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SCIENTIFIC PAPERS

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POSSIBILITIES OF MODIFICATION OF TOOLS FOR CRUSHING UNWANTED GROWTH AND EVALUATION OF THE FINANCIAL COMPLEXITY OF THESE MODIFICATIONS

MOŽNOSTI ÚPRAV NÁSTROJOV PRE DRVENIE NEŽIADÚCIH NÁRASTOV A HODNOTENIE FINANČNEJ NÁROČNOSTI TÝCHTO ÚPRAV

***Miroslava Ťavodová, Richard Hnilica**

Department of Manufacturing Technology and Quality Management, Faculty of Technology, Technical University in Zvolen, Študentská 26, 960 01 Zvolen, Slovakia
email: tavodova@is.tuzvo.sk, richard.hnilica@tuzvo.sk

ABSTRACT: The article is published proposes a price calculation of the costs of modifications on exposed parts of tools used for crushing unwanted growth in the forest industry. The tool is subject to wear and tear of functional surfaces during operation. By modifying these surfaces with suitable procedures and methods such as heat treatment or application hard facing, the effort is to increase their service life and increase the time of work in operation. The cost of modifying these parts is another investment that will increase the price of the tool. Therefore, it is advisable to assess whether the tool will be modified as new, before being put into operation, or whether some of the modifications will be considered as renovation of an already worn tool. Seven methods of modifying the tool for crushing unwanted growths were selected. Two processes of heat and chemical-heat treatment and five hardfacing electrodes, applied by different welding methods. A simple cost calculation per tool was developed to determine how the cost of a tool for crushing unwanted growth would increase after applying modifications to the identified exposed areas. The price of the new tool is EUR 70.00 including VAT. Based on the calculation, we can conclude that the LNM 420 FM welding wire, the E DUR 600 electrode and the E520 RB electrode are the least expensive possibilities. The treatment of the entire tool by heat and chemical-heat treatment proved to be the least effective.

Key words: tools for crushing unwanted growths, costs, renovation, hardfacing, service life.

ABSTRAKT: V článku je uverejnený návrh cenovej kalkulácie nákladov na úpravy na exponovaných častiach nástrojov, používaných na drvenie nežiaducich porastov v lesnom hospodárstve. Nástroj počas prevádzky podlieha opotrebovaniu funkčných povrchov. Úpravou týchto povrchov vhodnými postupmi a metódami, ako je tepelné spracovanie alebo nanášanie tvrdonávarov je snahou zvýšiť ich životnosť a predĺžiť čas práce v prevádzke. Náklady na úpravu týchto dielov sú ďalšou investíciou, ktorá zvýši cenu nástroja. Bolo vybraných sedem spôsobov úpravy nástroja na drvenie nežiadúcich nárastov. Dva postupy tepelného a chemicko-tepelného spracovania a päť tvrdonávarových elektród, aplikované rôznymi metódami navárania. Bola vypracovaná jednoduchá kalkulácia nákladov na jeden nástroj, pre zistenie, ako by sa zvýšila cena nástroja na drvenie nežiaducich nástrojov po aplikácií úprav na identifikovaných exponovaných plochách. Cena nového nástroja je 70,00Eur s DPH. Na základe kalkulácie môžeme konštatovať, že najmenej cenovo náročné sú návarový drôt LNM 420 FM, elektróda E DUR 600 a elektróda E520 RB. Najmenej sa osvedčila úprava celého nástroja tepelným a chemicko-tepelným spracovaním.

Kľúčové slová: nástroje na drvenie nežiaducich porastov, náklady, renovácia, naváranie, životnosť.
hydraulický systém, údržba

INTRODUCTION

Tools for the disposal and crushing of unwanted growths are fixed on additional work equipment - adapters, which are designed with the intention of effectively expanding the technological usability of universal mobile work machines and increasing their time utilization [HNILICA, R. et al. 2015, ŤAVODOVÁ, M. et al.2018] The tools used in forestry are not given as much attention as, for example, as a tool for use in agriculture, in the excavation and mining of rocks, construction and improvement of roads, etc. In doing so, they work in a heterogeneous environment where they are subject to abrasive wear, which results in their relatively early decommissioning [ŤAVODOVÁ, M. et al. 2018, KALINCOVÁ, D. et al. 2016]. Also, due to their price, they represent a non-negligible item for companies operating in forestry. Several methods can be used to increase the service life of tools. Several authors, e.g. [KALINCOVÁ, D. et al. 2016, ŽÚBOR, P. et al. 2014, WIESIK J., ANISZEWSKA M. et al. 2011] theoretically described in their research papers the influence of factors on the abrasive wear of materials. These are the effects of mechanical properties, structure, chemical elements and the influence of the abrasive.

Heat treatment affects not only mechanical properties (strength, toughness) but also technological and many physical properties. Since the achievement of the equilibrium state during phase transformations in the solid state is determined by diffusion, the course of diffusion has a decisive influence on the result of heat treatment. Its size is affected by temperature, duration (time) at the temperature at which diffusion should take place [ŤAVODOVÁ, M. et al.2017, CHELPURI R. 2016]. Through chemical-thermal processing, layers with different chemical compositions are formed on the surface of the material of parts and tools. In general, chemical-heat treatment is defined as a process in which the surface is saturated. By changing the chemical composition of the surfaces of metals and alloys, the desired mechanical properties are achieved - increased hardness, increased resistance to wear, corrosion, impact and fatigue, etc., or physical properties [HLUCHÝ M. 1995]

Hardfacing consumables materials represent a wide range of alloys based on Fe, Ni, Co with the addition of carbide-forming elements (Cr, W, Mo, V, Ti, Nb), or other alloys (B, Si, etc.). Electrodes with a high chromium content are often they are used for their low cost and good resistance to particle wear. More expensive alloys that contain carbide-forming elements such as W, V and Nb combine the high hardness of the carbide phases with the toughness of the metal matrix. Carbides, due to their high hardness, represent obstacles against the penetration of hard particles. The metal matrix must resist the scoring effect of the particles and at the same time prevent the carbides from breaking out. Relatively soft but tough alloys are sometimes used in the combined action of abrasion and impacts. This group of weld alloys includes austenitic manganese steels, ledeburitic materials, martensitic alloys, ferritic-carbiditic and high-alloy steels hardenable in air [FALAT, L., et al. 2019, PARI L. et al. 2017, KRAUZE, K., 2017, PADHIAR, S. A, VINCENT, S. 2020, CORREA, E. O., et al. 2015, BUCHELY, M. et al, 2015].

Although modifications of the functional surfaces of tools can ensure the extension of their service life, they represent an increase in their price. By evaluating the impact of tool modification in terms of increased service life in relation to the modification price, we can achieve satisfactory results that lead to a reduction in the cost of purchasing new tools.

MATERIALS AND METHODS

As the authors state in their research papers [ŤAVODOVÁ, M. et al. 2018, KALINCOVÁ, D. et al. 2016] the work of tools for environmental modification in forest cultivation is characterized by a high load in an inhomogeneous working environment. This environment is mainly processed wood of uneven composition, hardness and diameter. The second important component of this environment is the soil. On its surface, there are rocks and minerals of different size, hardness and origin, unpredictably and irregularly distributed. The high revolutions of the rotor of the adapter of the base machine ("Figure 1a., b."), on which the tools are stored, the uneven load of individual tools, in connection with the storage on the rotor, further contribute to their early wear, which affects their length of use in operation. In "Figure 1c.", nine tools are mounted in a row on the adapter cylinder to crush unwanted growth. As can be seen, the tools are in various stages of wear.

