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Testing the Wear of Cultivat or Coultersre in Forced with Cemented-Carbide Plates

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ABSTRACT : *Three constructional arrangements of coulters utilized in cultivators were surveyed with respect to their wear opposition in soil. The coulters were introduced on a four-shaft cultivator utilized for development of loamy-sandy soils with moistness ordinary for the mid year season. It was discovered that the measure of thickness decrease of the coulters in the territories with established carbide plates and cushioning welds was lower than that in the base-material zones. It was likewise discovered that the measure of wear of the coulters introduced on the principal cultivator shaft was the most elevated and diminished on the ensuing pillars. The ruling system of the wear of martensitic steel was microcutting and cutting. The cushion welded material was exposed to an unpredictable wear component (overwhelmed by microcutting). The wear component of the solidified carbide plates included trademark stages.*

Keywords:*Abrasive wear;Cultivator coulters;Cemented carbide;Hardfacing;Soil;Boron steels;Martensitic steels;Agriculture;*

INTRODUCTION

Underservice,workingpartsoftillagetoolsaresubjectedtocomplex influences dependent on their geometry, the tillage conditions, and the physico-chemicalconditionofsoil.Theactualityoftheproblemsrelated to wear and durability of the parts working in soil is determined by the high variability of the service conditions, the observed tendency to introduce new material and constructional solutions, as well as incom- plete knowledge about interactions between the working elements and soilabrasivemass.Researchonthistopichasmostlyfocusedonsome selectedaspectsofthe phenomenaoccurringinthe "workingele-ment–soil"system.Forexample,manyresearchstudiesconsideredtheinfluence of soil conditions and tillage parameters on the wear of the elements working in soil [1–12]. It was demonstrated that, among other factors, wear intensity and geometry changes of the working elements depend on the moisture content in soil [4,6,10,11], the granulometric composition of soil [1,13,14], or the tillage speed [2]. Research on the cognitive nature was also undertaken, in order to identify the mecha- nisms of abrasive wear of the materials used for elements working in soil. In this context, boronized steels and steels with a microadditiveof boron [15–18], pad-welded materials [19–24] or cemented carbides [25–27], and oxidic ceramics [28–30] were examined as perspective materials for agricultural applications.

In order to describe and estimate the interactions between the working elements and soil, methods based on computer-aided mathe- matical models, such as discrete element method (DEM) [31–33] and computational fluid dynamics (CFD) [34–37], have been proposed. In these methods, computer technology and numerical analysis tools are applied, proving their practical usability. However, with the incomplete knowledgeabouttheabrasive-wearmechanism,itshouldbenotedthat application of even the most sophisticated research methods does not guarantee reliable estimation of the actual course of wear of the ele- ments working in soil. This is especially true for elementscharacterised by complex geometrical structure, in which materials with various tribological properties are used. For such elements, field examinations mustbeconductedinordertoverifythequalityoftheobtained material-design solutions and to provide information about their usability. It should be noted that it is still valid to search for constructional solutions of the elements working in soil that, at relatively low.

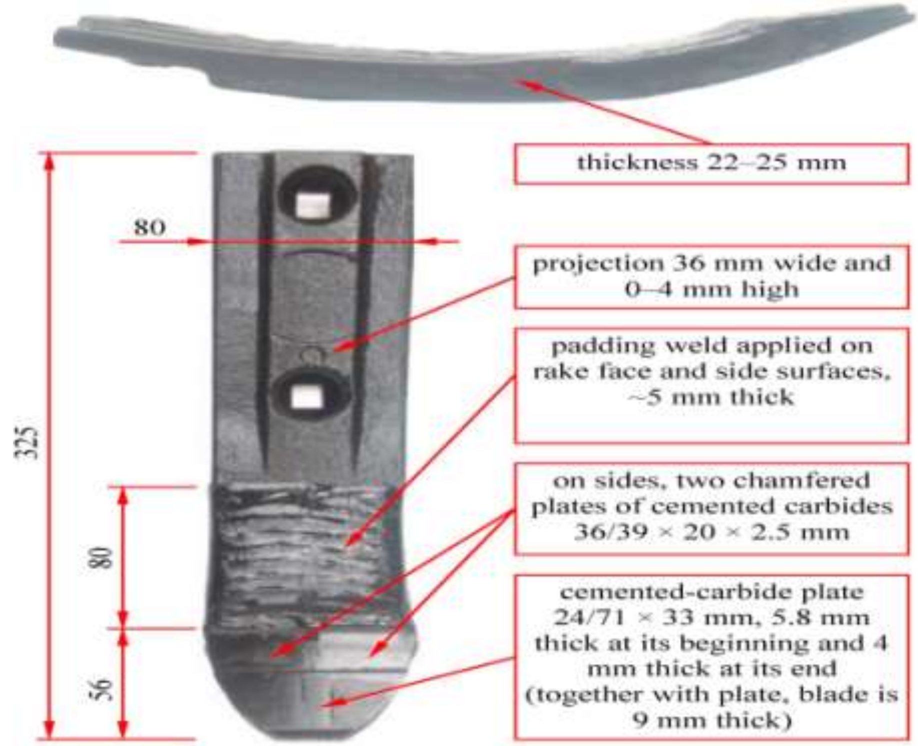


Fig. 1. Cultivator coulter used in tests – variant A/1.

production costs, would be resistant to abrasive wear and the impactof stonesinthesoil.Certainly,adesignsolutionofsuchelementsincludes theirgeometryandmaterialcomposition.Itseemsthatmanufacturersof replaceable elements for equipment designed for work in soil orground areawareofthisandareaimingtodevelopcheapanddurableelements. A known method for increasing the abrasive resistance of elements, which has been used in agricultural practice for many years, is the hardfacingtechnique.Practicalexperienceinthisfieldissupportedbya seriesofinvestigationsaimedatidentifyingthedeterminantsofabrasive resistance of the padding welds. In this approach, laboratory testswere carried out in accordance with ASTM G-65, in which welding materials with different chemical compositions were evaluated [38,39]. The in-fluenceofthehardfacingprocessparametersandthemicrostructureon the abrasion resistance was also analysed [21,40]. In laboratory tests, cemented-carbidewasalsostudied,whichcurrentlybelongstomaterials commonly used for reinforcing elements working in soil. The research aimedtodeterminethemechanismsofwearandtheabrasiveresistance of cemented-carbide depending on the size of the WC grains and the proportion of the matrix[41–44].

Ourresearchisaimedatdeterminingthewearresistanceofselected cultivator coulters reinforced by hardfacing and brazing-on platesmade of cemented carbides.

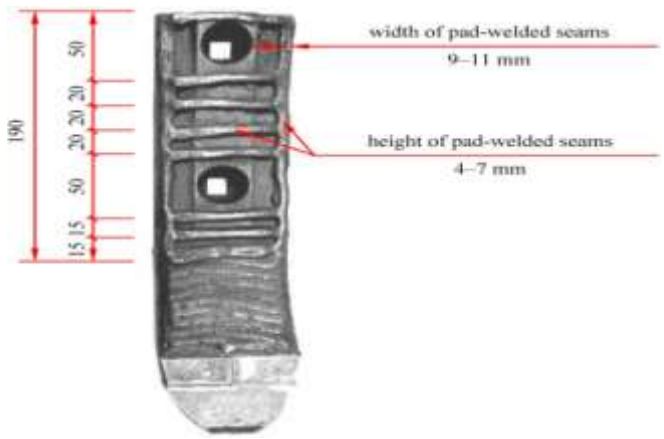


Fig. 2. Cultivator coulter used in tests – variant A/2. Other dimensions are

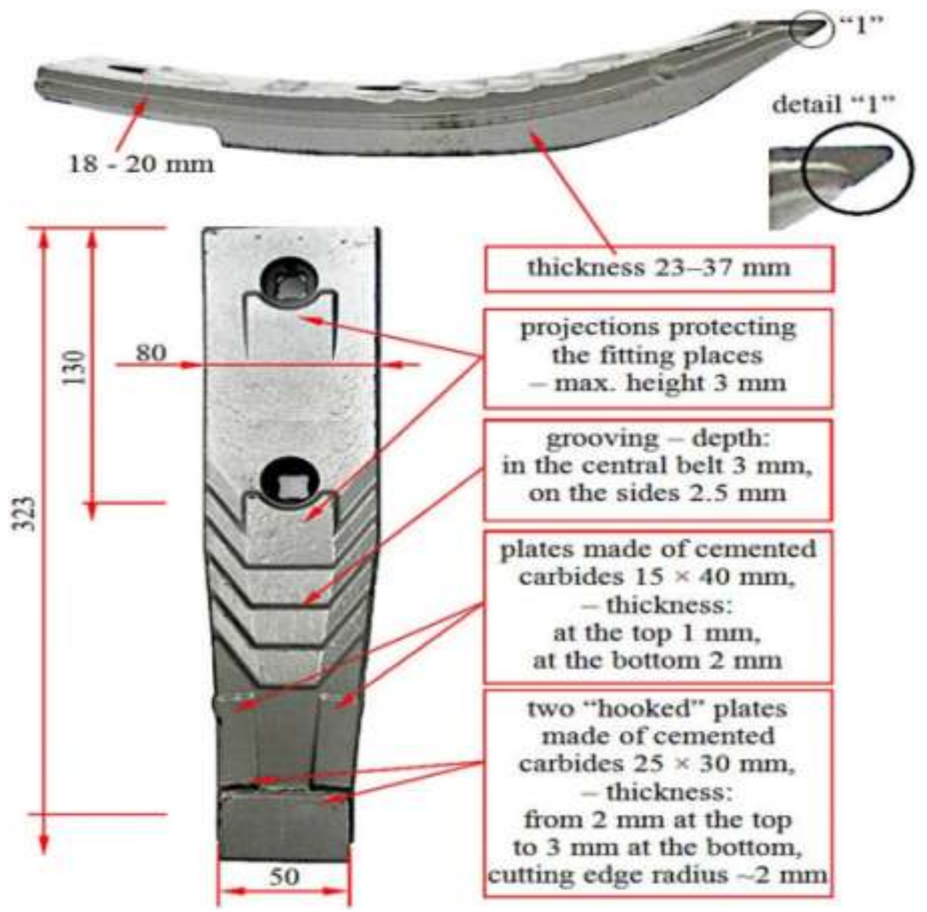


Fig. 3. Cultivator coulter used in tests – variant B.

MATERIALS AND METHODS

Figs.13showimageswithaddedbasicinformationaboutthedesignofthecultivatorcoultersusedintheresearch(markedwithsymbolsA/ 1, A/2, and B).The A/1 and A/2 coulters were reinforced by the manufacturer with cemented-carbide plates and by hardfacing. The carbide plates were brazedonrakefacesatthetipareasoftheelements,andthepad-welded material was applied on the surface above the plates (Fig. 1). The A/2 coulter was additionally reinforced by pad-welding in the form of in-dividualseamsappliedabovethehardfacedarea(Fig.2).However,the B coulters (Fig. 3) were reinforced by the manufacturer with two plates made of cemented carbide shaped to protect the coulter blade (Fig. 3, detail"1")andwithtwomoreplatesplacedabovethem.Duetothecurvatureoftheworkingsurfaceofalltypesoftestedcoulters,theangle betweenthissurfaceandthedirectionofmovementgraduallyincreasedfrom the minimum value of about 35� (for the blade) to 60� (for theendarea of the coulters).TheA/2andBcoultershavenotbeenthesubjectofresearchsofar,hereastheA/1coultershavealreadybeenstudiedbytheauthors[27]. Previous research was conducted under different cultivation conditions than those in the present tests, so in the case of the A/1 coulters, the results of two tests under different working conditions could be compared. Due to comparable problems in both investigations, similar methods were used (chemical composition and hardness of materials, assessment of working conditions, and changes ingeometry).

The chemical composition of individual materials used in the coul-terswasdeterminedusingaGDS500ALecoglowdischargeanalyserand a JEOL JED-2300 energy-dispersed X-ray spectrometer (EDS, EDX) coupled with a JEOL JSM-6610A scanning microscope. SEM observa- tions of the microstructures were carried-out on the JEOL JSM-6610A scanning microscope, using topographic contrast (SE detector) and material contrast (BSE detector). Microscopic examinations were per-formedusingaNikonEclipseMA200lightmicroscopewithaNikonDS-Fi5CCDcameraonetchedspecimens(thebasematerialofcoulterswas etched with 3% HNO_3; pad-welded materials and carbide plates were etchedelectrolyticallyinH_2CrO_4).Vickershardnesswasmeasuredona Zwick 321 tester at 9.807 and 294.2 N for 15s.

