>
<tr><td colspan="3">Ploughing rate, m·s^{-1}</td><td>2.16</td><td>s = 0.02</td></tr>
<tr><td colspan="3">Working depth, cm</td><td>21.5</td><td>s = 2.2</td></tr>
<tr><td colspan="3">Body working width, cm</td><td>47</td><td>s = 1</td></tr>
<tr><td colspan="3">Soil temperature, ºC</td><td>15.3</td><td>s = 0.3</td></tr>
<tr><td colspan="3">Air temperature, ºC</td><td>21.3</td><td>s = 0.9</td></tr>
</table>

s – standard aberration, * acc. to current designation of Polskiego Towarzystwa Gleboznawczego, ** acc. to earlier designation of PTG

Ploughing was done after the rapeseed harvest, on the field with previous crop cultivation. According to the data on the soil-agricultural map silt was cultivated; however, according to current rules of the classification of soil formations **[L. 16]**, the cultivated soil should be classified as fine sandy loam (**Tab. 1**). During the measurements, the soil was characterized by lower moisture that resulted in high values of its cohesion and shear stress at the typical volume density for after harvest state of soil (**Tab. 1**). Time and length of plough work from one side of the field to the other was ca 200 s and 430 m. In the course of the research, the temperature of ploughshare material was measured during the ploughing and during U-turns. During the cooling process of ploughshare while the plough was idle, the temperature was also measured.

RESULTS OF THE RESEARCH AND THEIR ANALYSIS

Figures 4 and **5** illustrate the change of temperature in chosen measuring points in the subsurface material layer respectively for the landside and trapezoidal part of the ploughshare evoked by the process of soil friction on the surface of the element during the working of the plough.

In the figure, dashed lines mark the beginning and end of soil cultivation, and the dotted line marks the moment in which the temperature of ploughshare material stabilizes. In the landside, the time of reaching this state in relation to beginning of soil cultivation was only 17 s in the place of taking measurements no 1, 34 s at point no 2, 41 s at point no 3 and 43 s at point no 4. However, in the case of the trapezoidal part, it took ca 34 s to stabilize the temperature at the measuring points. Therefore, after a very short time of ploughshare use in soil, stabilization of its material temperature followed. It can be assumed that it resulted from the alignment of the amount of heat supplied to the material in the process of the friction of soil on the surface of the element and given away in the process of cooling.

It must be noted that the increase in temperature of the landslide part of the ploughshare was higher than that of the trapezoidal part. Thus elementary increase of material temperature in the landslide part was higher than in the trapezoidal part and amounted to 1.12 and 0.52 $^{o}C{\cdot}s^{-1}$ respectively, at measuring points 1 and 2 and 0.34$°C{\cdot}s^{-1}$ at points 3 and 4. However, for the measuring places located in the trapezoidal part, this parameter was 0.08$°C{\cdot}s^{-1}$ in measuring point no 5; 0.11$°C{\cdot}s^{-1}$ in measuring point no 7; 0.13$°C{\cdot}s^{-1}$ in points 6 and 8 and 0.14$°C{\cdot}s^{-1}$ in measuring points 9 and 10. It was shown that the loss of thickness of ploughshares in the zone of landslide part is bigger than in the trapezoidal part **[L. 2, 17, 18]**. It can be bound to a higher load from the soil on the working surface of landslides causing more intense usage of the material of the elements. Probably, the higher pressure of soil caused the higher rate of the material of landslide part heating than in trapezoidal part. The elementary