Fig. 1 Base machine in the field (a.); crusher work in the thicket (b.); base machine adapter rotor with attached tools in various stages of wear (c.)
Obr. 1 Bázový stroj v teréne (a), drvič pracujúci v poraste (b), rotor adaptéra bázového stroja s pripevnenými nástrojmi v rôznych štádiách opotrebenia (c)

The tools themselves are available on the market either as monolithic or as a composite tool body with tips. Tips are usually made of sintered WC carbides [ŤAVODOVÁ, M. et al., 2018, KALINCOVÁ, D. et al. 2016]. In practice, it often happens that after a certain period of work in the forest, due to the heterogeneity of the environment and the dynamic load of the tool, the tip is lost, or tips, and further the body of the tool wears and deforms. In "Figure 2a." is a new tool for crushing unwanted growths and "Figure 2b." a discarded tool that, due to its damage, is unable to further process wood mass.

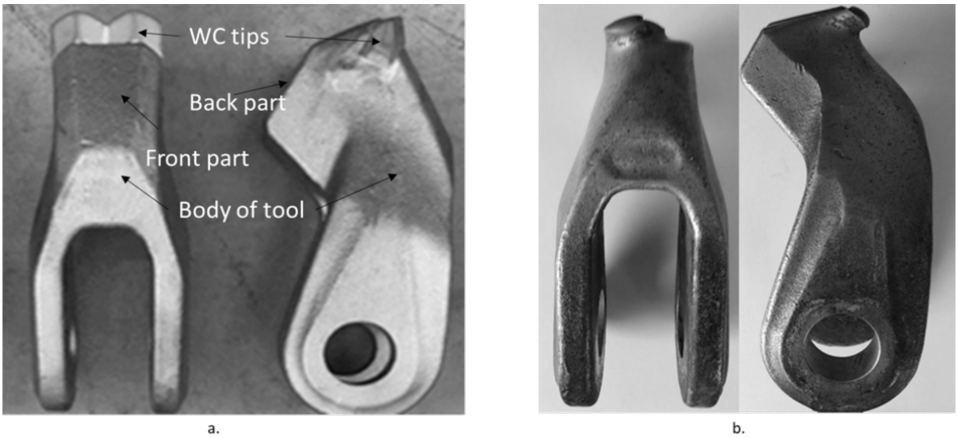


Fig. 2 New tool for crushing unwanted growth (a.) and worn after decommissioning (b.)
Obr. 2 Nový nástroj pre drvenie nežiadúcich nárastov (a) a opotrebenie po vyradení z prevádzky (b)

According to [KALINCOVÁ, D. et al. 2016], the tool body is made of 16MnCr5 material (Wr.Nr. 1.7131). It is a structural low-alloy cementing, chromium-manganese. It belongs to the group of steels with a low carbon content. This steel, with its mechanical properties and ferritic-pearlitic structure, cannot withstand the mechanical stress of the working environment even for a short time. Strengthening of the material from increased stress, which is a manifestation of cold plastic deformation, increases its hardness and thus also its fragility. Cyclic repetition of plastic deformation of the tool under abrasion conditions leads to strengthening of the surface of the material and, after the loss of tungsten carbide tips, the material on the back and sometimes the front surface of the tool decreases over time (“Figure 3”).

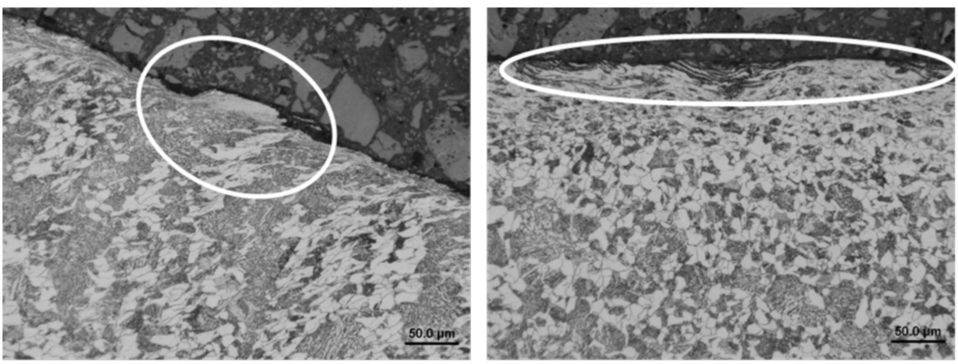
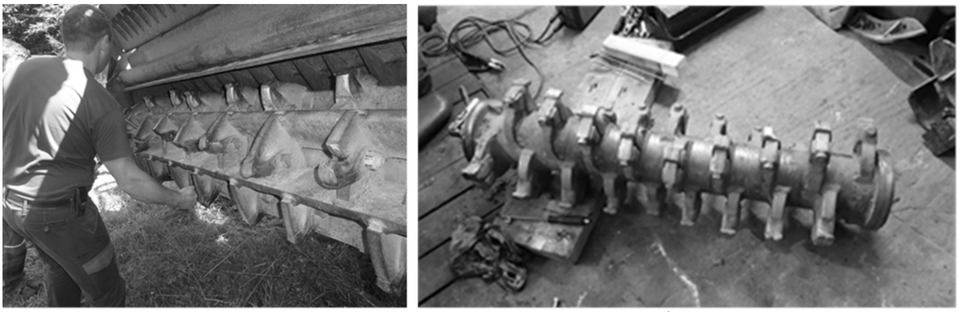


Fig. 3 Ferritic-pearlitic structure of 16MnCr5 steel with visible plastic deformation on the worn surface
Obr. 3 Feriticko-perlitická štruktúra ocele 16MnCr5 s viditeľnou plastickou deformáciou na opotrebovanom povrchu

This wear is then very significant after a short time, and this is what leads to the loss of functionality of the tool and its premature decommissioning [KALINCOVÁ, D. et al. 2016]. It is very often necessary to replace tools directly in the field (“Figure 4a”). It is difficult mainly because two men need to do it. In “Figure. 4b.” is the assembled rotor of the adapter of the base machine in the workshop before replacement, or by renovating tools.



a. b.

Fig. 4 Rotor of the adapter in the terrene (a.) and in the workshop before changing the tools (b.)
Obr. 4 Rotor adaptéra v teréne (a) a v dielni pred výmenou nástrojov (b)

Basic research works in the field of application of methods that lead to higher resistance to abrasive wear of metal materials when rubbing against an abrasive surface have been described by several authors in older and newer literature [ZUM GAHR K.– H., 1998, SUCHÁNEK J., KUKLÍK V., ZDRAVECKÁ E., 2007, Kolektív autorov 2003, PRŮCHA V., HÁJEK J., KŘÍŽ A. 2015].

Resistance to abrasive wear of exposed surfaces of machine parts, tools, etc., is generally achieved by technological interventions on the surface, which qualitatively change the properties of the basic material [SUCHÁNEK J., KUKLÍK V., ZDRAVECKÁ E., 2007; Kolektív autorov 2003]. We can state that there are several options for increasing the wear resistance of tools:

- application of elements from WC or properties of similar materials on parts of the body of the instrument,
- technological processes of heat treatment of the body of the tool in order to create a structure more resistant to wear,
- hardfacing on the exposed, most heavily loaded parts of the tool body,
- complete change of tool material – e.g. steels such as HARDOX, SECURE, ABRACORR, etc.

RESULTS AND DISCUSION

On the basis of the preliminary analyses carried out on the worn tool of the crusher of unwanted growth, in order to achieve such structures that would ensure an increase in the resistance to abrasive wear of the tools and thus an increase in their service life, published in [ŤAVODOVÁ, M. et al., 2018; KALINCOVÁ, D. et al., 2016; ŤAVODOVÁ, M., HNILICOVÁ, M., MITURSKA, I. 2019] and also based on theoretical knowledge, the following procedures and methods were selected:

– technological procedures of heat and chemical-heat treatment - all tools were modified:
  1. hardening followed by tempering;
  2. carburizing;
– application of hardfacing materials on exposed parts, where the following hardfacing materials were selected:
  3. electrode E520 RB;
  4. filled rod for manual flame welding RD 571;
  5. hardfacing wire LNM 420FM;
  6. electrode E DUR 600;
  7. WEARTRODE 62 electrode.