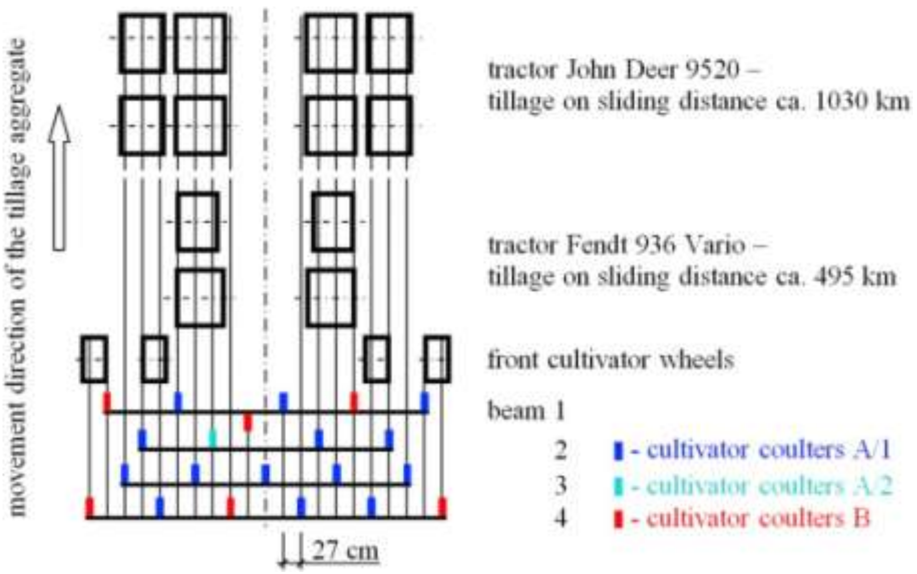


Fig. 4. Arrangement of examined coulters on cultivator beams.

Table 1 Workingconditionsofexaminedelements.

Quantity	Soil layer	Parameter value		
Percentage of soil grade, %	arable	sandy loam	(gl)	-

soil grades present in the cultivated area were determined based on information from soil-agricultural maps covering the test area. These maps were developed some time ago, when the soil classification in Poland was somewhat different to the current classification. In Table 1,

layer

41

loamysand (pgm) –

26

(pgmp) –

next to the information on the percentage of individual soil grades, the symbols used in the former polish classification are given in brackets. Thesesymbolsareusedinthedescriptionbelow.Accordingtothedata from the soil-agricultural maps, the cultivated soils were sandy loam(gl

light loamy sand

12

(pgl) –

10

–41%),loamysand(pgm–26%andpgmp–12%)andlightloamysand (pgl – 10% and pglp – 9%) (Table 1). According to the formerclassifi-

Percentage of gravel (0.2–3 cm),

(pglp) 9

loam (gsp) 1

siltloam (płz) 1

cation, sandy loam (gl) contains 20%–35% of particles with d <0.02 mm. Loamy sand (pgm) mainly contains particleswith

d¼0.1–1mmand15%–20%ofparticleswithd<0.02mm,andlight

2.6 s ¼0.9

%

loamy sand (pgl) mainly contains particles with d ¼ 0.1–1 mm and 10%–

Percentage of fine stones (3–9 cm)

9.6 pc./m^2 s ¼ 4.0 pc./m^2

0.50 kg/m^2 s ¼ 0.32 kg/m^2

15%ofparticleswithd<0.02mm.Inaddition,sandscontaining25%– 40% of particles with d ¼ 0.02–0.1 mm are named silty soils(pgmp,

Percentage ofhumus,% 1.78 s ¼0.25

Reaction,pH$_{KCl}$ 5.52–6.88

Actualhumidity,wt% 0–10cm 12.7s¼1.7

10–20cm 12.2s¼1.6

Volumetric density,g cm^{-3} 0–10cm 1.43s¼0.09

pglp).

Standard results of the granulation measurements of the cultivatedsoils according to the currently used principles are presented in Table 2. According to the tillage technology used in the company where the

Soil compaction kPa Shearing stress, kPa

Working depth, cm Working speed, m · s $^{-1}$

s – standard deviation.

10–20cm 1.52s¼0.07

0–10cm 1231s¼621

10–20cm 2141s¼828

0–10cm 42s¼16

10–20cm 62s¼22

10.6 s ¼ 2.0

2.88 s ¼ 0.24

tests were carried-out, the planned area was to be tilled twice with a cultivator. The depth of tillage was first ~10 cm and then ~20 cm. Basic examinationsofthewearresistanceofthecoulterswerecarriedoutuntil thetillagewas10cmdeep.Duringthistillage,theslidingdistanceofthe coulters was 1524.9 km, while the three coulters reached their wear limit at shorter sliding distances. After operation in soil, the coulters were examined with regard to changes in their geometry. Using the 3D AtosTripleScan3DGOMopticalscanner,thechangeinthegeometryof the coulters was evaluated through comparison with 3D models ofnew

In the tests, a 4-beam cultivator was equipped with 6 teeth on the firstbeam,4onthesecond,5onthethird,and6onthefourthbeam.In this investigation, 14 coulters marked with the symbol A/1, 1 coulter marked with A/2, and 6 coulters marked with B were installedas shown inFig.4.Becausethedistancebetweenthetracesoftheteethfromthe third and fourth beam was the same (27 cm) in relation to the traces of the teeth from the first and second beam (27 cm), the teeth from these beamsworkedundersimilarconditions(Fig.4).Thus,theforcesexerted by the soil on the teeth installed on the third and fourth beam were the same.

Tables 1 and 2 present the data on the working conditions of the examined coulters. Methods for measuring thevalue of the soil param- eters were presented in the work by Stawicki et al. [27]. Percentagesofcoulters. Thus, the reduction in the length and the change in the width and thickness at the selected measurement points were established (Fig. 5). The obtained results of the geometry measurements allowed estimation of the intensity of linear wear at the selected measurement points. This intensity was calculated as the ratio between the material lossandthetravelledslidingdistanceoftheelements.Itshouldbeadded that, in the A/1 and A/2 coulters, the carbide plates were brazed-on in such a way that the base material protruded beyond the plates (Fig. 1), on average 3.2 mm in the measurement line L2 (axis of the element). When determining the extent of length reduction of these coulters,thisprotrusionwastakenintoaccount.Theslidingdistancewasdeterminedusingtheworkingdistancecounter, whichthecultivatorwasnormallyequipped with from its manufacturer (reading accuracy 0.01 km, in

Standard percentages of granulometric fractions in the cultivated soil (soil layer 0–10 cm).

No. Percentageofgranulometricfraction,%			Granulometricgroup				
sand					silt		clay
very coarse	coarse	medium	fine	very fine	coarse	fine	d0.002
1.0<d2.	0.5<d1.	0	0.25 <d 0.5	0.10	0.02	<d 0.05	

0		5.6	<d 0.25	0.05<d0.10			0.002<d0.02	5.9	fsl
1	1.9		12.1	29.1	19.9	11.8	13.7		
2	2.3	7.0	13.8	26.7	17.0	10.7	16.6	5.9	fsl
3	2.1	5.0	11.1	25.1	15.5	12.7	22.6	5.9	fsl
4	2.1	6.7	17.7	35.2	18.6	7.9	7.9	3.9	lfs
5	1.7	6.0	14.7	31.1	19.0	12.8	10.8	3.9	fsl
6	1.9	5.8	13.7	24.8	23.4	10.8	13.7	5.9	fsl
7	1.7	5.4	14.0	26.2	17.3	12.8	17.7	4.9	fsl

d – size of soil grains, mm; fsl – fine sandy loam, lfs – loamy fine sand.

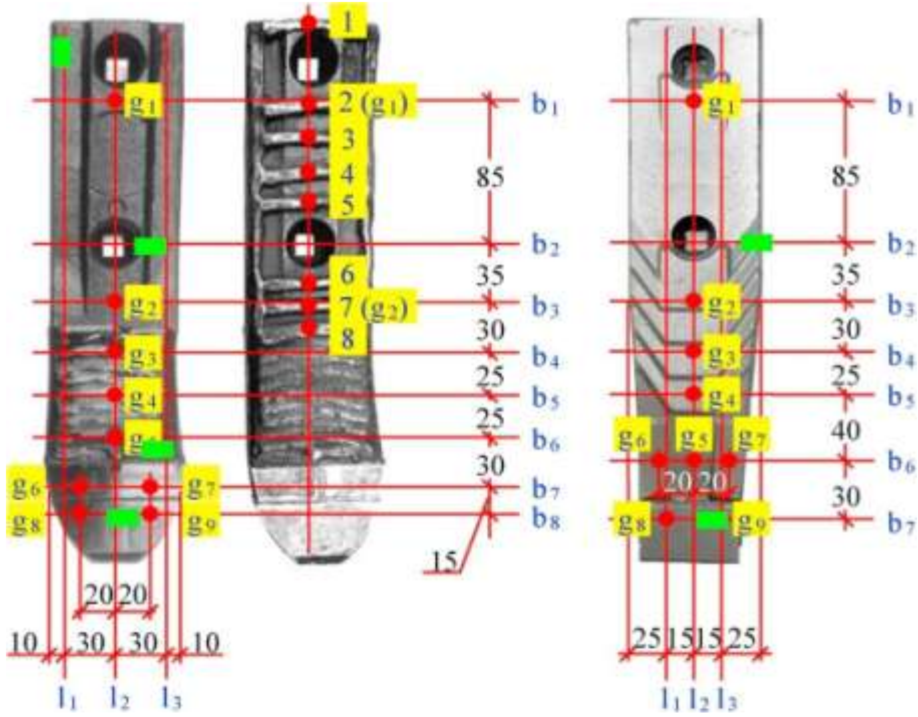


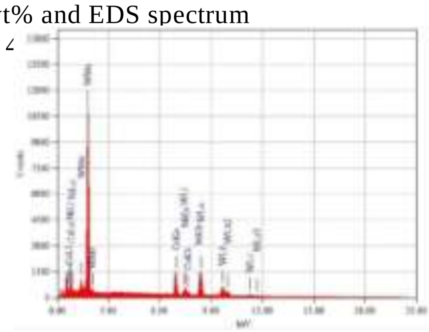
Fig. 5. A/1, A/2, and B coulters – measurement points of geometry

changes:l $_1$, l $_2$, l $_3$– length mea- surementpoints,$b_1,b_2,b_3,b_4,b_5,b_6,b_7,b_8$– widthmeasurementpoints;$g_1,g_2,g_3,g_4,g_5,g_6,g_7,g_8,g_9$(fortheA/2coulterinaddition:1,2,3,4,5, 6, 7, 8) – thickness measurement points; lines of cross-sectionmeasurements:elementsA/1andA/2:l_1, l_2, l_3, b_1, b_2, b_3, b_4, b_5, b_6, b_7, b_8; element B: l_1, l_2, l_3, b_1, b_2, b_3, b_4, b_5, b_6, b_7; areas of surface roughness measurements: element A/1, A/2 and B: places g_1, g_2, g_4 and between g_8 - g_9.

Table 3
Chemical composition and hardness of materials used for the A/1, A/2, and B coulters.