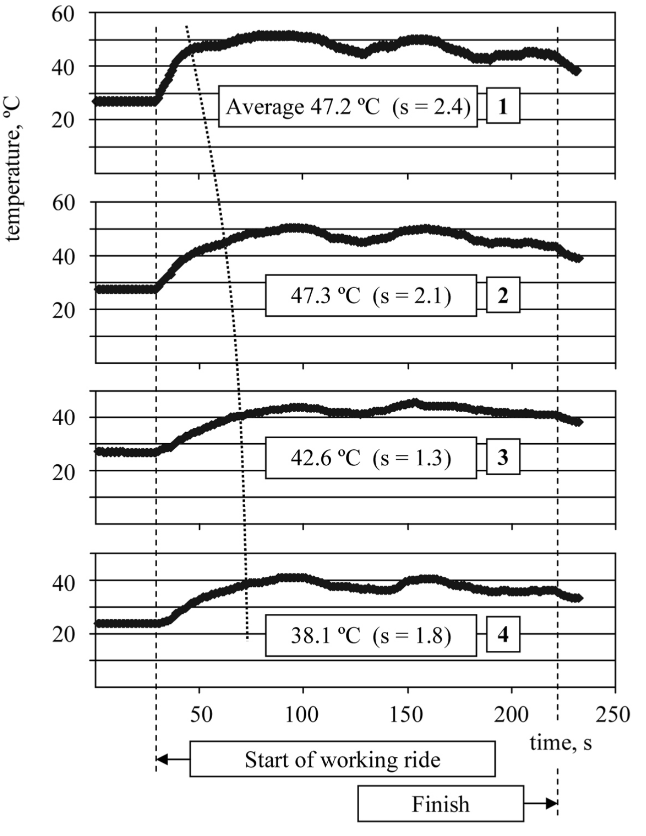

Fig. 4. Temperature at measuring points 1, 2, 3 and 4 in the subsurface layer of the material of landslide part of ploughshare in the course of ploughing

Rys. 4. Temperatura w miejscach pomiarowych 1, 2, 3 i 4 przypowierzchniowej warstwy materiału części dziobowej lemiesza płużnego podczas wykonywania orki

increase of temperature was especially high in measuring point 1 (by about 2.2 times higher than at measuring point no 2; by 3.3 times higher than in points no 3 and 4 and by from 8 to14 times higher than in points of measuring lying on the trapezoid part). It proves that there is a larger load of soil in the landslide part in the area of measuring point no 1.

After achieving the state of relative stabilization, the temperature of subsurface layer of the ploughshare material undergoes slight fluctuations (**Figs. 4** and **5**). It is most observable in case of measuring points placed on landslide part of the element, that is in the area of higher load of the surface of the soil attack on ploughshare. In these places, the difference between the highest and the lowest measured value of temperature was from 5.5 to 6.7°C

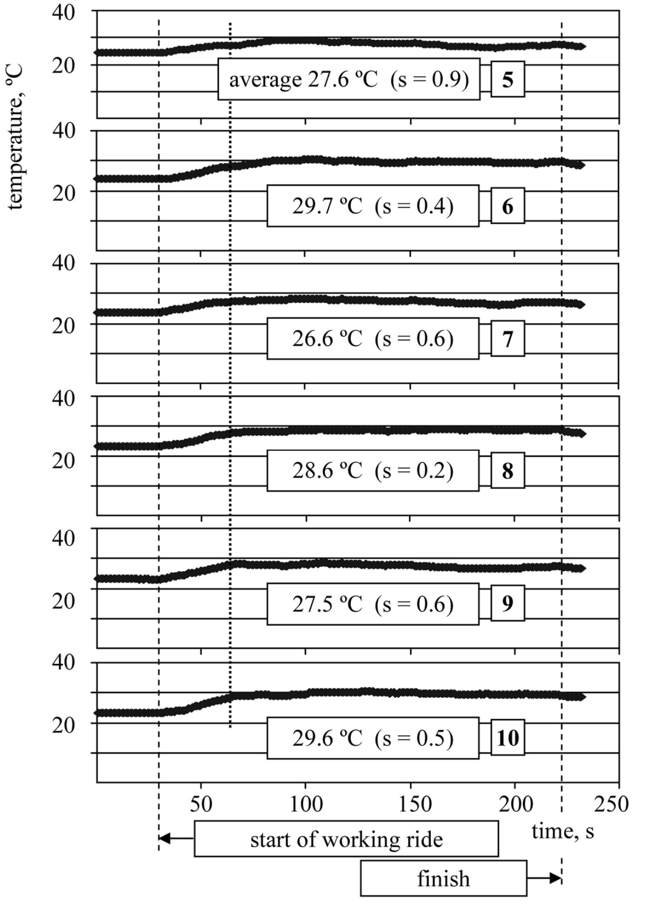

Fig. 5. Temperature at measuring points 5, 6, 7, 8, 9 and 10 in the subsurface layer of material of ploughshare trapezoid part in the course of ploughing