A simple cost calculation per tool was therefore developed to determine how the cost of a tool for crushing unwanted tools would increase after applying modifications to the identified exposed areas. The price of the new tool is 70.00 Eur, including VAT. For heat and chemical-heat treatment, the price for overheads is listed in "Table 1". On average, for heat treatment, the price for hardening is EUR 3.00 per kilogram of material and for cementation 6.00 Eur per kilogram of material. The tool for crushing unwanted growths has a weight of 1,730 kg.

Table 1. Calculation of the costs of modifying the tool by heat and chemical-heat treatment
Tabuľka 1 Výpočet nákladov úpravy nástroja tepelným a chemicko-tepelným spracovaním

Method of Treatment	Costs (Eur)	Total price of the tool (Eur)
Hardening and tempering	5.20	70.00 + 5.20 = 75.20
Carburizing	10.38 + 5.20 = 15.60	70.00 + 15.60 = 85.60

Overhead during welding is determined by the price of the welder‘s work. This is an average of 7.00 Eur/hour. [Careerjet, 2023]. When we add to this the price for energy consumption, which cannot be clearly quantified, in the same value as the welder‘s work, we get a price of 14.00Eur/hour. The price of the hardfacing material is added to this.

According to the information of the workers of the welding operations, during electrode hardfacing and manual flame hardfacing, on average, a skilled welder adjusts 6 tools in one hour. This means that the total overhead for editing one tool is 2.40 Eur. When hardfacing with solid wire, an average skilled welder adjusts about 10 tools in one hour. In this case, this means that the total overhead for editing one tool is 1.40 Eur. The availability of hardfacing material on the market was also evaluated ("Table 2").

Table 2. Calculation of the costs of modifying the tool by hardfacing on the surface of the back and (front) face of the tool
Tabuľka 2 Výpočet nákladov úpravy nástroja tvrdonávarom na povrchu chrbta a čela

Hardfacing material	**Availability on the market**	**Price for kg (Eur)**	**Used material for hardfacing (kg)**	**Costs (Eur)**	**Total price of the tool (Eur)**
Electrode E520 RB	Purchase only from the manufacturer VÚZ Bratislava	10.07	3pc x 0.031 = 0.093	2.40+0.93 = 3.33	70+3.33 = 73.33
Filled rod RD 571	Purchase only from the manufacturer VÚZ Bratislava	80.91	3pc x 0.066 = 0.198	2.40+16.02 =18.42	70+18.42 = 88.42
Hardfacing wire LNM 420FM	Available in stores with welding equipment	16.67	6m x 0,008 = 0.048	1.40+0.80 = 2.20	70.00+2.20 = 72.20
Electrode E DUR 600	Available in stores with welding equipment	9.80	2pc x 0.017 = 0.034	2.40+0.33 = 2.73	70.00+2.73 = 72.73
Electrode WEARTRODE 62	Available in stores with welding equipment	51.5	2ks x 0.017 =0.034	2.40+1.75 =4.15	70+4.15 = 74.15

In the case of hardface on the face, front and back of the tool, its price will increase in some cases by more than 15.00 Euros, which represents a price increase of 20% of the price of a new, unmodified tool.

Table 3. Order of the price value of tools with hardface on the surface of the back and front of the tool
Tabuľka 3 Poradie cien nástrojov s tvrdonávrom na povrchu chrbta a čela nástroja

Tool number	Tool modification type	Serial number according to modification	Price increase (Eur)	The final price of the tool (Eur)
0	**unedited**	0	0.00	70.00
1	**Hardfacing wire LNM 420 FM**	5	2.20	72.20
2	**Electrode E DUR 600**	6	2.73	72.73
3	**Electrode E520 RB**	3	3.33	73.33
4	**Electrode WEARTRODE 62**	7	4.15	74.15
5	**Heat treatment**	1	5.20	75.20
6	**Carburized**	2	15.60	85.60
7	**Filled rod RD 571**	4	18.42	88.42

According to the calculated values, a graph was made from the values in "Table 3" (Figure 5).

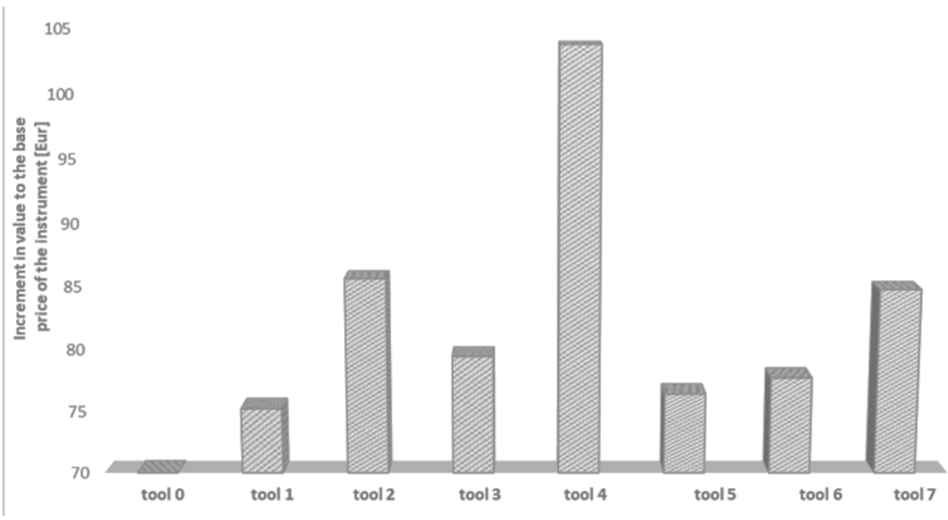


Fig. 5 Cost of modifying individual tools
Obr. 5 Náklady na úpravu jednotlivých nástrojov

The research prompted by the requirements of practice was aimed at solving the problem of low service life of tools for crushing unwanted growths, which were quickly subject to wear in a heterogeneous environment. Therefore, in order to increase the service life of these tools, procedures and methods of modifying the body of the tool were specified, namely by heat and chemical-heat treatment and hardface - application of hard facing materials.

We hypothesized that a tool with a more durable structure and more suitable mechanical properties could better withstand adverse operating conditions. As can be seen from "Table 3" and the graph in "Figure 3", both methods of modifying the tool by heat treatment proved to be financially demanding. According to the research results published in works [KALINCOVÁ, D. et al., 2016; ŤAVODOVÁ M., KALINCOVÁ, D., ŠVANTNER T. 2017; FALAT, L., et al. 2019], these two methods did not prove themselves even in terms of increasing resistance to abrasive wear. On the contrary, treatment with hardfacing materials - welding wire LNM 420 FM, electrode E DUR 600 and electrode E520 RB is the least expensive. From the evaluation of mechanical properties, microstructure, quality of mixing and cohesion of individual layers of materials as well as the overall quality of weld metals, from the results obtained by laboratory tests and tests published in [KALINCOVÁ, D. et al.., 2016; ŤAVODOVÁ, M et al., 2018; ŤAVODOVÁ, M., KALINCOVÁ, D., SLOVÁKOVÁ, I. 2018 FALAT, L., et al. 2019], we can recommend these for practice.

CONCLUSION

The research prompted by the requirements of practice was aimed at solving the problem of low service life of tools for crushing unwanted growths, which were quickly subject to wear in a heterogeneous environment. Therefore, in order to increase the service life of these tools, procedures and methods of modifying the body of the tool were specified, namely by heat and chemical-heat treatment and welding - application of hard welding materials. We hypothesized that a tool with a more durable structure and more suitable mechanical properties could better withstand adverse operating conditions.

On the basis of the price calculation, three hardfacing materials were evaluated as affordable, considering the increase in the price of the tool. When recommending these coatings, their overall suitability for increasing tool life was also taken into account. These were mainly mechanical properties, mixing of the hardfacing metal with the base material as well as their resistance to abrasive wear. Heat treatment methods are expensive and, in the overall assessment, they are not considered appropriate to use in practice.