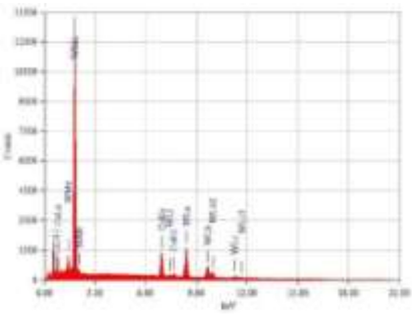
Material	Designation	Value A/1 and A/2coulters
Basematerial	Chemicalcompositionwt%	C0.328;Mn1.300;Si0.272;P0.027;S0.014;Cr0.342; Ni 0.062; Mo 0.013; V 0.002; Cu 0.274; Al 0,026; Ti 0.042; Co 0.009; B 0.003; Pb 0.005; Zr 0.013; rem. Fe

Plates of cemented carbides
Hardness,HV1 433s¼9
Chemical composition wt% and EDS spectrum
WC 79.79; Co 15.67; Ni 4



Surface padding weld
Paddingweldinformofseams,(coulters) A/ 2
B coulters
Hardness,HV30 986s¼47
Chemicalcompositionwt% C4.320;Mn0.373;Si1.040;P0.005;S0.015;Cr16.790;
V 0.039; Cu 0.080; Al 0.189; Ti 0.078; Nb 3.920;
Co 0.084; W 0.037; N 0.031; rem. Fe
Chemicalcompositionwt% C3.670;Mn0.438;Si0.881;P0.005;S0.012;Cr14.160;
V 0.029; Cu 0.104; Al 0.191; Ti 0.071; Nb 3.350;
Co 0.070; W 0.028; N 0.041; rem. Fe

Basematerial Chemicalcompositionwt% C0.392;Mn1.450;Si0.307;P0.011;S0.022;Cr0.448;
Ni 0.106; Mo 0.044; V 0.002; Cu 0.158; Al 0.036;
Ti 0.034; Co 0.009; B 0.002; Pb 0.005; Zr 0.013 rem. Fe
Plates of cemented carbides



Hardness,HV1 531s¼9
Chemical composition wt% and EDS spectrum
WC 85.65; Co 14.35

s – standard deviation.
Hardness,HV30 1057s¼57

manganese sulphides (Fig. 6). The presence of ferrite and manganese sulphidesinthestructurecoulddecreasetheabrasive-wearresistanceof these steels. The hardness of the steel used in the B coulters was approximately 1.2 times higher than that used in the A/1 and A/2 coulters.
The cemented-carbide plates used in the A/1 and A/2 coulters were characterisedbymorefine-grainedstructureandslightlylowerhardness in comparison to the plates used in the B coulters (Fig. 6 and Table 3). The grain size of tungsten carbide was determined in accordance with thePN-ENISO4499-2:2008standard.Thecemented-carbidegrainsize wasclassifiedasfine(about0.8–1.3μm)fortheA/1andA/2coulters andascoarse(2.5–6.0μm)fortheBcoulters.
Figs.7aand8ashowthecross-sectionsofthepaddingweldsusedin

theA/1andA/2coulters,respectively,aswellasthecross-sectionofthe pad-welded seams additionally used in the A/2 coulter, together with hardness measurements taken every 0.5 mm (first measurement was taken approximately 0.2 mm from the pad-welded face). Thedifference betweenthemaximumandminimumhardnessofthepad-weldwas 120.3 HV1 (Fig. 7a), and the difference in the hardness of the pad- welded seams was 300.4 HV1 (Fig. 8a).

The pad-welded material was characterised by a heterogeneous macrostructure and microstructure. Fig. 7b shows the microstructure of the padding weld used in the A/1 and A/2 coulters, consisting of three layers. In the subsurface layer, large primary chromium carbides were identifiedinthematrixofamixtureofausteniteandchromiumcarbides, most often characterised by lath structure and irregular distribution. Locally, the occurrence of niobium carbides was identified (Fig. 7b–1and 1a). The subsurface layer progressively changed to the next layer with the highest hardness, which was composed of a more dispersive matrix including primary chromium and niobium carbides (Figs. 7b–2and 2a). The number of primary chromium carbides decreased withthe distance from the face of the padding weld. The lowest layer, located close to the fusion line, showed dendritic structure of austenite. Fine carbidesandaustenitewerelocatedintheinterdendriticareas.Inthese areas,noprimarychromiumcarbideswereidentifiedandthequantityof fine-dispersive niobium carbides was small (Fig. 7b–3 and3a).

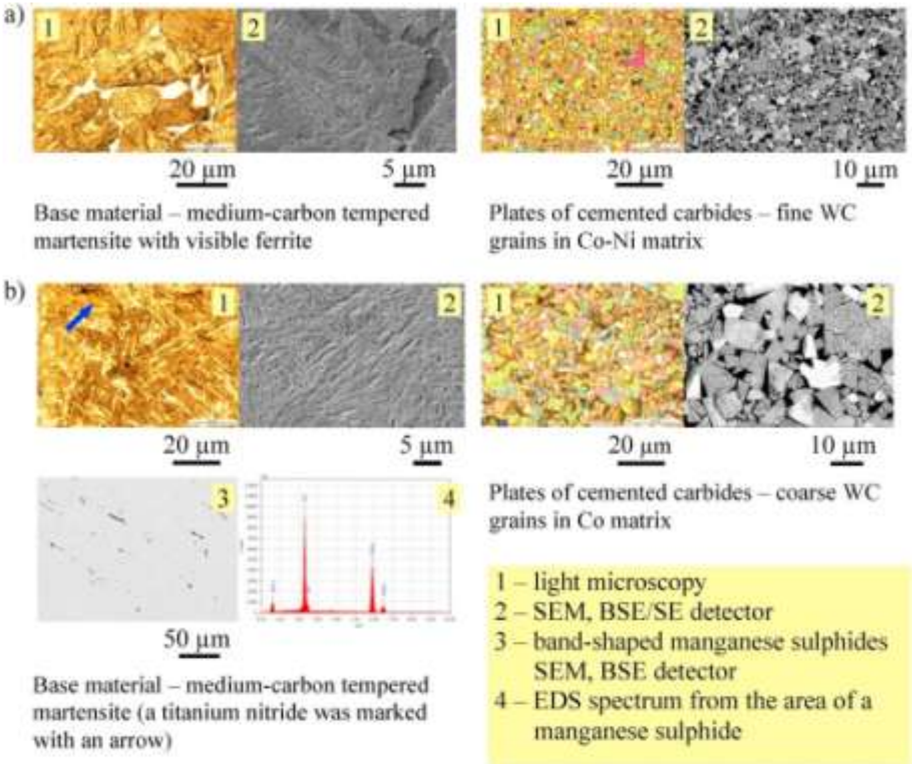


Fig. 6. Microstructure of base material and plates made of cemented carbide: a - A/1 and A/2 coulters, b - B coulters.

InthepaddingweldappliedontheA/2coulterinformofindividualseams,twolayerswithhighlydifferenthardnesswerefound(Fig.8a).Inthesurfacelayer,thepresenceoflargeprimarychromiumcarbidesinthematrixofausteniteand finechromiumcarbideswasfound.Muchmoredispersiveniobiumcarbideswerealsoobserved(Fig.8b1and1a).Thelowerlayerofthepaddingweld,characterisedbymuchlower hardness, was built of dendritic austenite and eutectic mixture inthe interdendriticareas.Thepresenceofalargequantityofevenlydistrib-uted fine niobium carbides was also found (Fig. 8b–2 and 2a).

It can be supposed that the differences between structures of both padding welds were related to the action of heat supplied at applying individual layers, which resulted in different hardness and microstruc- ture of the welded material.

The brazing alloys used for fitting the carbide plates to the coulters varied with respect to their chemical compositions, but they were all typical alloys used for this purpose. The Cu48ZnNi10 brazing alloywas identified for the A/1 and A/2 coulters and the Cu67MnNi9 brazing alloy for the Bcoulters.

*3.2.*Descriptionofthewearofthecoulters

When evaluating the general geometry changes of the coulters, it should be noted that the average depth of their operation in soil was10.6 cm. Due to shapes of the elements and their setting angle in the cultivator, the coulters were plunged in soil approximately to a half of their length during operation. As a result of dynamic action of inertial forces, the soil moved on the coulter surface above their penetration depth.

Fig. 9 show the stages of wear of the A/1 and B coulters. In both cases, the geometry change consisted mostly of length reduction. The thicknessofthecoulterswasalsoreduced,especiallyintheareabeyond the padding weld for the elements A/1 (Fig. 9a) andbeyond the carbide platesfortheelementsB(Fig.9b).ItwascharacteristicintheBcoulters that,asaresultoftheabrasiveactionofsoil,agroovewascreated between the side carbide plates, running along almost the entire length of the elements (Fig. 9b). A reduction in the width was also observed in the top area of these coulters.

Withtheabove-describedformofwear,thewearlimitofthecoulterswas determined by their length reduction of the bearingpartsthatwereexposedtoabrasion.InthecaseoftwoA/1coulters,emergencywearoccurred,i.e.theywerebroken duringloweringfromthetransportpo-sition to the working position. The fracturewascharacteristicallylocatedinthecrosssectionwherethecoulterswereweakenedbyholesforassemblyboltsand,inaddition,byarelativelylargereductionofwidth(Fig.9a)andthickness(Fig.10)inthatarea.Asaresult,duringfurtheroperation,theweakenedfittingsofthecoulterscouldbebrokenoffinthecaseofanoverloadcausedbyhittingstonespresentinsoil.However,theBcoultersdidnotundergoanyemergencformsofwear.Fig.10showstheA/2coulterwhosewearlimitconditionwasalsorelatedtothereductionoflength.Thehardfacingusedintheformofpad-weldedseamssignificantlycontributedtolessintensivemateriallossintheupperzoneoftherakeface(abovethelowerassemblyhole).Inpractice,thicknessreductiondidnotoccurinthiszoneoftheA/2coulter(Fig.10)since,duringoperation,soil wasretainedintheareasbetween the pad-welded seams, protecting the basematerialagainstwear,andonlytheharderpaddingweldmaterialwassubjectedtoabrasion(Fig.11).Itshouldbeadded thatforworkingelementsoper-atinginsoil,replacementofthe"metal-soil"frictiontypewith"soil-soil" friction may be unfavorable in terms of energy consumption of culti-vation,duetothehigherfrictionresistanceof"soil-soil"frictiontype. However, the pad-welded seams below the lower assembly hole were completely rubbed-off (Fig. 11) and the base material in this area was subjected to wear, although to a lesser degree than it was in the A/1 coulters (Fig. 10). The boundary between the retained fragment of the pad-weldedseamandtheabradedzonecoincidedwiththeboundaryof penetration insoil.

Fig. 12 illustrates the two quite typical observed phenomena related to wear of the coulters, i.e. spalling of the cemented-carbide plates and

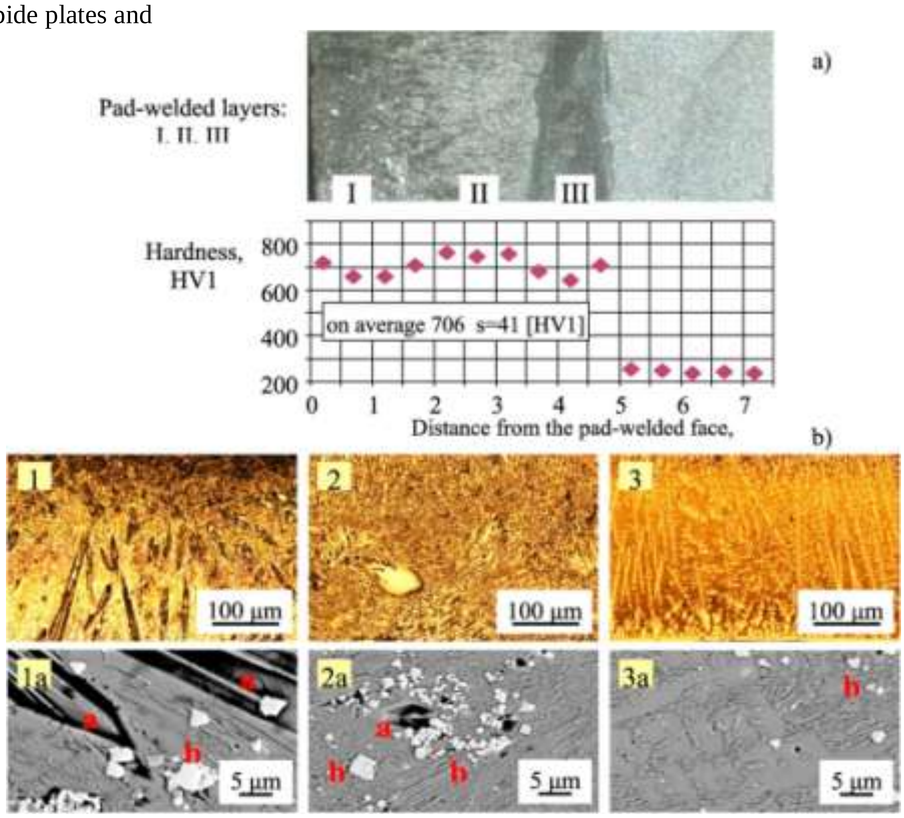


Fig. 7. Hardfacing weld (A/1 and A/2 coulters): a) macroscopic view and hardness profile;

b)microstructuresoftheweldlayers:1and1a–

irregularlyarrangedlargeprimarychromiumcarbides(marked"a")inthematrixofamixtureofaustenitewith carbides,visibleniobiumcarbides(marked"b");2and2a–fine-dispersivemixtureofausteniteandchromiumcarbides(marked"a"),visiblefineniobiumcarbides;3 and3a–dendriticareasofaustenite,finecarbidesandausteniteininterdendriticareas,locallyvisibleniobiumcarbides(marked"b").1,2,3–lightmicroscopy;1a, 2a, 3a – SEM, BSEdetector.

washing-out of the welded material.