Rys. 5. Temperatura w miejscach pomiarowych 5, 6, 7, 8, 9 i 10 przypowierzchniowej warstwy materiału części trapezowej lemiesza płużnego podczas wykonywania orki

(that is from 12.1 to 14.4% of the average value of temperature). In the trapezoidal part of the ploughshare, the established differences were from 1.2 to 3°C (that is from 4.2 to 10.9% of the average value of temperature). The alleged reason for temperature fluctuations were the changing conditions of conducted ploughing. It seems that the most significant conditions could have been the changes in moisture content, volume density, and the grain size of cultivated soil, projecting the variability of the soil cohesion and shear stress of soil (**Tab. 1**). In addition, fluctuations in moisture content in the soil could have had an influence on the cooling process of the element. The state of the load on the surface attack of the ploughshare is also bound with depth and rate of crop, thus fluctuations of these parameters in the course of measuring could also influence the increase or decrease in the temperature of the ploughshare material.

In the course of soil cultivation, the initial area of the attack of landslide part of ploughshare and area adjacent to the field ridge part - measuring points 1, 2 and 3 (**Fig. 1, 4** and **5**) – had the greatest temperature increases, especially the area of measuring points 1 and 2. In measuring points 1 and 2, the temperature of the ploughshare material was 32°C higher than the soil temperature (15.3°C), and in point 3 by ca 27.3°C (at measuring point no 4, the increase of temperature was lower and was 22.8°C). However, the average temperature of the trapezoidal part of the ploughshare material was ca 1.6 times lower, relative to average temperatures occurring at points 1, 2, and 3. At the established measuring points, the increase in the temperature of the trapezoidal part of the ploughshare relative to soil temperature ranged from 11.3 to 14.4°C. It should be taken into consideration that, at the trapezoidal part of ploughshare, the value of temperature established at the top line of measurement (measuring points 6, 8 and 10) was 2°C higher than at the bottom line of measurement (measuring points 5, 7 and 9). It could have resulted from two reasons – the higher soil load on the trapezoidal part in the top measuring line or reduced element cooling due to the location of measuring points in the neighbourhood of flat holder (**Fig. 1**), which concerns measuring points 6 and 8. Therefore, this small difference in temperature most likely results from a stronger load on the trapezoidal part in the top zone of the measuring line.

The values of ploughshare material temperature are presented in **Figures 4** and 5, including the analysis of mono factor variance in the system of complete randomization, which showed the significance of differences between the averages. To compare the averages, the Tukey test was applied ($\alpha = 0.05$). It was ascertained that average values are in following groups: measuring points 1 and 2; 3; 4; 5, 7, and 9; 8; 6 and 10 do not vary significantly statistically; however, between average values from each group, the difference is significant.

Figure 6a illustrates an example occurring at selected measuring points of a decrease in the temperature of the subsurface material of ploughshare during its cooling, while it was not working. At measuring points 1 and 2, the cooling rate of material (for 30 s time) was ca 0.028 $^{o}C{\cdot}s^{-1}$, at points 3 and 4 – respectively ca 0.019 and 0.018$°C{\cdot}s^{-1}$, and at measuring points from 5 to 10 ranged from ca 0.007 to 0.010$°C{\cdot}s^{-1}$. Of course, the cooling rate of the element depends on the occurring temperature difference and, additionally, it may be intensified by air movement. Thus the given values apply to the certain cooling conditions of the element. In the course of the U-turns of the plough, the decrease in ploughshare material temperature was much faster (**Fig. 6b**). It probably resulted from additional cooling caused by the plough’s movement in