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REFERENCES

BUČKO, M., SCHINDLEROVÁ, V., KREJČÍ, L., HLAVATÝ, P., HLAVATÝ, J. 2019 Application of welds on the high-carbon steel rails. In *METAL 2019* : conference proceedings : peer reviewed : 28th International Conference on Metallurgy and Materials : May 22nd-24th 2019, Hotel Voronez I, Brno, Czech Republic, EU. Ostrava: Tanger, 2019, s.1003-1009. https://doi.org/10.37904/metal.2019.886

BUCHELY, M.F., GUTIERREZ, J.C., LEÓN, L.M., TORO, A. 2005. The effect of microstructure on abrasive wear of hardfacing alloys. In. *Wear*, Volume 259, Issues 1-6, pp. 52-61. https://doi.org/10.1016/j.wear.2005.03.002

Careerjet [online]. [cit.02.9.2023]. Dostupné na https://www.careerjet.sk/zamestnanie-zivnost-zvarac.html.

CORREA, E. O., ALCÂNTARA, N. G., VALERIANO, L. C., BARBEDO, N. D., & CHAVES, R. R. 2015 The effect of microstructure on abrasive wear of a Fe–Cr–C–Nb hardfacing alloy deposited by the open arc welding process. In *Surface and Coatings Technology*, 276, 479-484. https://doi.org/10.1016/j.surfcoat.2015.06.026

FALAT, L., DŽUPON, M., ŤAVODOVÁ, M., HNILICA, R., ĽUPTÁČIKOVÁ, V., ČIRIPOVÁ, L., HMOLOVÁ, V., ĎURIŠINOVÁ, K. 2019. Microstructure and abrasive wear resistance of various alloy hardfacings for application on heavy-duty chipper tools in forestry shredding and mulching operations. In Materials. 2019, no. 12, vol. 13. ISSN 1996-1944.

HLUCHÝ M. 1995 Strojírenská technologie, Metalografie a tepelné zpracovaní, Scientia, spol. s r.o. 1995 ISBN 80-7183-034-8.

HNILICA, R., MESSINGEROVÁ, V., STANOVSKÝ, M., SLUGEŇ, J., HNILICOVÁ, M., FERENČÍK, M. 2015 Možnosti mechanizácie prác pri zakladaní a výchove lesa. *Vedecká monografia* 2015, 99 strán, ISBN 978-80-228-2722-5.

CHELPURI R. (2016) Some studies on wear characteristic of rotavator blades, Indirra Gandhi Krishi Vishwavidyalaya Raipur 2016. [online]. [cit. 13.11.2023]. http://krishikosh.egranth.ac.in/handle/1/68838

KALINCOVÁ, D., ŤAVODOVÁ, M., HNILICOVÁ, M., VEVERKOVÁ, D. 2016. Machinery for forest cultivation - increase of resistance to abrasive wear of the tool. In *MM science journal*. No. November (2016), p. 1269-1272. - ISSN 1803-1269.

Kolektív autorov. Materiály a ich správanie sa pri zváraní. VÚZ – Priemyselný inštitút, Bratislava (2003) 355 s. ISBN 80-88734-10-X.

KRAUZE K., BOŁOZ Ł., WYDRO T., MUCHA K. 2017 Durability testing of tangential-rotary picks made of different materials, In: *Mining – Informatics, Automation and Electrical Engineering* nr 1, 2017, pp. 26-34. http://dx.doi.org/10.7494/miag.2017.1.529.26

PADHIAR, S. A, VINCENT, S. 2020 Effect of hard facing processes on Mild steel A-36 by arc welding. In *Materials Today*: Proceedings, Volume 28, Part 2, 2020, Pages 526-531, ISSN 2214-7853, https://doi.org/10.1016/j.matpr.2019.12.213.

PARI L., SUARDI A., SANTANGELO E., GARCÍA-GALINDO D., SCARFONE A., ALFANO V. 2017 Current and innovative technologies for pruning harvesting: A review. *Biomass and Bioenergy* 107, (2017) 398e410. journal homepage: [online]. [cit.11.11.2023]. http://www.elsevier.com/locate/biombioe.

PRŮCHA V., HÁJEK J., KŘÍŽ A. 2015. Analýza tribologických vlastností - odolnost proti kontaktnímu namáhání. In *Vrstvy a povlaky 2015*. Trečianska Teplá: M-Press s.r.o., 2015. s. 145-150. ISBN: 978-80-972133-0-5.

SUCHÁNEK J., KUKLÍK V., ZDRAVECKÁ E. 2007 Abrazívní opotřebení materiálů. Praha ČVUT, 2007. 162s. ISBN 978-80-01-03659-4

ŤAVODOVÁ, M., KALINCOVÁ, D., KOTUS, M., PAVLÍK, Ľ. 2018. The possibility of increasing the wearing resistance of mulcher tools In *Acta technologica agriculturae*, 2018, Vol. 21, no. 2, p. 87-93, ISSN 1335-2555.

ZUM GAHR K.– H. 1998. Wear by hard particles, *Tribology International*, Vol. 31, No. 10, 1998 pp. 587-596.

ŤAVODOVÁ, M., DŽUPON, M., KALINCOVÁ, D., HNILICOVÁ, M. 2018. Deformation of exposed parts tool for crushing of undesirable advance growths. In *Acta technologica agriculturae*: 2018. č. no. 4, s. 169--176. ISSN 1335-2555.

ŤAVODOVÁ, M., HNILICOVÁ, M., MITURSKA, I. 2019. Analysis of hard facing material designed for application on the forestry tools In *Advances in science and technology research journal.* 2019. č. no. 4 , s. 111-119. ISSN 2080-4075.

ŤAVODOVÁ M., KALINCOVÁ, D., ŠVANTNER T. 2017. Heat treatment - the tool for increasing wear resistance of material In: *26th national conference on heat treatment : 21. - 23.11.2017, Jihlava, Czech Republic. –* Čerčany*, 2017*, ISBN 978-80-907043-0-5. - s.8.

ŤAVODOVÁ, M., KALINCOVÁ, D., SLOVÁKOVÁ, I. 2018. Evaluation of some parameters of hard surfacing treatment of the functional surfaces of forestry tools In *Management systems in production engineering*. 2018. s. 222-226. ISSN 2299-0461.

WIESIK J., ANISZEWSKA M. 2011 Urzadzenia Techniczne w produkcji lesnej, Tom 1 Urzadzenia do hodowli i ochrony lasu, Warszawa 2011, ISBN 978-83-7583-219-8, s.237-240.

ŽÚBOR, P., IŽDINSKÁ, Z., KOVAŘÍKOVÁ, I. 2014 Materiály a ich správanie sa pri zváraní, Prvá zváračská, a.s., 2014.

Corresponding author:
Miroslava Ťavodová, tavodova@tuzvo.sk

DETERMINING THE BASIC TECHNICAL PARAMETERS OF THE KNIFE SHREDDER USING THEORETICAL CALCULATION

ZISŤOVANIE ZÁKLADNÝCH TECHNICKÝCH PARAMETROV NOŽOVÉHO DRVIČA POMOCOU TEORETICKÉHO VÝPOČTU

Vladimír Mancel[1], Jozef Krilek[1]

[1]Department of Environmental and Forestry Machinery, Faculty of Technology, Technical University in Zvolen, Študentská 26, 960 01, Zvolen, Slovakia, mancelvladimir@gmail.com, jkrilek@gmail.com

ABSTRACT: The focus of the contribution is on the theoretical computation of the knife shredder DP 11-240/350's technical specifications and the following comparison of the required theoretical cutting power with information from the manufacturer. The aforementioned knife shredder can be used to shred smaller pieces of wood, rubber, paper, or textiles in addition to its primary purpose of breaking plastics. The DP 11-240/350 knife shredder is described in detail along with the fundamental theory of shredders. The methodology for calculating the cutting speed, shear stress, mean hole length, cutting force, required power of the electric motor, cutting power, and torque is also covered in the paper, and the results are evaluated at the end. The contribution's goal is to theoretically determine the technical specifications of the shredder for a particular kind of material, specifically polypropylene (PP). According to calculations, the required cutting power was at a level of about 11.17 kW, but the manufacturer indicates that this value is at a level of 11 kW. Based on the findings, it can be concluded that the shredder's cutting capabilities for the polypropylene material are enough for its shredding.