Thespallingmechanismofthecarbideplatesisratherobvious.Asa brittle material, carbides were subjected to spalling when hit by stones present in soil). However, the washing-out mechanism of the pad- welded material is not so obvious. It can be supposed that the washing-out mechanism occurred as a result of intensive abrasion of more soft base material of the coulters in front of the pad-welded area, whichresultedinexpositionoftheweldface.Asaresult,theuncovered padding weld was more exposed to abrasive action ofsoil.

3.3. Intensity of the wear of thecoulters

Fig. 13 shows the values of unit mass wear of the coulters. These values depended on the mass intensity of wear of the individual mate- rials used in construction of the coulters. For the A/1 coulters fitted on thefirstandsecondcultivatorbeams,thevaluesofthisparameterwere higher than those established for the elements from the third and the fourth beams –on average approximately 1.3 times. For the B coulters, themassintensityofwearoftheelementsinstalledonthefirstcultivator beamwashigherthanthatfortheelementsinstalledonthefourthbeam –byapproximately1.7times.Therefore,measurementsoftheunitmass wear of the coulters indicate more intensive wear of theelements working with larger distances between the traces of operation of the teeth,i.e.thecoultersinstalledonthefirstandthesecondbeamsofthe cultivator. The A/2 coulter showed the lowest intensity of mass wear, which proves the effectiveness of the applied padding weld in the form ofseams.

The unit reduction of the length, thickness and width of the exam-inedcoulters,obtainedfromtheexperiments,areshowninFigs.14–16, respectively. Owing to the similar rate of wear of the A/1 coulters installedonthethirdandfourthbeams,theresultsfortheseelementsare combinedinthefigures.Insomecases,theelementsbecamewornin the plannedmeasurementareas.Thus,severalrepetitionswerecarriedout for the determined measurement areas. Therefore, in order to describe thevariabilityoftheseparameters,standarddeviationsandrangeswere used,asfaraspossible.Insomemeasurementareas,theparametervalue was not determined because of too aggressive wear (such areas are marked with an asterisk in Figs. 15 and16).

For the A/1 coulters installed on the first cultivator beam, the in-tensityoflengthreductionatthemeasurementlineL_2(coulteraxis)was 2.4timeshigherthanthatfortheelementsinstalledonthesecondbeam and3.6timeshigherthanthatfortheelementsinstalledonthethirdand fourth beams (Fig. 14). However, for the B coulters, the value of this parameter for the elements installed on the first beam was 8.3times

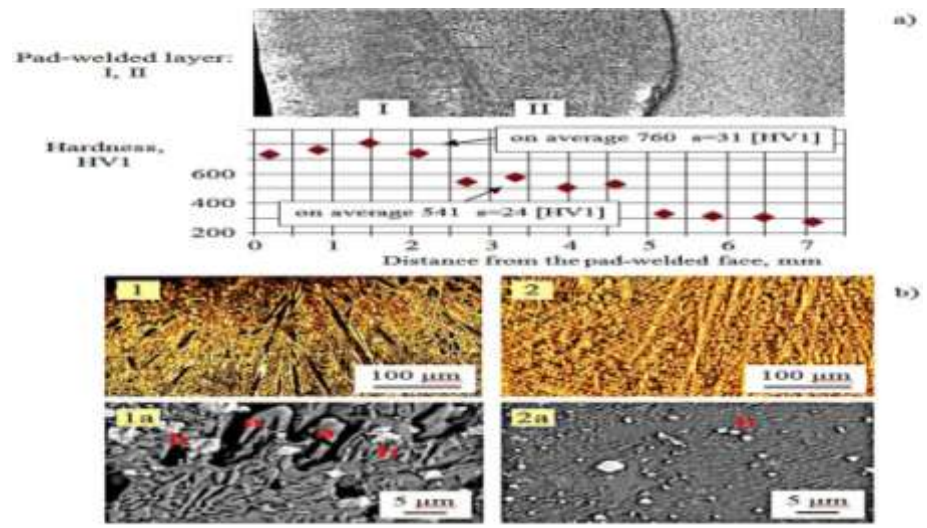


Fig. 8. Hardfacing weld in the form of a seam (A/2 coulter): a) macro

scopic view and hardness profile; b) microstructures of the weld layers: 1 and 1a – irreg- ularly arranged large primary chromium carbides (marked“a”)inthematrixofamixtureofaustenitewith carbides, visible fine niobium carbides (marked “b”);2and 2a–dendriticareasofaustenite,finecarbides and austenite in interdendritic areas, visible fine, evenly distributed niobium carbides (marked “b”).1,2–lightmicroscopy;1a,2a–SEM,BSE detector.

higher than that for the elements installed on the fourth beam. This indicates distinctly harder working conditions for the elements on the first beam, which interact with soil having an untouched structure, thus lowering the load exerted to the soil by the coulters on the subsequent cultivator beams.

Itwasobservedduringthetests,thatlengthreductionofthecoulters installed on the first cultivator beam is irregular. This was reflected by the high values of standard deviation of the parameter of unit length reductionoftheA/1andBcoulters.Suchcourseofwearwascausedby thespallingofthecemented-carbideplateswhentheyhitagainststones randomly distributed in the soil. According to the authors, the coulters installed on the first beam were particularly exposed to that wear mechanism, when they hit against stones present in soil. However, this facilitated shifting of the stones by the coulters installed on the subse- quent cultivator beams, since the soil was already partially hoed by the elements operating before. Due to the described phenomenon, higher wear intensity of the coulters working in the track of the tractor wheels, thus cultivating the possibly more compressed soil, was notfound.

NosignificantdifferenceswerefoundbetweenthelengthreductionratesoftheA/1andA/2coultersinstalledonthesecondbeamofthe cultivator.However,unitlengthreductionvaluesfortheBcoulters
installed on the first beam were on average 1.7 times higher thanthose for the A/1 coulters installed on the same beam (on the basis of the parameter values in the L_1, L_2 and L_3 lines). The unit length reduction valuesfortheBcoultersinstalledonthefourthbeamandfortheA/1
coulters installed on the third and fourth beams were comparable –on
average7.9and9.3mm/10^3km,respectivelyfortheBandA/1coulters.The highest unit thickness reduction of the A/1 coultersoccurredatthemeasurementpointsg_1,g_2,andg_5,seeFig.15.Thepoints$g_1$and$g_2$were located within the base material (point g_1 above thelineofpenetrationintothesoil),andthepoint$g_5$waslocatedintheareaofthe
padding weld (Fig. 5).

An increased rate of wear at the point g_5, which especially affected the A/1 coulters working on the first and second cultivator beams, can berelatedtoheavyloadingbythesoil,resultingincompletewear-outof the pad-welded material, followed by abrasion of the base materialwith muchlowerhardness.Inthatarea,thephenomenonof“washing-out”of the pad-welded material occurred, as shown in Fig. 12. A lower rate of thickness reduction of the coulters was observed at the measurement points g_3 and g_4, owing to the protective action of the applied padding weld.

The cemented-carbide plates brazed on the A/1 coulters slowed

Fig. 9. Exemplary stages of wear of the coulters: a) A/1; b) B (1 - new element, 2 - elements after operation in soil).

downthethicknessreductionoftheelementstoahigherdegreethanthe pad-welded material (Fig. 15). Unit thickness reduction of the lower platewaslarger(Fig.15,measurementpoints$g_8$andg_9)thanthatofthe plates brazed-on behind (Fig. 15, measurement points g_6 and g_7) – approximately 1.4 times for the coulters on the first beam and 1.3times for the coulters on the otherbeams.

The unit thickness reduction in the base material areas of the A/1 coulters (measurement points g_1 and g_2) was approximately 2.1 times higher than the reduction in the pad-welded area (measurement points g_3 and g_4; the point g_5 is not considered) and approximately 5.6 times higher than the area with the brazed-on carbide plates (measurement pointsg_6,g_7,g_8,andg_9).Theunitthicknessreductioninthepad-welded area (measurement points g_3 and g_4) was approximately 2.6 times higher than that in the area with the brazed-on carbide plates (mea- surement points g_6, g_7, g_8, and g_9). The above calculations were per- formedinconsiderationoftheparametervaluesforthecoulters installed on all the cultivator beams. It should be noted that the pre- sented relations indirectly characterise the abrasion resistance of the analysed materials, since the surface loads of the coulters by the soil were different at individual measurement points (the soil pressure sys- tematically increased towards the blades of the elements).

The padding weld in form of seams used in the A/2 coulters signif- icantly lowered the amount of thickness reduction of these elements compared to the A/1 coulters installed on the second beam of the cultivator (Fig. 15). At the measurement point g_1, the amount of thick- ness reduction of the A/1 coulters was approximately 6.9 times higher than that for the A/2 coulter (measurement point g_1 was located in the zones of the A/1 and A/2 coulters that were not plunged in soil). At the measurement points 6, 7 (g_2) and 8, located in the penetration area of the A/2 coulter, the material of the pad-welded seams was completely worn (Fig. 11). Nevertheless, at the measurement point g_2, the amount of thickness reduction of the A/1 coulters was about 1.3 times higher

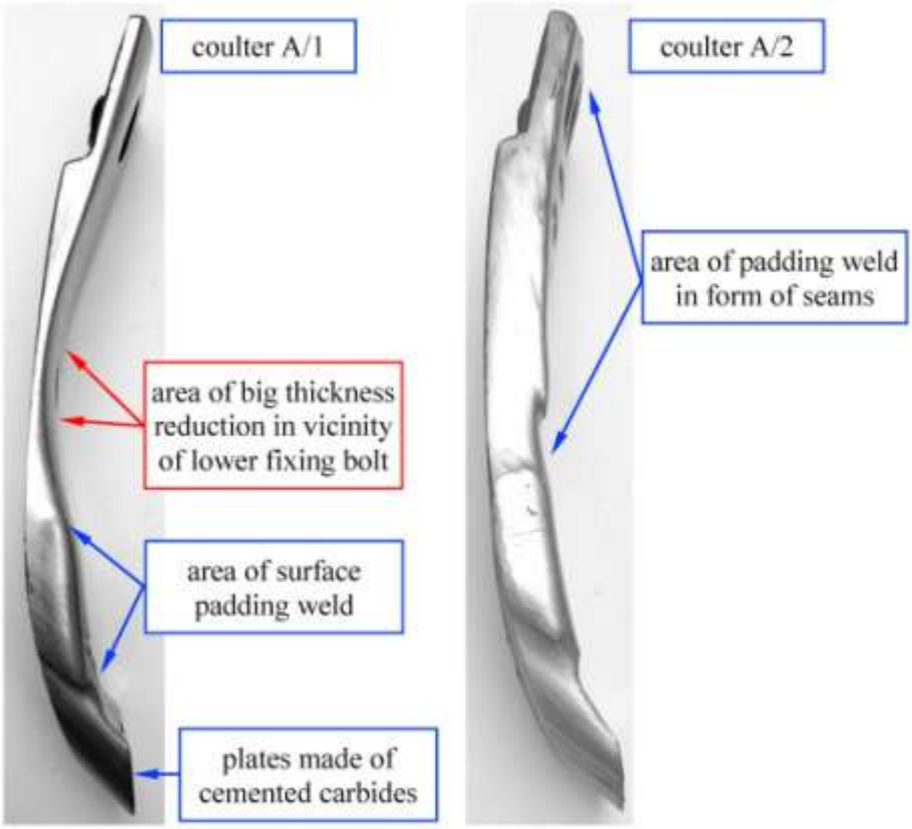


Fig. 10. Side view of the A/1 and A/2 coulters – clearly visible large thickness reduction of A/1 (sliding distance of both elements – 1524.9 km).