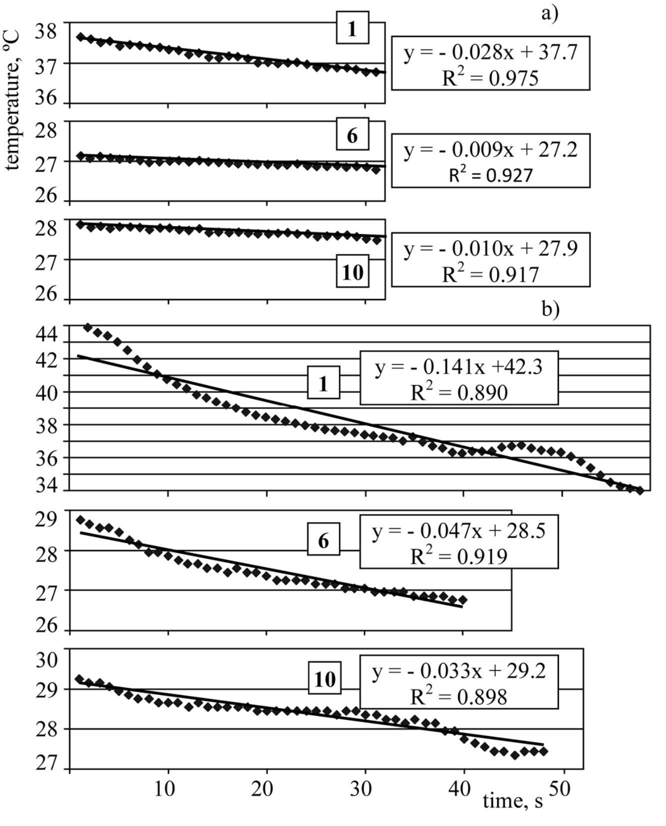

Fig. 6. Decrease in the temperature of the subsurface layer of the material of ploughshare at chosen measuring points in the process of cooling, a) during the plough standstill, b) during U-turn

Rys. 6. Obniżanie temperatury przypowierzchniowej warstwy materiału lemiesza w wybranych miejscach pomiarowych w procesie stygnięcia: a) podczas postoju pługa, b) w czasie wykonywania nawrotu

relation to the air, which was 21.3°C, and hence lower than the temperature of the friction-heated element. During U-turns, the rate of ploughshare material cooling was 3 to 7 times higher than in stationary conditions.

Directional coefficients of linear functions describing the cooling rate of the ploughshare material were compared by the t-Student ($\alpha = 0.05$) test. It was ascertained that, during cooling of the ploughshare while plough was standing, no statistically significant differences in coefficients of regression between measuring points 1 and 2 and 3 and 4 and also between measuring points 5, 6, 8, 9 and 10, which were located on trapezoidal part of the ploughshare occurred. However, during U-Turns, for the data concerning the cooling of the ploughshare at measuring points located on trapezoidal part, t-Student test showed significant differences in the cooling rate of ploughshare material expressed by the coefficient of regression in the vast majority of cases.

Figure 7 presents the change in the ploughshare material temperature at exemplary measuring points, during the four following working conditions of the plough, divided by the time of making U-turns. Similarly as on **Figures 4** and 5, the temperature of element material during its movement in soil in the course of each working mode oscillated around average values. Temperature fluctuations resulted from variable times in the soil and the exploitation conditions of ploughing which was mentioned earlier. However, during U-turns of the plough, the temperature of plough element decreased. Making U-turns was, on average, ca 50 s (from 40 to 70 s).

The cooling of ploughshare material at the time was different for each measuring point. This can be understood by taking into consideration that the material of element does not heat evenly in different zones, and in the areas in which material was heated more, the lowering of temperature caused by cooling was greater. Of course, lowering of ploughshare material temperature was bound to the time of making U-turn. Lowering the temperature of ploughshare material caused by its cooling during U-turn was ca 2°C at measuring points located on the trapezoidal part of the ploughshare to 10°C for measuring points on the landslide part. It should be noted that full cooling of the ploughshare did not take place, which is lowering its temperature to temperature of air. This was caused by short time needed to make U-turns in relation to existing conditions