Key words: knife shredder, cutting power, polypropylene, theoretical calculation

ABSTRAKT: Zameraním príspevku je teoretický výpočet technických špecifikácií nožového drviča DP 11-240/350 a následné porovnanie požadovaného teoretického rezného výkonu s informáciami od výrobcu. Spomínaný nožový drvič je možné použiť na drvenie menších kusov dreva, gumy, papiera alebo textílií okrem jeho primárneho účelu, ktorým je drvenie plastov. Nožový drvič DP 11-240/350 je podrobne opísaný spolu so základnou teóriou drvičov. Príspevok sa zaoberá aj metodikou výpočtu reznej rýchlosti, šmykového napätia, strednej dĺžky otvoru, reznej sily, požadovaného výkonu elektromotora, rezného výkonu a krútiaceho momentu a v závere sú vyhodnotené výsledky. Cieľom príspevku je teoreticky určiť technické špecifikácie drviča pre konkrétny druh materiálu, konkrétne polypropylén (PP). Požadovaný rezný výkon bol podľa prepočtov na úrovni cca 11.17 kW, no výrobca uvádza túto hodnotu na úrovni 11 kW. Na základe zistení možno usúdiť, že rezné schopnosti drviča pre polypropylénový materiál postačujú na jeho drvenie.

Kľúčové slová: nožový drvič, polypropylén, rezný výkon, teoretický výpočet

INTRODUCTION

Most of the processing companies require that the waste from reprocessing reaches them in the cleanest and best processable form possible. Shredders are primarily used for these purposes. Band saws or ultrasonic cutters are also used to reduce large pieces of waste. The shredder is therefore a very important part of waste processing in general. The input is objects of various sizes, which, after passing through the shredder, turn into pieces of approximately the same size with a smaller fraction than the input one. There are many types of shredders, which are divided according to different criteria. When shredding, it is necessary to know well the materials that will be shredded. Accordingly, it is possible to subsequently choose a suitable type of shredder. Shredders can be divided into slow-speed (on the order of units to tens of revolutions per minute) and high-speed (on the order of hundreds of revolutions per minute). Slow-moving ones are often used for initial shredding of large pieces. In contrast, high-speed ones are used more to fine-tune the final size of the granulate fraction, the output of which has smaller dimensions. When shredding, it is necessary to take into account that some plastics have a low melting point and can partially melt in the shredder and stick to its cutting tools. Another phenomenon that can occur with a bad setting of a high-speed machine is excessive dust (Junga *et al*. 2015; Gunaratne *et al*. 2022).

Historically, shredders were first used to crush rocks and ores. Today, jaw shredders, impact shredders, cone shredders, hammer shredders or roller shredders are used for shredding these materials. However, some shredders cannot be used for optimal shredders of plastics with a fine fraction or their use would be inefficient. Their possible use would only make sense as before shredding bulky plastic parts (bumpers, tanks). Hammer, roller and knife shredders are used for pre-shredding and shredding of plastics (Pospíšil 2010; Gunaratne *et al*. 2022).

Hammer shredders

They are used for fine shredding of soft and medium hard non-sticky materials. The basic parts of the shredder are made up of a steel chamber, a rotor with rigidly or rotatably fixed arms (hammers) that crush the material during impacts, and a screen that determines the output fraction of the granulate. This type of shredder is usually used in the processing of construction and demolition waste. When recycling plastic, its use is suitable where there are large bulky plastic parts, such as the front bumper, rear bumper or fuel tank, which need to be reduced to smaller fractions. This type of shredder is not very suitable for obtaining a fraction with a size of 5 mm and smaller (Kuta 1999). The shredding scheme of the hammer shredder is shown in the following figure (Figure 1).

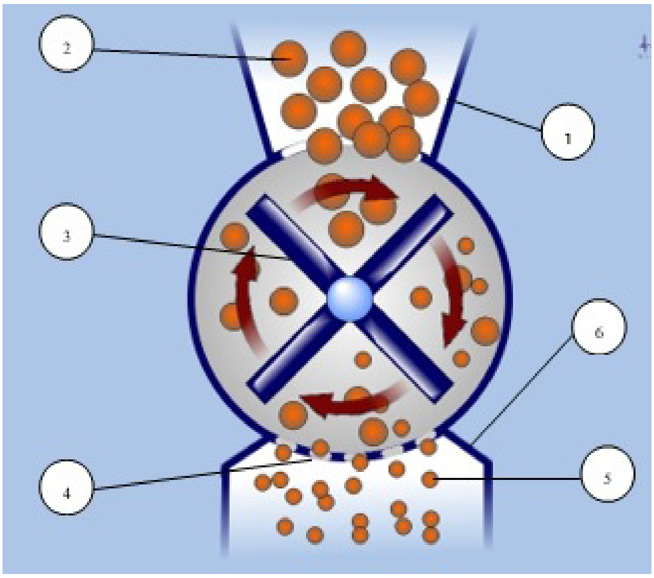

Fig. 1 Hammer shredder crushing scheme (www.lat.zshk.cz)
Obr. 1 Schéma drvenia kladivového drviča (www.lat.zshk.cz)
1 – input, 2 – material, 3 – hammer, 4 – sieve, 5 – granulate, 6 – output

Roller shredders

The single-shaft roller shredder is a slow-moving type of shredder. Its main part consists of a slowly rotating cylinder, which can be smooth, grooved, equipped with spikes, knives, blades or can be shaped differently. A fixed counter knife of different shape is placed against this rotating cylinder. There is a clearance between the rotating cylinder and the counter knife, which is designed according to the desired size of the output fraction. As a rule, the design of this clearance must be tested and adjusted in practice as necessary, because the deformation, shredding, shearing and splintering of plastics is an unpredictable process. To make the output from the shredder as homogeneous as possible, sieves are placed under the shredder. The size of the mesh holes defines the size of the output granulate. The material that does not pass through the screen is driven back into the shredding area and shredded until it reaches a size that will pass through the screen. In general, the smaller the output fraction, the longer the shredding process takes. This type of shredder normally achieves fractions of size from 5 to 100 mm. The advantage of roller shredders is quiet operation and high shredding power. These types of shredders have higher torque and lower revolutions than, for example, knife shredders (Junga *et al*. 2015). The shredding scheme of a single shaft roller shredder is shown in the following figure (Figure 2).

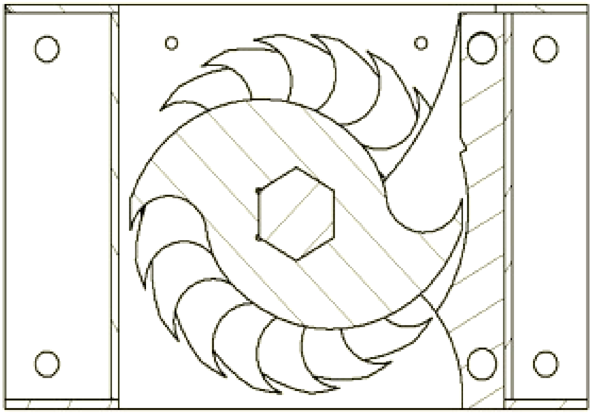

Fig. 2 Shredding scheme of a single-shaft roller shredder (Květoun 2019)
Obr. 2 Schéma drvenia jednohriadeľového valcového drviča (Květoun 2019)

A roller shredder with two or more shafts is classified as a low-speed shredder. The principle of a twin-shaft or multi-shaft shredder is the same. Adding more shafts will increase the crushing power. Multi-shaft shredders are suitable for large volumes of materials and in large recycling lines. The principle is the same for single-shaft shredders, except that the shredding process also takes place between individual cylinders. The cylinders can rotate against each other at the same or different angular velocities. The advantage of a two-shaft shredder is greater shredding power and the possibility of processing larger pieces (Štepek 1989). The shredding scheme of the two-shaft shredder is shown in the following figure (Figure 3).