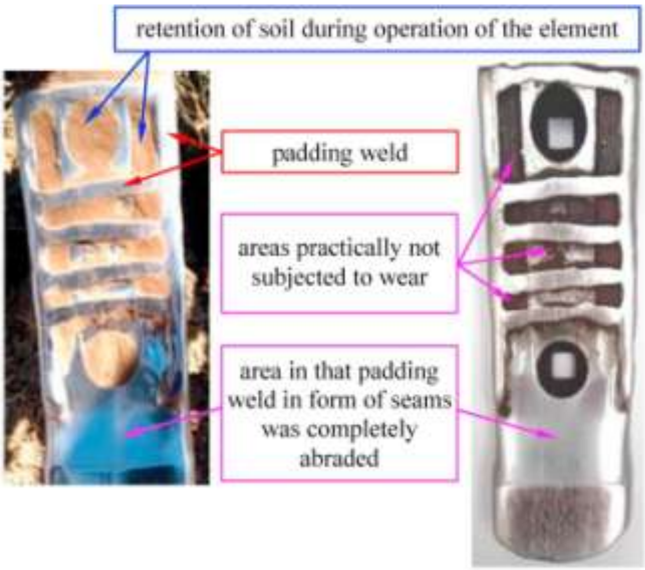


Fig. 11. Coulter A/2 – protective action of the padding weld in form of seams.

the working surfaces of the coulters. In contrast, a decrease in the parameter values at the measurement point g_5 most probably resulted fromitslocation–betweentwocarbideplatesbrazedonthesidesofthe coulters (Figs. 3 and 5).

Cemented-carbide plates relieved the base material,especiallywhenagroovewasformedbetweenthemasaresult of the abrasive action of the soil (Fig.9).
As was found for the A/1 coulters, the values of unit thickness reduction of the B coulters, measured in the areas of carbide plates (measurementpointsg_6,g_7,g_8,andg_9),werelowerthanthoseforthe base material. The ratio of the average unit thickness reduction of the coultersinthebasematerialarea(measurementpointsg_1,g_2,g_3,g_4, and g_5) and the unit thickness reduction of the carbide plates (mea-surementpointsg_6,g_7,g_8,andg_9)wasabout8.7.Similarly,inthecase of the B coulters, the values of unit thickness reduction of the lower plates were higher than those for the upper plates, by about 1.7 times (basedonthewearoftheplatesfromthecoultersinstalledonthefourth cultivatorbeam).
It should be added that the estimated amount of thicknessreduction ofthecemented-carbideplatesinstalledontheexaminedcoulterswere similar, which indicates similar abrasion resistance of theplates.
At all the measurement points, the lowest value of unit thickness thanthatfortheA/2coulter.Therefore,thepaddingweldintheformofseamsinthisareaalsocontributedtolimitation oftheabrasionintensityoftheelement,buttoalesserdegreethanitdidintheareaabove,seeFig.10.IntheBcoulters,the valuesofunitthicknessreductionwerealsothehighestforthebasematerialarea(Fig.15).Atthemeasurementpointsg_1, g_2, g_3, and g_4, the values of this parameter gradually increased, which corresponded with the increased pressure exerted by the soilonreduction was observed for the coulters installed on the third andfourth cultivator beams. As in the case of the B coulters, the values of unit thickness reduction were lower for the elements installed on the fourth beam (Fig. 15). Therefore, it can be stated again that the coulters installed on the back cultivator beams operate under less difficult conditions.Asignificantincreaseintherateofwidthreductionofthe A/1andA/2coulterswasfoundinthemeasurementlin esb$_6$,b$_7$,andb$_8$,locatedin the lower coulter areas (zone of padding weld and brazing of plates made of cemented carbides) (Fig. 16). However, in the B coulters, the highest rate of width reduction occurred in the measurement line b_5, locatedintheareaofthebasematerial,abovethecemented-carbide

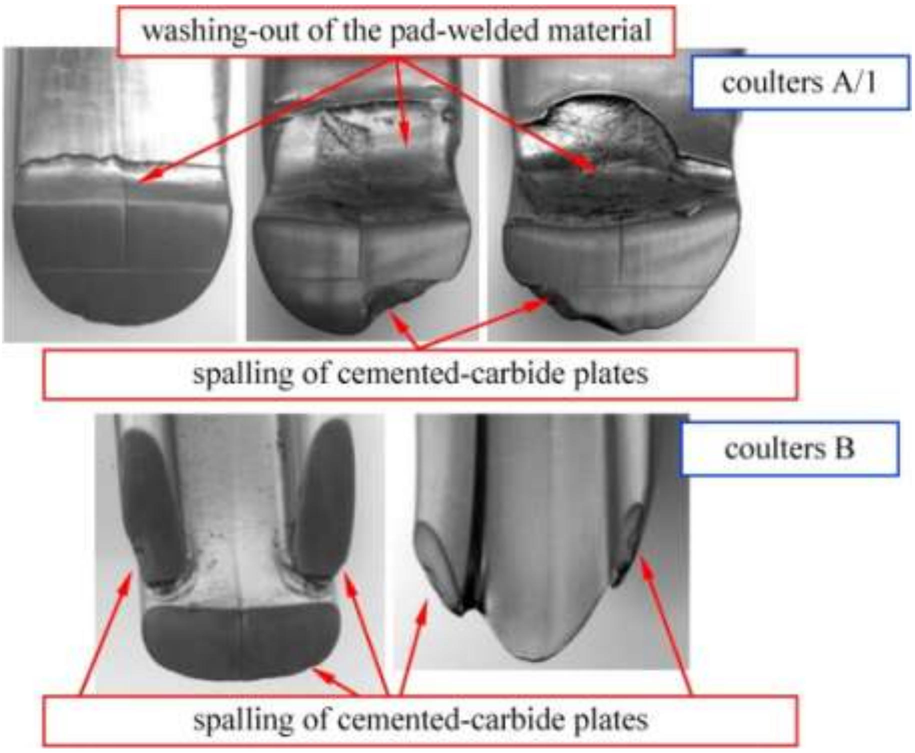


Fig. 12. Wear of top area of the A/1 and B coulters.

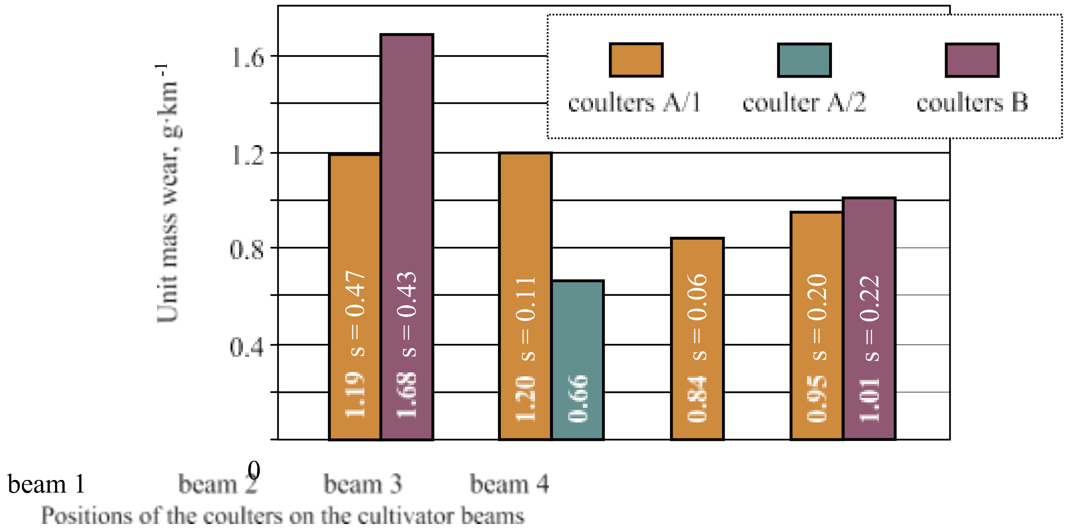


Fig. 13. Unit mass wear of the coulters (s – standard deviation).

plates (Fig. 16). Measurements of the unit width reduction of the A/1 and B coulters also indicate more difficult working conditions of the elements installed on the first cultivator beams compared to those installedonthesubsequentbeams.InthecaseoftheA1coulters,thisis especially visible in the measurement lines b $_5$, b $_6$, b $_7$, and b $_8$, but for theBcoulters,thisisobservedinthemeasurementlinesb$_4$,b$_5$,andb$_6$ (Fig.16).

3.4. Mechanismofwearofthematerialsusedinthecoulters

In all the examined coulters, the wear process of the cemented- carbide plates proceeded in a similar way (Figs. 17 and 22). At the beginning, the matrix was abradedunderaction of the finestfractionsoftheabrasivemass.Asaresult,cracksandmasslossesoccurredaround the carbide grains, weakening their mounting in the material. In the second stage of destruction, the weakened carbides were chipped-out from the matrix, which resulted in formation of characteristic craters owing to theremovedcarbidegrains(pits)(Figs.17and22).Itwasalso found that a part of the carbides firmly seated in the matrix were sub- jectedtocrushingorcracking(Figs.17band22b).IntheA/1coulters,in the initial area of partially worn carbide plates, i.e. in the area most strongly loaded by soil, grinding effects were identified with cracks covering many carbide grains and propagating deep into the plates (Fig. 17a). A similar effect, although less intensive, occurred in the B coulters (Fig.22b).

The condition of the surfaces of the padding welds used in the A/1

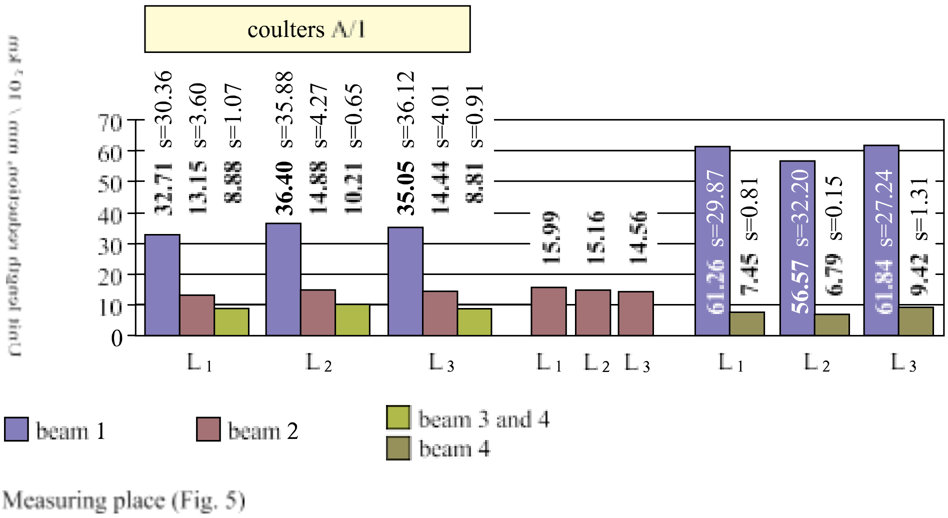


Fig. 14. Unit length reduction of the coulters (s – standard deviation).

andA/2coultersaftertheirapplicationinsoilisshowninFigs.1921.Thepaddingweldswerecharacterisedbythepresence ofcracksthatoccurredduringthehardfacingprocess(Figs.19c,20cand21a).Inboththeformsofpaddingwelds,therewer eclearscratchesinthemovementdirection of the soil particles. Wide and shallowgroovingcharacterisedbyverysmall(Fig.19)orevenmissingplasticdeformation(Fig.20)alsooccurred.Thelar geprimarychromiumcarbidescharacterisedbyhighhardnessandbrittleness,presentinthepaddingweld,contributedtot he delaminationofthematerial(Figs.19c,20band21).Therewerealsoareaswheresoilparticlesshiftingovertheweldsurfac eremovedthe materialaroundthefirmlyseatedcarbides(Fig.19a).Withregardtodiversified, heterogeneous microstructure of the padding weldsbuiltofseverallayers,theeffectofacomplexprocessofabrasivewearwasfound. However, the dominating mechanism of wearwasmicrocutting.Inbothsteelsusedasbasematerialsofthecoulters,thedominantmechanismofwearwasgrooving andmicrocutting(Figs.18and23).The observed scratches related to the microcuttingmechanismwerecharacterisedbysmallwidthandlargerdepthincomparisontothe grooves(Figs.18aand23a).Ingeneral,thedirectionofgroovesandscratchescoincidedwiththemovementdirectionofthe abrasivefrac-tion; only a small part was distinguished by otherdirections.More plastically deformed areas were found on the surfaces of theA/1coul- ters,whichcanbeexplainedbythehigherplasticityofthebasesteelusedinthesecoulterscomparedtothebasesteelusedint heBcoulters.Moreover, a ploughing effect was identified in the A/1coulters,directed perpendiculartothemovementdirectionoftheabrasive fraction(Fig. 18c). On the surfaces of both examined steels, pinholes werealsofound (Figs. 18b and 23a).