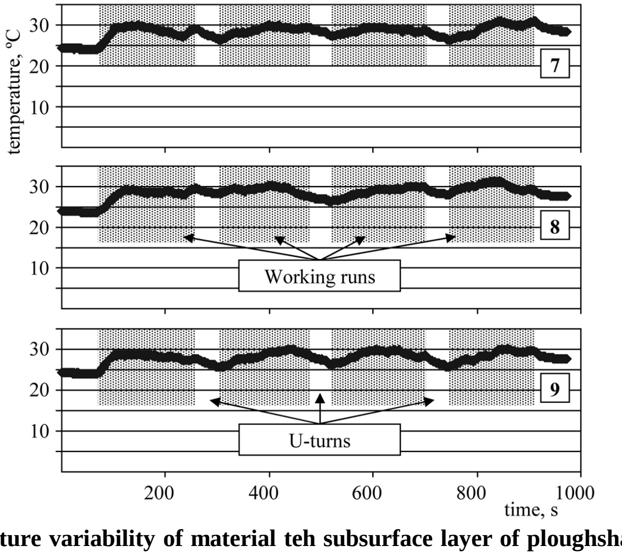

Fig. 7. Temperature variability of material teh subsurface layer of ploughshare at measuring points 7, 8 and 9 during four consecutive working runs of the plough

Rys. 7. Zmienność temperatury przypowierzchniowej warstwy materiału lemiesza płużnego w miejscach pomiarowych 7, 8 i 9 w czasie czterech kolejnych przejazdów roboczych pługa of ploughshare cooling. If ploughing had been done with a reversible plough, the lowering of temperature would have been definitely larger because of the longer cooling time.

SUMMARY

1. The temperature of the material of working elements of agricultural tools used in soil increases in relation to soil temperature. A general increase in the temperature of element materials is the result of friction and wear taking place in contact micro-areas of soil grains with their material. The increase in temperature in the zones of direct reaction with soil grains might be great and influence material properties, which the elements are made from, thus on friction and wear and tear.
2. The used measuring system enables one to register the subsurface layer temperature of a ploughshare in the course of ploughing. The advantage of this system is the ability to record temperature changes occurring during this time. Such measurement probably enables the assessment of friction intensity and wear on the working surfaces of elements. However, it requires experimental confirmation.
3. It was ascertained that the increase in the temperature of the subsurface layer of the material of the ploughshare in soil happens fast. In the conditions of the conducted experiment, the time required for stabilization of its temperature was from 17 to 43 seconds, depending on the location of the measuring point. However, an elementary temperature increase of ploughshare material was contained in the range from 0.08 to 1.12°C$\cdot$s^{-1}, while a higher rate of heating occurred by landslide part of ploughshare which had a higher soil load.
4. In the course of ploughing, the most heated was the initial area of landslide part of ploughshare attack and the area adjacent to the field ridge - from 42.6 to 47.3°C. The temperatures of ploughshare material in this area were (27.3 to 32°C) higher than soil temperature (15.3°C). The temperature of the trapezoidal part ranged from 26.6 to 29.7°C and was 11.3 to 14.4°C higher than soil temperature.
5. In the conditions of conducted measurements, the rate of the cooling of near surface layer of ploughshare material during plough standstill was from ca 0.007 to 0.028°C$\cdot$s^{-1}. While during making U-turns, it was from ca 3.2 to 7.2 times higher. In the places where ploughshare material was more heated, the rate of cooling was also expectedly higher. However, the higher rate of ploughshare cooling in the course of U-turns probably resulted from increased cooling induced by movement of the plough relative to air.