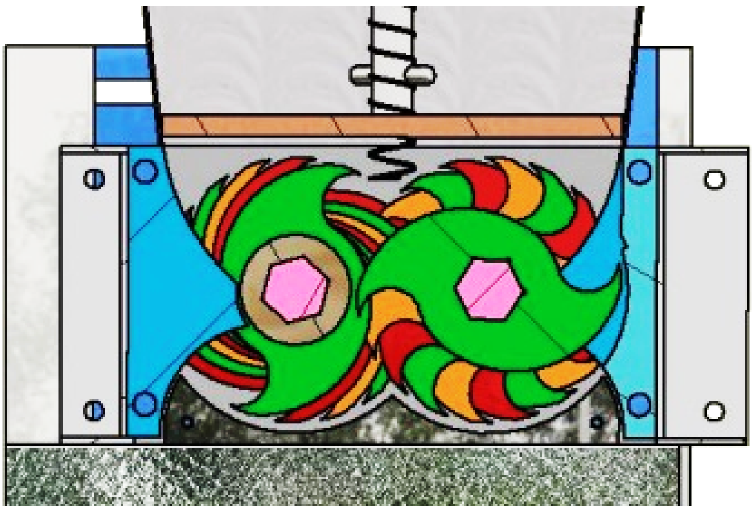

Fig. 3 Shredding scheme of a two-shaft roller shredder (Květoun 2019)
Obr. 3 Schéma drvenia dvojhriadeľového valcového drviča (Květoun 2019)

Knife shredders

A knife shredder is a high-speed type of shredder. Its main part is rotating and stationary knives. As a rule, they consist of two to six knives, rotating on the order of hundreds of revolutions per minute. There are usually at least two stationary knives. There is a clearance between the rotating and stationary knives, thanks to which the knives do not collide and the material is cut. The size of this clearance has a great influence on the resulting granulate fraction. Thanks to their design and sieves, knife shredders can achieve very low and uniform fractions of granules (on the order of a few millimetres). Another advantage is that a large gear ratio is not required. Their disadvantage is relatively high noise, approximately 90 dB, which can be removed by placing the shredder in a sound-proof space. Another disadvantage is that the shredder is not suitable for shredding bulky symmetrical parts, because materials get stuck between the blunt parts of the rotor and stator (Pospíšil 2010; Wong *et al*. 2022). The shredding scheme of the knife shredder is shown in the following figure (Figure 4).

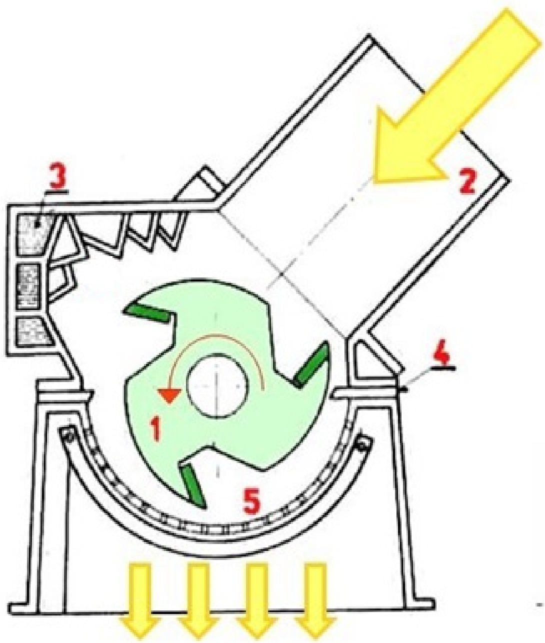

Fig. 4 Knife shredder crushing scheme (Holík 2021)
Obr. 4 Schéma drvenia nožového drviča (Holík 2021)
1 – rotating knives, 2 – input, 3 – construction, 4 – stationary knife, 5 – sieve

MATERIAL AND METHODS

This chapter describes a specific knife shredder, available in the laboratories of the Technical University in Zvolen, as well as the methodology for calculating the basic technical parameters of the mentioned shredder.

Knife shredder DP 11-240/350

The DP 11-240/350 shredder (Profing Piešťany s.r.o., Slovakia) (Figure 5) belongs to the group of high-speed knife shredders. The shredder is intended primarily for shredding plastics. However, it also reliably shreds rubber, wood shavings, textiles, paper, electrical scrap, electrical cables, polystyrene, as well as root and herb crops. The shredder finds effective use especially among manufacturers engaged in the production of plastic products, but also when shredding technological and municipal waste for the purpose of its subsequent recovery. The shredder can be operated with a suction device that transports the shredded material to the collection point. Without an extractor, shredded material falls directly into a bag attached to the dump. The rotor is housed in steel bearing bodies, which brings with it a longer service life and safety. Slanted knives ensure shredding of thick-walled materials. The possibility of setting a minimum shear clearance of 0.1 mm predetermines the shredder for crushing PET bottles, polyethylene films and microtene films. Mesh sizes of 1 mm, 2 mm, 4 mm, 6 mm, 8 mm and 11 mm are available for the shredder (www.profing.sk; Muthiah *et al*. 2022).

Fig. 5 Knife shredder DP 11-240/350
Obr. 5 Nožový drvič DP 11-240/350

The technical parameters are listed in the table (Table 1). The advantages of this crusher are a shear cut that ensures high material crushing efficiency, an easily replaceable sieve for the required size of crushed material, easy cleaning, adjustment and replacement of the cutting knives, which ensures easy maintenance, and a large addition of sharpening material, which ensures a long service life of the cutting knives (www.profing.sk).

Table 1 Technical parameters of the knife shredder DP 11-240/350 (www.profing.sk)
Tabuľka 1 Technické parametre nožového drviča DP 11-240/350 (www.profing.sk)

Parameter	Value
Shredder performance[1)] [kg.hod^{-1}]	80 - 220
Engine power[2)] [kW]	11
Rotor diameter[3)] [mm]	240
Length of rotor - knives[4)] [mm]	350
Number of knives - rotary/stationary[5)] [QTY]	3 / 2
Diameters of screen holes[6)] [mm]	1 - 40
Hopper opening[7)] (W x H) [mm]	280 x 250
Electrical connection[8)] [V/A]	400 / 32
Weight[9)] [kg]	290
Dimensions[10)] (L x W x H) [mm]	1070 x 610 x 1800

[1)]Výkon drviča, [2)]Výkon motora, [3)]Priemer rotora, [4)]Dĺžka rotora - nožov, [5)]Počet nožov - rotačné/pevné, [6)]Priemery otvorov v site, [7)]Otvor násypky, [8)]Elektrické pripojenie, [9)]Hmotnosť, [10)]Rozmery

The material of the cutting knives is highly alloyed ledeburitic tool steel 1.2379 / 19 573 / X155CrVMo121. The properties of the steel are high abrasion resistance, good hardenability, higher corrosion resistance. The steel must not be cooled with coolant during machining. The maximum achievable hardness is approximately 61 - 63 HRC (www.toolsteel.cz). As already mentioned in the disadvantages of high-speed shredders, it is necessary to have the required dimensions of the input material according to the parameters of the hopper, in this case a maximum of 200 x 250 x 10 mm.