Theroughnessmeasurementresultsoftherakefacesurfacesofthecoultersarepresentedin Table4.Becauseofsimilarroug hnessvaluesfor the A/1 coulters on the first and the second cultivator beams and for those installed on the third and fourth beams, the average roughness values for all the A/1 elements installed on these beams are given. For the B coulters, it was impossible to measure the roughness at several measurement points because of the geometry of the elements after operation in soil (Fig. 9) and the limitations of the profilographometric method.

Surfaceroughness(Ra)ofthecementedcarbideplatesbrazedonthe A/1, A/2, and B coulters was about 3.0–3.4 times higher than that for thebasematerial(atmeasurementpointsg$_8$,g$_9$,andg$_2$).Similarly,the surfaceroughness(Ra)ofthepaddingweldsappliedontheA/1coulters onthefirstandsecondbeamsandthethirdandfourthbeamswasabout 3.7 and 2.6 times higher than that for the base material times (at mea- surement points g $_4$ and g $_2$).

Thesurfaceroughness(Ra)ofthecementedcarbideplatesbrazedontheBcoulterswasabout1.6timeshigherthanthatofth eplatesinstalled ontheA/1andA/2coulters.Thestatisticalsignificancetestshowedthat theaveragevaluesoftheparametersRa,Rt,Rp,andRvfortheBcoulters installed on the fourth beam are significantly higher than the values for the A/1 coulters installed on the third and fourth beams. This can be explained by the more coarse-grained structure of the carbide plates usedontheBcoultersandthewearmechanismdominatedbycrushing and chipping carbide grains from thematrix.

In the case of the A/2 coulter, the measurements of the surface roughness of the padding weld in the form of seams (Fig. 5) were planned among others at the measurement point g $_2$. During the oper- ation, the weld material at this point was completely abraded, so the surface roughness measured at that point was related to the base ma- terial(thisiswhyinTable4,thematerialatg$_2$ismarkedas"base").The roughness of the pad-welded seam (measurement point g$_1$ situated above the zone of penetration in the soil) was slightly lower than that of the padding weld (measurement point g$_4$) (Table 4). This probably resulted from the fact that the surface of the welded seam was less loadedbysoil,aswellasfromaslightlyhigherhardnessofthematerial (Figs. 7 and8).

IntherangeofparameterRa,itwasfoundthattheworkingsurfaces of the pad-weld material and cemented-carbide plates have a higher roughness than the base material of the coulters, owing to the different wear mechanisms of these materials. This observation confirms the analysis of the relationship between the values of the parameters Rv to Rp.Ingeneral,foralltheexaminedcoulters,theratiooftheparameters Rv to Rp ranged between 1.3 and 4.0 for the base material, between ca1.8 and 3.9 for the padding weld in the A/1 and A/2 coulters, and about 1.5 for the welded seams in the A/2 coulter. In the case of the cemented-carbide plates, this ratio ranged from about 1.1 to 1.3. The surfaceconditionofthebasematerialsandthepaddingweldsindicatesa differentcourseofdestructioncomparedtothecementedcarbideplates, for which the Rv to Rp ratio ranged from 1.1 to 1.3. The lowerhardness of the base material and the padding weld corresponded with their higher susceptibility to destruction by elementary forms of abrasive wear, i.e. microcutting andscratching.

DISCUSSION

The results of mass wear and the results of wear intensity of the length, thickness and width indicate that the coulters installed on the first beam of the cultivator are under the hardest working conditions, owing to the impact of soil with an intact structure. In contrast, the

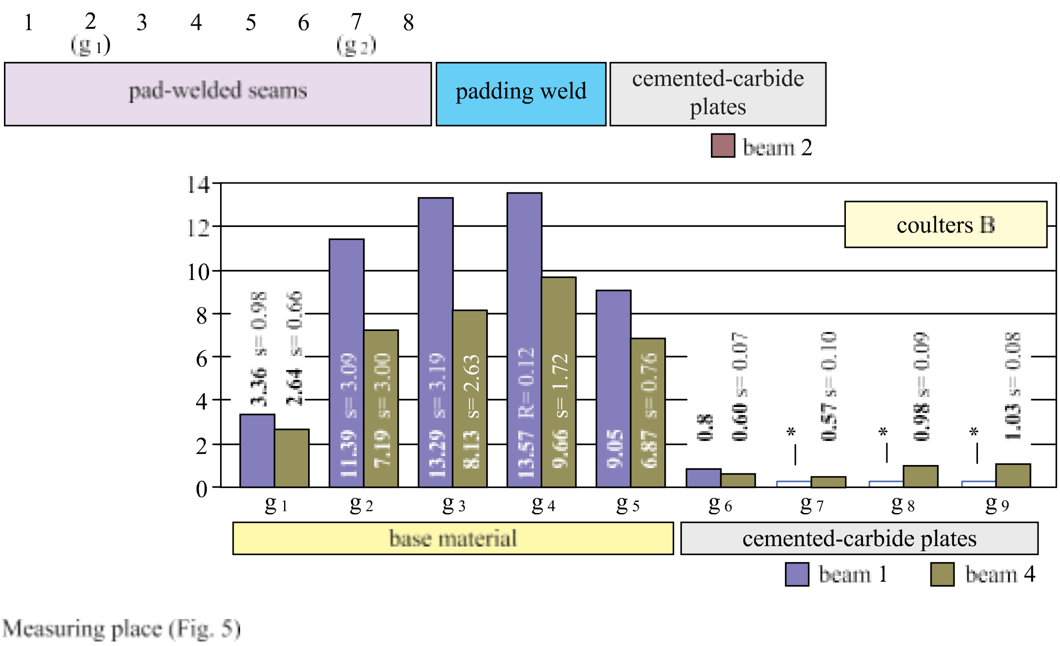


Fig. 15. Unit thickness reduction of the coulters (* – no data due to wearing of the elements at the measurement point, s – standard deviation, R – range).

intensity of wear of the coulters installed on the third andfourthbeamswasthesmallest,indicatingthelowestloadoftheseelementsinthesoil.Duringoperationoftheexamined coulters,theirwearprocesswasrelatedtothereductionoflength,thickness,andwidth.Figs.24–26show the longitudinal and perpendicular sections of the A/1, A/2,and Bcoulters.Thepresentedconditionsdonotcorrespondtothelimitwearcondition of the coulters, but these figures showtheproportionsofmaterialreductionalongtheelementsandinthedirectionsrelatedtotheirthicknessandwidth,aswellastheplaceswherethehighestshapechangesoccurred.ItcanbeseeninFig.24thatthethicknessoftheA/1coulterwassignificantlyreducedinvicinityofthelowerassemblybolt(basematerialarea)anditswidthwasconsiderablyreducedinitslowerarea(Fig.24b,measurementpointsb_6,b_7,andb_8).Inpreviousresearch[38]wheretheA/1coulterswereusedamongothers,moreintensive thickness reduction was found in the base material area(unit thickness reduction at the measurement points g_1 and g_2 was about 1.1–2.6timeshigherthanthevaluesfoundinouttests)and,atthesame time, mostly less intensive thickness reduction of the padding weld material and the carbide plates was found. The unit length reduction of the A/1 coulters was also smaller (5.0, 3.5, and 1.5 times in the mea-surementlineL_2fortheelementsinstalledonthefirst,second,andthird and fourth beams, respectively). Substantial thickness reduction resul- ted in breakages of the coulters, abrasion-through, or failure resulting from abrasion of conical heads of the assembly bolts. Such caseswere not found in the present examinations (apart from the previously described breakage of two elements during lowering of thetool).

The presented difference in the forms of wear of the A/1 coulters probably resulted from their different working conditions, in particular from the higher humidity of the cultivated soil (17.2%) (influencing its lowercompactness–691kPaandlowershearingstress–38kPa)and

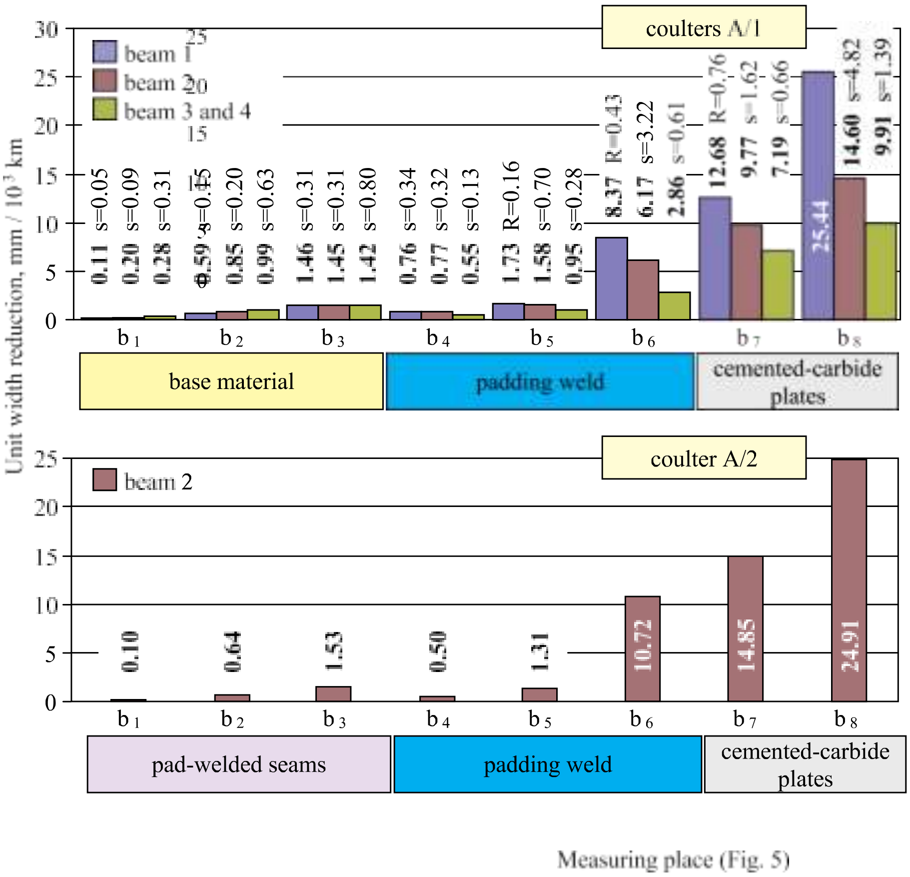


Fig. 16. Unit width reduction of the coulters (*–no data due to wearing of the elements at the measurement point, s – standard deviation, R – range).

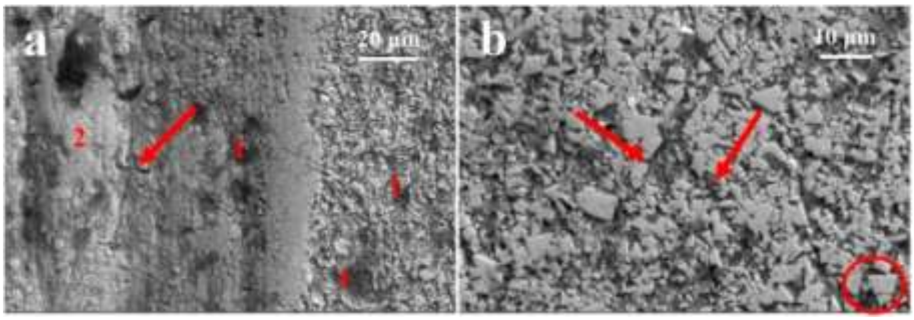


Fig.17. Wornsurfaceofthefine grainedcementedcarbideplatesintheA/1coulter:a)pits(markedas"1"),areaofextremelyintensivegrindingeffect(markedas "2"), and acrackpropagatinginsidethecementedcarbideplate(markedwithanarrow);b)fully cracked WCgrains(markedwithacircle) and crackspropagating inside the cemented carbide plate (marked with arrows). SEM, SE detector.