REFERENCES

1. Hebda M., Wachal A. 1980. Trybologia. WNT. Warszawa.
2. Owsiak Z. 1998. Narzędzia skrawające glebę. Zeszyty Naukowe Akademii Rolniczej we Wrocławiu nr 348. Monografie XV. Wydawnictwo Akademii Rolniczej we Wrocławiu.
3. Napiórkowski J., Szczyglak P, Kołakowski K. 2013. Analiza geometrii ziaren glebowej masy ściernej. Inżynieria Rolnicza/Agricultural Engineering, Z. 4 (147) T. 1, s. 237–247.
4. Napiórkowski J., Kołakowski K., Pergoł A. 2011. Ocena zużycia nowoczesnych materiałów konstrukcyjnych stosowanych na narzędzia obrabiające glebę. Inżynieria Rolnicza 5 (130), s. 191–197.
5. Napiórkowski J. 2005. Zużyciowe oddziaływanie gleby na elementy robocze narzędzi rolniczych (rozprawa habilitacyjna). Inżynieria Rolnicza. Nr 12 (72).
6. Zwierzycki W. (red.) 1990. Wybrane zagadnienia zużywania się materiałów w ślizgowych węzłach maszyn. PWN. Warszawa-Poznań.
7. Zwierzycki W. (red.) 2002. Modele prognostyczne korozyjno-mechanicznego zużywania się elementów maszyn. Wydawnictwo i Zakład Poligrafii Instytutu Technologii Eksploatacji. Biblioteka Problemów Eksploatacji. Radom-Poznań.
8. Napiórkowski J. 1997. Wpływ odczynu gleby na intensywność zużycia elementów roboczych. Tribologia. Nr 5–6 (155–156). s. 793–801.
9. Stabryła J., Starczewski L. 2006. Oddziaływanie wodoronośnych składników gleby na zużycie ścierne narzędzi rolniczych. Problemy Eksploatacji. Nr 1 (60). s. 199–206.
10. Hsu S.M., Shen M.C., Klaus E.E., Cheng H.S., Lacey P.J. 1994. Mechanochemical model: reaction temperatures in a concentrated contact. Wear, 175, s. 209–218.
11. Wysokiński K. 1993. Fullereny. Postępy Fizyki, nr 44, s. 339–363.
12. Kostencki P., Stawicki T. 2014. Wzrost temperatury lemieszy płużnych wywołany tarciem gleby podczas ich użytkowania. Tribologia 1 (253), s. 11–25.
13. Kostencki P., Stawicki T. 2015. Temperatura warstwy wierzchniej elementów roboczych narzędzi rolniczych przeznaczonych do uprawy gleby. Część I - Obiekty badań i warunki ich pracy, Kontaktowe pomiary temperatury. Tribologia 2 (260), s. 41–58.
14. Kostencki P., Stawicki T., Sędłak P. 2015. Temperatura warstwy wierzchniej elementów roboczych narzędzi rolniczych przeznaczonych do uprawy gleby. Część II - Pomiary termowizyjne. Tribologia 2 (260), s. 59–73.
15. Blicharski M. 2004. Inżynieria materiałowa. Stal. Wydawnictwo Naukowo-Techniczne. Warszawa.
16. Polskie Towarzystwo Gleboznawcze. Klasyfikacja uziarnienia gleb i utworów mineralnych. 2008. Uziarnienie_PTG_2008.pdf.
17. Sevierniev M. (red.) 1972. Iznos detalej sel´skohozâjstviennyh mašin. Kolos. Leningrad.
18. Kostencki P. 2007. Geometria zużycia lemieszy płużnych użytkowanych w glebach piaszczystych. Problemy Inżynierii Rolniczej 3 (57), s. 49–64.

Streszczenie

Ustalono zmianę temperatury przypowierzchniowej warstwy materiału lemiesza płużnego występującą podczas uprawy gliny drobnopiaszczystej o wilgotności 8% i temperaturze 15,3°C, wykonywanej z zastosowaniem pługa zagonowego. W badaniach wykorzystano układ pomiarowy z 10 czujnikami temperatury wbudowanymi w materiał lemiesza. Wartość temperatury rejestrowana była z częstotliwością 1 Hz. Zwiększanie temperatury przypowierzchniowej warstwy materiału lemiesza użytkowanego w glebie następowało szybko – czas do stabilizacji temperatury wynosił w zależności od lokalizacji miejsca pomiarowego od 17 do 43 s. Podczas orki największemu nagrzewaniu ulegał początkowy obszar powierzchni natarcia części dziobowej lemiesza i obszar przyległy do krawędzi polowej – od 42,6 do 47,3°C. Temperatura materiału części trapezowej lemiesza zawierała się w przedziale od 26,6 do 29,7°C. W warunkach prowadzonych pomiarów tempo ochładzania się przypowierzchniowej warstwy materiału lemiesza na skutek jego stygnięcia wynosiło od 0,007 do 0,028°C·s^{-1} przy postoju pługa, natomiast podczas wykonywania przez pług nawrotów było od 3 do 7 razy większe. W miejscach, w których materiał lemiesza ulegał większemu nagrzaniu, tempo stygnięcia było oczywiście większe. Szybsze ochładzanie się lemiesza podczas wykonywania nawrotów wynikało przypuszczalnie ze wzmożonego chłodzenia wywołanego ruchem pługa względem powietrza.