Methodology for calculating technical parameters

To achieve the goal of the work, it is necessary to define the input parameters: shaft speed, shaft diameter, hole length, input material, failure strength of input material, electric motor efficiency and calculate the following parameters: cutting speed (v_c), shear stress (τ_s), mean hole length (l_{str}), cutting force (F_c), required electric motor power (P_r), cutting power (P_c), torque (M_k). We calculate the given parameters according to the following relations (www.garant-tools.com; Muthiah *et al*. 2022):

$$v_c = \frac{\pi . D . n}{1000} \qquad [m.min^{-1}] \tag{1}$$

$$\tau_s = 0.8.R_m \qquad [MPa] \tag{2}$$

$$l_{str} = \frac{L}{2} \qquad [mm] \tag{3}$$

$$F_c = \tau_s.l_{str} \qquad [N] \tag{4}$$

$$P_r = \frac{F_c.v_c}{1000} \qquad [kW] \tag{5}$$

$$P_c = \frac{P_r}{\eta} \qquad [kW] \tag{6}$$

$$M_k = 9554.\frac{P_c}{n} \qquad [N.m] \tag{7}$$

where D is shaft diameter [mm],
n is shaft speed [min^{-1}],
R_m is failure strength [MPa],
L is hole length [mm],
η is electric motor efficiency [%].

RESULTS AND DISCUSSION

Input parameters:
shaft speed n = 1060 min^{-1},
shaft diameter D = 60 mm,
hole length L = 250 mm,
input material - polypropylene,
failure strength R_m = 30 MPa,
electric motor efficiency η = 89.4 %.

Cutting speed:

$$v_c = \frac{\pi.60.1060}{1000} = \mathbf{199.81\ m.min^{-1}} \tag{8}$$

Shear stress:

$$\tau_s = 0.8.30 = \mathbf{24\ MPa} \tag{9}$$

Mean hole length:

$$l_{str} = \frac{250}{2} = \mathbf{125\ mm} \tag{10}$$

Cutting force:

$$F_c = 24.125 = \mathbf{3000\ N} \tag{11}$$

Required electric motor power:

$$P_r = \frac{3000.\frac{199.81}{60}}{1000} = \mathbf{9.99\ kW} \tag{12}$$

Cutting power:

$$P_c = \frac{9.99}{0.894} = \mathbf{11.17\ kW} \tag{13}$$

Torque:

$$M_k = 9554.\frac{11.17}{1060} = \mathbf{100.68\ N.m} \tag{14}$$

According to the above formulas, there were theoretically calculated the basic technical parameters of the DP 11-240/350 shredder. There were calculated the cutting speed, shear stress, mean hole length, cutting force, required electric motor power, cutting power and torque. Based on the calculated cutting power, the value of which was 11.17 kW, it can be concluded that the cutting power stated by the manufacturer (11 kW) is sufficient for shredding plastic materials composed of polypropylene. The deviation between the stated and the calculated value of the cutting power could be caused by the rounding of the values.

CONCLUSION

The theoretical basis of the contribution consists in the description of the types of shredders that are commonly used for shredding plastics, rubber, wood, paper or textiles, their advantages and disadvantages. Subsequently, the knife shredder type DP 11-240/350 from the company Profing s.r.o. which is available in the workshops of the Technical University in Zvolen, and the methodology for calculating basic technical parameters were described. In the final part of the contribution, there were calculated the basic technical parameters of the knife shredder DP 11-240/350, namely cutting speed with the value of 199.81 $m.min^{-1}$, shear stress with the value of 24 MPa, mean hole length with the value of 125 mm, cutting force with the value of 3000 N, required electric motor power with the value of 9.99 kW, cutting power with the value of 11.17 kW and torque with the value of 100.68 N.m. Based on the calculated result of the cutting force, it can be concluded that the stated value of the cutting force from the manufacturer for the polypropylene material is sufficient for shredding.

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REFERENCES

GARANT. Machining manual. [online], [cit. 2023-09-25]. Available on: www.garant-tools.com.

GUNARATNE, T., JOHANSSON, J., SVENSSON, N. 2022. Environmental potential of shredder fines valorisation. *Waste Management*, vol. 154, pp. 223-231. ISSN 1879-2456, DOI: 10.1016/j.wasman.2022.10.011.

HOLÍK, R. 2021. Structural design of a plastic disintegrator. Zvolen: Technical University in Zvolen. Diploma thesis.

JUNGA, P. VÍTĚZ, T., TRÁVNÍČEK, P. 2015. Waste treatment technique 1. Brno: Mendel University in Brno. ISBN 978-80-7509-207-6.

KUTA, A. 1999. Technology and equipment for processing rubbers and plastics. Prague: University of Chemistry and Technology Prague. ISBN 978-80-7080-367-7.

KVĚTOUN, J. 2019. Production of a shredder for plastic waste. Brno: Brno University of technology. Diploma thesis.

LABORATORY TECHNIQUE. Hammer mill. [online], [cit. 2023-09-25]. Available on: https://lat.zshk.cz/media.aspx?id=SLT023&TB_iframe=true&height=750&width=820.

MUTHIAH, E., RATHANASAMY, R., RAVICHANDRAN, D., PALANICHAMY, D., SIVARAJ, S. 2022. Experimental analysis on shredder for recycling thermoplastics using injection moulder. *Materials Today: Proceedings*, vol. 66, no. 3, pp. 797-803. ISSN 2214-7853, DOI: 10.1016/j.matpr.2022.04.353.

POSPÍŠIL, L. 2014. Recycling of thermoplastics, thermosets and rubber. [online], [cit. 2023-09-25]. Available on: https://docplayer.cz/11702199-Prakticke-priklady-z-literatury-a-praxe-vyrobky--patenty-recyklace-termoplastu-termosetu-a-pryti.html.

PROFING. Shredder DP 11-240/350. [online], [cit. 2023-09-25]. Available on: https://www.profing.sk/drvice-plastov/drvic-dp-11-240350.

ŠTEPEK, J., ZELINGER, J., KUTA, A. 1989. Processing technology and properties of plastics 1. Prague, Bratislava: SNTL, Alfa. ISBN 80-227-2256-1.

TOOLSTEEL. Tool steel 19 573. [online], [cit. 2023-09-25]. Available on: http://toolsteel.cz/1-2379-19-573-x153crmov12-x155crvmo12-1/.

WONG, J.H., KAREN, W.M.J., BAHRIN, S.A., CHUA, B.L., MELVIN, G.J.H., SIAMBUM, N.J. 2022. Wear Mechanisms and Performance of PET Shredder Blade with Various Geometries and Orientations. *Machines*, vol. 10, no. 9, pp. 760. ISSN 2075-1702, DOI: 10.3390/machines10090760.

Corresponding author:
Vladimír Mancel, tel. 045/5206878, email: mancelvladimir@gmail.com

REDUCTION OF THE HYDRAULIC POWER UNITS‘ ENVIRONMENTAL IMPACT USING CONDITION MONITORING TOOLS

ZNÍŽENIE ENVIRONMENTÁLNEHO DOPADU HYDRAULICKÝCH AGREGÁTOV S VYUŽITÍM NÁSTROJOV NA SLEDOVANIE STAVU PREVÁDZKOVÝCH KVAPALÍN

Jakub Drmla[1]

[1]*Katedra mechaniky, strojníctva a dizajnu, Fakulta techniky, Technická univerzita vo Zvolene, Študentská 26, 960 53 Zvolen, Slovenská republika, jdrmla@gmail.com*

ABSTRACT: The article emphasises tools which modern technical practice offers to mitigate the environmental impact of hydraulic power systems in general industry. We describe the basic measures to be considered when designing the hydraulic power unit (HPU) and share good practices when running the systems. However, the main focus of this article is on the periodical maintenance of the hydraulic systems with attention drawn to the use of condition monitoring tools. We highlight a practical example of 4 HPUs where regular condition monitoring and well-designed filtration can save hundreds of litres of hydraulic oil per year. Apart from the resource savings, good operational conditions of the machine are ensured, hydraulic components are running smoothly without breakdowns and the environmental impact of the machine is reduced thanks to the effective use of condition monitoring tools, leakages are prevented and most importantly, hydraulic oil is regularly filtered, re-used and not wasted routinely. As shown in our research example, the hydraulic oil cleanliness after 6 months does not correspond to the oil cleanliness levels recommended by the manufacturer of key hydraulic components. Despite operating in a rather clean, indoor environment, the lifting crane oil cleanliness was not satisfactory and dirt particles constitute a significant risk which underlines the importance of regular condition monitoring. By using advanced filtration and oil cleanliness monitoring we were able to re-use the hydraulic oil and save several hundred litres of hydraulic oil which would otherwise be wasted.