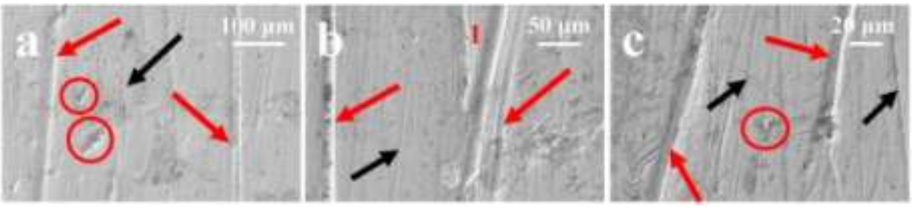


Fig. 18. Worn surfaces of the investigated steel used in the A/1 coulter: a) grooves (marked with red ar- rows), pinholes (marked with circles), scratches (marked with a black arrow), b) grooves (marked with a red arrow), scratches (marked with a black arrow)andplasticallydeformedmaterialonagroove (markedas"1"),c)grooves(markedwithared arrow), scratches (marked with a black arrow), and ploughing (marked with a circle). SEM, SE detector. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

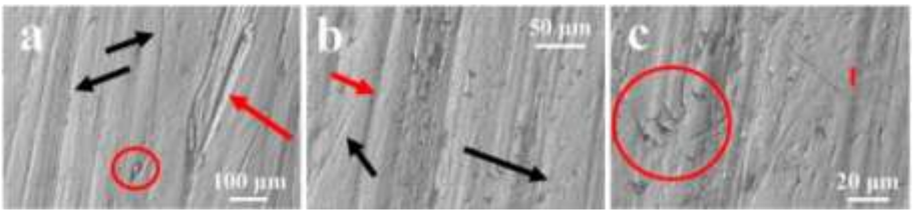


Fig. 19. Worn surfaces of the investigated padding weldusedintheA/1coulter:a)grooves(markedwith a red arrow), scratches (marked with black arrows), and pressed-in particles (marked with a circle), b) grooves (marked with a red arrow), scratches (marked with black arrows), and pinholes, c) magni- fication of area shown in Fig. 4b, delamination (markedwitharedcircle),crack(markedas"1") and pinholes.SEM,SEdetector.(Forinterpretationofthe referencestocolourinthisfigurelegend,thereaderis referred to the Web version of thisarticle.)

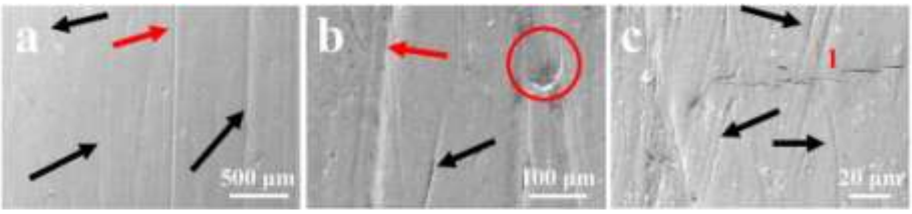


Fig. 20. Worn surfaces of the investigated padding weldusedintheA/2coulter:a)grooves(markedwith redarrows),scratches(markedwithblackarrows),b) grooves(markedwithredarrows),scratches(marked with black arrows), pinholes, and delamination (marked with circles), c) scratches (marked with

blackarrows),crack(markedas"1"),and alarge numberofpinholes.SEM,SEdetector.(Forinterpre- tationofthereferencestocolourinthisfigurelegend, the reader is referred to the Web version of thisarticle.)

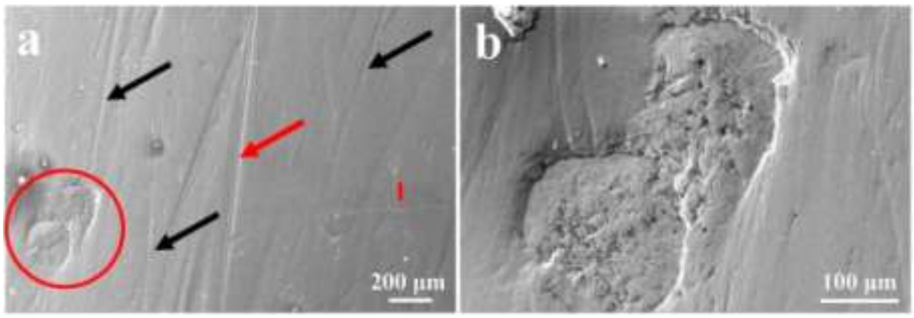


Fig.21.
Wornsurfacesoftheinvestigatedpaddingweldusedinthe A/2coulter:a)grooves(markedwitharedarrow),scratches(markedwithablackarrow),crack (markedas"1"),anddelamination(markedwithacircle),b)magnificationofthedelaminationareashowninFig.6a,andvisiblepinholes.SEM,SEdetector.(For interpretationofthereferencestocolourinthisfigurelegend,thereaderisreferredtotheWebversionofthisarticle.)

slightly deeper tillage (13.1 cm). In more humid soil, fastening of the abrasive grains (quartz) by its remaining fraction is weaker (this is indicatedbylowercompactnessandlowershearingstressesoccurringin humid soils). Thus, abrasive particles lose their wearing contact due to the lower forces acting on the abraded material, thus reducing their ability to wear the material. This can explain the less intensive wear of thecementedcarbideplatesandpad-weldedmaterial,aswellastheless intensive length reduction of the A/1 coulters operating in more humid soil. In contrast, a larger unit thickness reduction of the coulters in the base material area (points g_1 and g_2) during operation in morehumid soilcanbeattributedtotheslightlylargerdepthoftillageandthehigher plasticity of humid soil. Plastic soil can be more easily deformed and crushed, albeit to a lower degree. It can therefore be supposed that humid soil moved over the coulter surface in the form of a plastic monolith in permanent contact with the surface, as opposed to soil with lower humidity that is not subjected to crushing. Thus, permanent contact of humid soil with the coulter surfaces could result in more intensive thickness reduction at points g_1 andg_2.

In contrast, the highest thickness reduction of the B coulter (Fig.26) occurredintheareabetweenthecarbideplatesandthelowerassembly

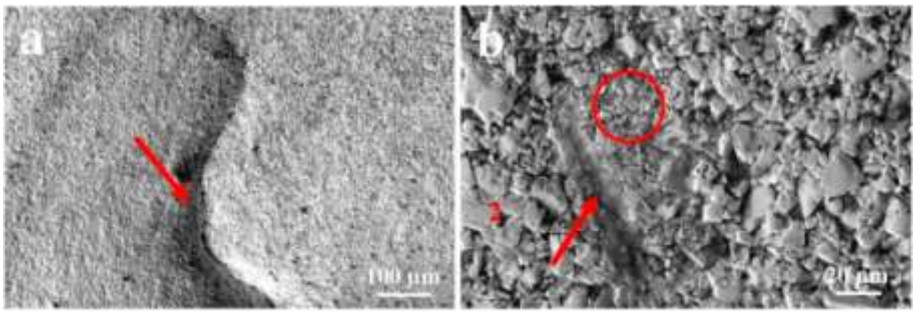


Fig. 22. Worn surface of the coarse-grained cemented carbide in the B coulter: a) pits on worn surface and visible crack propagating inside the cemented carbide plate (marked with an arrow); b) pits on the surface, grinding effects (marked with an arrow), and visible crushed (marked with a circle) and fully cracked (marked as "2")WCgrains.SEM,SEdetector.

bolt (base material area), and the highest width reduction occurred in thelowerpartoftheelement(Fig.26b,measurementpointsb_5,b_6,b_7– areasofthebasematerialandthebrazed-oncarbideplates).InFig.26b, a groove is clearly visible in the coulter axis resulting from soil moving alongthebasematerialsurface(measurementpointsb_3,b_4,b_5,andb_6).

In summary, it can be said that the cemented-carbide plates usedin the A/1, A/2, and B coulters were characterised by the highestabrasion resistance in relation to the other materials. Therefore, they effectively decreased the reduction rate of the thickness, length and width, while this limitation of length reduction is related to the stoniness of the cultivated soil because of the brittleness of the carbide plates. The padding weld used in the A/1 coulters also decreased the thickness reduction rate of the elements. In contrast, the pad-welded seams applied on the A/2 coulter additionally contributed to the limitation of the thickness reduction in the area above the padding weld, especially above the lower assemblybolt.

The coarse-grained and fine-grained carbide plates used in the examined coulters were subjected to similar mechanisms of wear: removal of the matrix under action of the finest fractions of theabrasive mass, next cracking, and crushing or chipping of carbides from the matrix.Thiswasreflectedbyhighvaluesofroughnessparametersofthe platesurfaces.Asimilarwearprocessofcarbideplateswasfoundby Gee and others [45]. In our own research, cracks propagating inside the plates and covering a number of carbide grains were additionally observed.However,nosubsurfacecracks(paralleltothesurface)were observed, similar to the findings of Gant and others[46].

Duringserviceofthecoulters,crushingofthecarbideplatesoccurred when they were hit by stones present in the soil. In the fine-grained carbide plates used in the A/1 and A/2 coulters, the percentage of the cobalt–nickel matrix amounted to about 20.2%, but in the coarse- grained carbide plates used in the B coulters, the percentage of theco- balt matrix amounted to approximately 14.3% (Table 3). Differences in the volume fraction of the matrix influenced the hardness, which was higher (1057 HV30) in case of the B coulters than the A/1 coulters(986

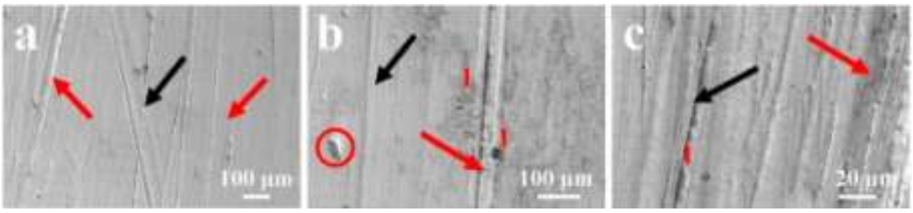


Fig. 23. Worn surfaces of the investigated steel used intheBcoulter:a)grooves(markedwithredarrows), scratches (marked with a black arrow) andpinholes,
b) grooves (marked with red arrows), scratches (marked with a black arrow), large pinhole (marked with a circle), and plastically deformed material on a groove(markedas"1"),b)grooves(markedwitharedarrow),deepscratchwith"extrudedlip"(markedwith a black arrow), plastically deformed material on agroove(markedas"1").SEM,SEdetector.(Forinterpretationofthereferencestocolourinthisfigure legend, the reader is referred to the Web version of thisarticle.)

HV30).Theproportionofthematrixandthegrainsizeofthecemented- carbide materials determine their wear resistance [41–44]. However, thetestedcemented-carbideplatesrevealedcomparablewearintensity despite significant differences in thestructure.

In order to increase the abrasive wear resistance of the A/1 and A/2 coulters, the hardfacing technique was applied, which is widely used in themining,agriculture,andconstructionindustries.Thesurfacelayerof the padding welds applied on the coulters was composed of large pri- mary chromium carbides and relatively ductile eutectic mixture built of chromium carbides with austenite. In previous works [47–49], primary chromium carbides and carbides in the eutectic mixture, occurring in similar padding welds, were identified as carbides type M7C3. As was found in Ref. [50], large primary brittle chromium carbides, unevenly distributed in the weld structure, determine the irregular abrasive-wear processes and can result in delamination and crushing. Similar phe- nomenawereobservedinthepresentstudy.Belowthesurfacelayer,the fraction of dispersive niobium carbides in the welds increased (except thethird,i.e.lowest,layerofthepaddingwelds).Itwasdemonstratedin Ref. [51] that the content of dispersive and evenly arranged niobium carbides significantly increase the abrasion-wear resistance and hard- nessofthewelds.Insummary,itcanbesaidthatthepaddingweldsused in the A/1 and A/2 coulters, composed of two or three layers with differentstructureandhardness,weresubjectedtounstableanduneven wear processes, which determined the rate of theirwear.

The base materials of the coulters were martensitic steels with microadditivesofboron,whichincreasestheabrasivewearresistanceofsteel[16,17].Thesurfaceroughnessofthecoulter sinthebasematerialareawaslow,sothewearprocessofthatmaterialwasdifferentthanthat of the carbide plates and padding welds. The dominant mechanism of wear of the base steels was grooving and microcutting with a relatively intensive course, as shown by the large thickness reduction of the coulters in the base material area in comparison to the areas of other materialscharacterisedbyhigherhardness.Itseemsthatafinefraction ofsoils,whoseparticlesarenotsofirmlyfixedinthesoilmass,wasmore significantinthewearofthebasematerialthaninwearoftheother

Table 4

Roughness of rake surfaces of coulters after operation in soil.

Coulter and its fitting place		Measurement point (Fig. 5)	Roughness parameter value, µm			
			Ra	Rt	Rp	Rv
A/1	Beam 1 and 2	g_1 1)	0.40s=0.21	5.95 s=3.85	1.18 s=0.66	4.77s=3.22
		g_2	0.26s=0.03	4.21 s=1.40	1.40 s=1.18	2.81 s=0.81
			0.96s=0.44	9.74s=3.76	2.84s=1.13	6.90s=2.67
		g_8	0.73 s=0.12	5.87 s=1.57	2.85 s=0.85	3.02s=0.75
	Beam 3 and 4	g_1 1)	0.42s=0.12	5.06 s=1.99	1.34 s=0.61	3.71 s=1.76
		g_2	0.20s=0.08	2.38s=0.98	1.02 s=0.76	1.36 s=0.49
		g_4	0.52s=0.18	7.12s=2.65	1.45 s=0.54	5.67 s=2.33
		between and g_9	0.77s=0.12	5.81 s=0.67	2.80s=0.47	3.01 s=0.71
A/2	Beam 2	g_1 1)	0.89	7.30	2.91	4.39
		g_2	0.24	2.35	1.23	1.12
			1.00	9.26	3.32	5.94
		g_8	0.81	5.68	2.46	3.22
B	Beam 1	g_1 1)	0.36s=0.15	4.63 s=2.47	1.10 s=0.58	1.34 s=1.96
		g_2	0.38R=0.22 *	3.99R=2.15 *	1.09R=0.52 *	2.90R=1.33 *
			**	**	**	**

		g8				
	Beam 4	g1 1)	0.50s=0.33	7.68 s=5.81	1.61 s=0.76	6.07 s=5.05
		g2	0.37*** * –	9.59*** * –	2.48*** * –	7.11*** * –
		g8	1.23 s=0.09	9.32s=0.32	4.05s=0.14	5.26 s=0.33

1) –measurement pointssituated above the zone of penetration in soil,

* – no result due to wear geometry of the elements making the measurements impossible,

** – no result due to wear of the cemented carbide plates,

– established for one element only due to wear geometry of the other elements making the measurements impossible

s– standard deviation, R – range

materials.Itshouldbeaddedthattheparticipationofgroovingwasthe highest in the A/1 and A/2 coulters, which can be explained by the higherplasticityofthesteelusedintheirstructure,resultingfromthe presenceofferrite.Inalltypesoftheexaminedcoulters,thedirectionsof grooves and scratches were coincident with the movement direction of the abrasive mass. Only a small part had with different directions of groovesandscratches,whichindicatesthattheabrasivefractionsactingonthesteelsurfaceterediversifiedwithregardtot hegraincoarseness.

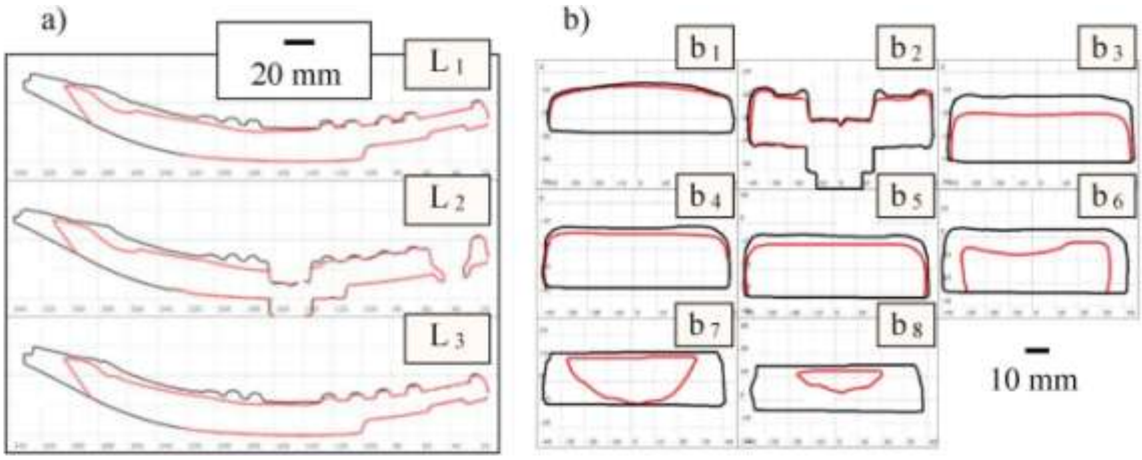


Fig.24. Cross-sectionsoftheA/1coulter(elementinstalledonthefourthcultivatorbeam,slidingdistance:1524.9km):a–longitudinalsections,b–perpendicular sections:b_1,b_2,b_3–sectionsintheareaofbasematerial,b_4,b_5,b_6–sectionsintheareaofpaddingweld,b_7,b_8–sectionsintheareaofcementedcarbideplates.

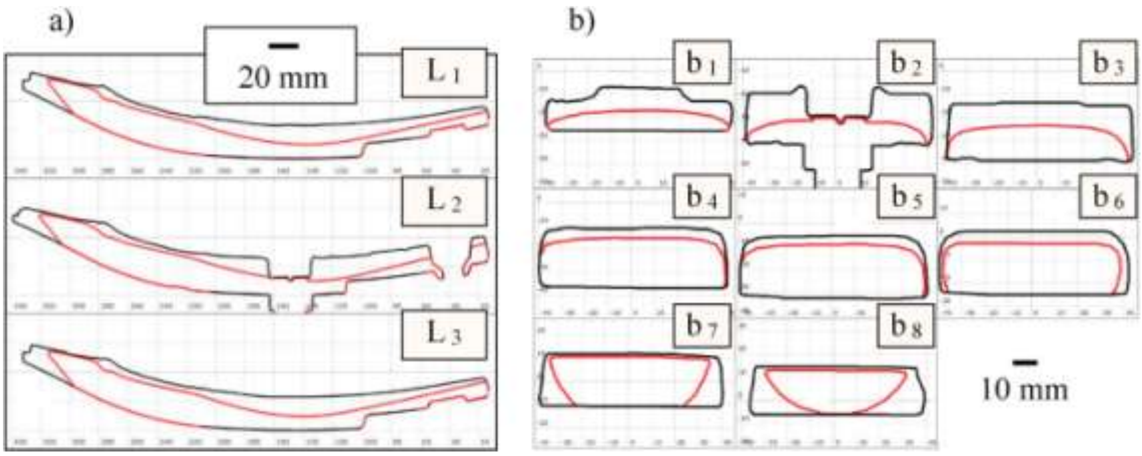


Fig. 25. Cross-sections of the A/2 coulter (element installed on the second cultivator beam, sliding distance: 1524.9 km): a – longitudinal sections,b–perpendicularsections:b_1,b_2,b_3 sectionsintheareaofbasematerial,b_4,b_5,b_6–sectionsintheareaofpaddingweld,b_7,b_8–sectionsintheareaof cemented carbideplates.

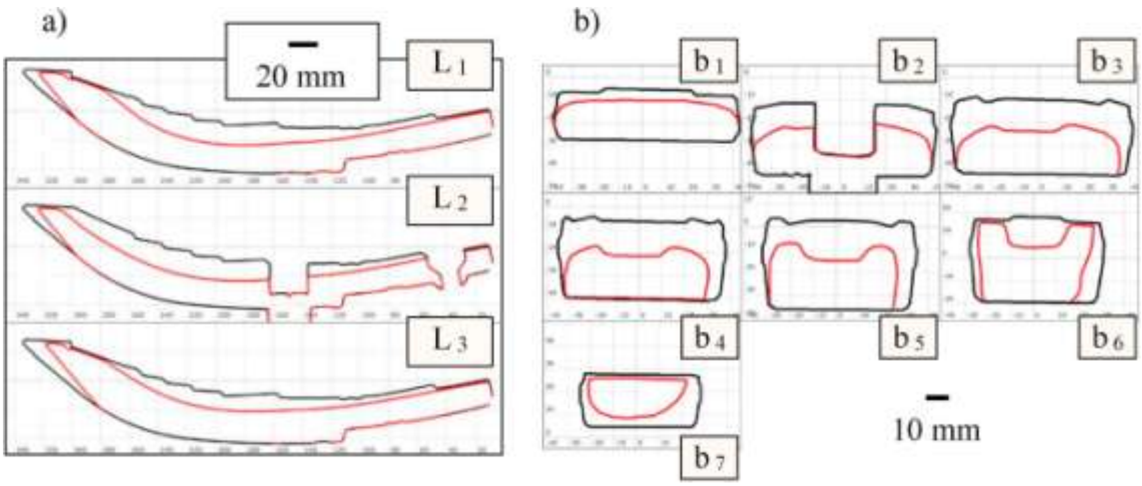


Fig. 26. Cross-sections of the B coulter (element installed on the fourth cultivator beam, sliding distance: 1524.9 km): a – longitudinal sections, b – perpendicular sections: b_1, b_2, b_3, b_4, b_5– sections in the area of base material, b_6, b_7– sections in the area of cemented carbide plates.

Thisisalsoconfirmedbythepresenceofpinholesonthesurfacesofthe base material of the coulters (Figs. 18 and 23), owing to the large and hard soilparticles.

CONCLUSIONS

Thetestedcoulters(A/1andB)werecharacterisedbyasimilarłuznychcharacterised by the highest intensity of wear (especially the B coulters installed on the first cultivator beam), in spite of their reinforcement by cemented carbide plates that formed blades. This indicates high load of the cutting edge of the elements, where the materialiswornbysoil,aswellasfromthesidesoftheflankfaceand the rake face. The most width reduction of the elements occurred in the area located directly behind the cemented-carbide plates and in the area of their brazing. However, the most thickness reduction of the coulters occurred in the base material area, which was particu- larly noticeable in the B coulters reinforced only with cemented- carbides plates. The amount of length, width, and thickness reduc- tion was the highest for the coulters on the first cultivator beam and was lower for the elements installed on the subsequentbeams.

1. Thebasicformofwearofthecemented-carbideplateswasremoval of the matrix by fine fraction of soil, leading to weaker mounting of carbide grains, followed by cracking, crushing or chipping of the grains due to the action of larger soil particles. Padding welds were subjected to a complex mechanism of abrasive wear, including delamination of the material, microcutting, and grooving. Such a course of wear of the padding welds was related to their irregular, multilayer microstructure. The dominant wear mechanism of the

steelwithmicroadditionofboronwasgroovingandmicrocutting.

2. Cemented carbide plates, which formed the blade of the coulters, were subjected to crushing on the edges, resulting in a rapid length reduction.Thus,crushingoftheplates(duetothepresenceofstones inthecultivatedsoils)canaffectthedurabilityoftheelements.
3. Thecoulterswere subjectedtovariousmechanismsandintensitiesof wear. With regard to the unit thickness reduction, the cemented carbideplateswerecharacterisedbythehighestresistancetowear. However, the material subjected to the most intensive wear wasthebase material.

Theuseofpaddingwelds(A/1coulters)resultedinimproved abrasive-wear resistance, as demonstrated by the lower rate of thickness and width reduction in relation to B coulters, in which this form of reinforcement did notoccur.

4. Thesurfacesofthecemented-carbideplatesandthepaddingwelds werecharacterisedbyhigherroughnessthanthesurfaceoftheless abrasive-wear-resistant base material of the coulters. This means that, in the present research, the roughness measurements of the working surfaces of the coulters should not be connected with the intensity of the destruction process but with the mechanism of this process.
5. The A/1 coulters were already tested in previous field research car- riedoutunderdifferentsoilconditions.Theresultsofthosetestsand our results indicate that, depending on the tillage conditions, abra- sivewearcausesvariousgeometricalchangesoftheelements.This indicates that further field research is necessary for objective eval- uation of the practical usefulness of tools working in soil, especially whentheyarebuiltofmaterialswithdifferentresistancestoabrasive wear.
6.

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