Keywords: oil cleanliness measurement, laser particle detector, hydraulic oil, hydraulic system, maintenance

ABSTRAKT: Článok kladie dôraz na nástroje, ktoré moderná technická prax ponúka na zmiernenie environmentálnych dopadov hydraulických energetických systémov vo všeobecnom priemysle. Opisujeme základné opatrenia, ktoré je potrebné zvážiť pri navrhovaní hydraulických agregátov a tiež zdieľame osvedčené postupy pri prevádzke týchto systémov. Hlavným zameraním tohto článku je však pravidelná údržba hydraulických systémov s dôrazom na používanie nástrojov na monitorovanie ich stavu. Vyzdvihujeme praktický príklad 4 hydraulických agregátov, kde pravidelné monitorovanie stavu a dobre navrhnutá filtrácia môžu ušetriť stovky litrov hydraulického oleja ročne. Okrem šetrenia zdrojov je zabezpečený dobrý prevádzkový stav stroja, plynulý chod hydraulických komponentov bez porúch a vďaka efektívnemu využívaniu nástrojov na monitorovanie stavu hydraulických kvapalín sa znižuje dopad stroja na životné prostredie, zabraňuje sa únikom oleja a hlavne, hydraulický olej sa pravidelne filtruje, opätovne používa a rutinne neplytvá. Ako ukazujú zistenia v našom prípade, čistota hydraulického oleja po 6 mesiacoch prevádzky nezodpovedá úrovniam čistoty oleja odporúčaným výrobcom kľúčových hydraulických komponentov. Napriek prevádzke v pomerne čistom vnútornom prostredí, čistota oleja zdvíhacieho žeriava nebola uspokojivá pretože častice nečistôt predstavujú značné riziko, čo len podčiarkuje dôležitosť pravidelného monitorovania stavu hydraulického oleja. Použitím pokročilej filtrácie a monitorovania čistoty oleja sa nám podarilo opätovne použiť hydraulický olej a ušetriť niekoľko stoviek litrov hydraulického oleja, ktorý by sa inak vyhodil.

Kľúčové slová: meranie čistoty oleja, laserový detektor častíc, hydraulický olej, hydraulický systém, údržba

INTRODUCTION

Nowadays, hydraulic systems are a very widespread source of energy transmission to industrial appliances, which ensures various types of movements. The major advantage of hydraulic systems is a high performance-to-installed weight ratio including small installation dimensions (Baczewski and Szczawinski 2016). Hydraulic power units (HPUs) are devices that convert mechanical energy into hydraulic energy, which can be then used to power various machines and equipment. HPUs are widely used in heavy industries such as mechanical engineering, construction, mining, agriculture, and marine, as they offer high power density, efficiency, and reliability.

However, HPUs also hold environmental impacts, such as noise, emissions, leaks, and waste. In this article, you will learn how it is possible to reduce the environmental impact of HPUs by following some of the best practices and choosing the right options for different applications.

In the beginning, there are some basic rules when sizing the right HPU. That means, one of the first steps to reduce the environmental impact of HPUs is to choose the right size and design for the specific application. A properly sized HPU will optimize the power output and minimize energy consumption, which in the end, will reduce the emissions and noise. A well-designed HPU may also be equipped with modern features such as variable speed drives, pressure and flow control valves, advanced filters, and cooling systems, which will improve the performance and efficiency of the HPU and prevent contamination, cavitation, and overheating. Modern and especially larger HPUs may be equipped with advanced condition monitoring devices such as online particle detectors or at least, interfaces to provide for easy condition monitoring with the use of external devices.

It is worthwhile to pay attention to the HPU design before investing in it. There are some practical nuances that are good to be followed. The ergonomics of the HPU should ensure easy maintenance, especially the replacement of filter elements. Since one of the most common and harmful environmental impacts of HPUs is hydraulic fluid leakage it is strongly advised to invest in quality components, such as fittings, hoses, seals, and couplings, check them regularly, and replace them if they are worn or damaged. Even a small hydraulic oil leakage of a few litres can cause serious soil and water pollution, fire hazards, and health risks. To systematically prevent and detect leaks, HPUs need to be regularly inspected and maintained. Proper tools and techniques need to be used to install and tighten the connections and avoid overloading or overpressurizing the HPU. Additionally, leak detection devices, such as sensors, gauges, or indicators, to monitor the fluid level and pressure can be used to alert the operator of any abnormality (Dowson 1998).

When choosing the HPU operational fluid there is another possibility to reduce possible environmental impact. Modern biodegradable hydraulic fluids can with minor compromises replace conventional mineral-based fluids. Instead of synthetic sources, biodegradable fluids are made from natural sources, such as vegetable oils, esters, or polyglycols, which have lower toxicity, flammability, and volatility than mineral-based fluids. Higher caution should be taken to choose the right lubricity and viscosity as these parameters might be different for biodegradable fluids. Additionally, there is a risk of lesser corrosion resistance which may reduce the working life and increase maintenance costs if not designed correctly. Other drawbacks are higher costs, lower compatibility and shorter shelf life. On the other hand, these aspects can be mitigated with careful use of condition monitoring of operational fluid and overall machine conditions.

Condition monitoring procedures should be the first one to look for when aiming to improve the operational life of any working fluid (Fitch 2001, Totten et al. 2001). It is said that the cleanliness and overall condition of the working fluid is the cause of over 80% of all hydraulic system failures (Stachowiak and Batchelor 2013, Peťková 2012, Kučera and Aleš 2017, Kopčanová et al. 2020). Therefore, reliable and well-functioning filtration and organized monitoring of HPUs are the first steps to implement. The practical use of condition-monitoring equipment will be discussed further in the following chapter.

Finally, when the hydraulic fluid reaches the point of replacement, great caution must be taken to dispose of the waste properly. Hydraulic oil is classified as dangerous waste across the world so special rules apply when disposing of it. One needs to bear in mind that dangerous waste can include also used hydraulic filters, hoses, fittings, and other HPU parts that are no longer functional or safe. To dispose of waste, local regulations and guidelines must be followed and waste management facilities or services must be authorised. In general, storage of dangerous waste needs to be properly labelled and waste placed in appropriate containers while avoiding mixing different types of waste. Moreover, some of the waste materials, such as metal, plastic, or rubber, may be recycled or reused to reduce the amount of waste and save natural resources.

Last but not least, machines, including HPUs, are still operated by people. Environmental impacts of HPUs might also be reduced by educating and training staff on how to operate and maintain the hydraulic equipment safely and responsibly. Operators and maintenance technicians need to be provided with adequate information and instructions on how to use the HPU functions and features, how to handle and store hydraulic fluids and waste, how to prevent and detect leaks, and how to respond to emergencies. For all these processes, local operating regulations documents should be issued. After training, the staff should be monitored and the staff's performance and compliance evaluated. After evaluation, it is important to provide feedback and suggest improvements. By educating and training the staff, the manufacturing plant can ensure that they are aware of the environmental impact of their HPUs and that they can mitigate risks effectively.

MATERIAL AND METHODS

In this article, focus will be drawn to preventive maintenance in manufacturing plants. For every HPU, there is a maintenance plan with scheduled hydraulic oil change intervals. However, evaluating oil cleanliness and quality before scheduled intervals can potentially save thousands of euros and natural resources. The problem is, that maintenance manuals usually contain only information based on time. Based on practical experience, the usual interval for oil change is 2 years. There are facilities where contaminants from the external environment may degrade hydraulic oil even sooner but most of the modern manufacturing plans operate in a rather clean (or regularly cleaned) environment. Therefore, it is desired to evaluate the actual oil quality and the necessity to change the oil filling before doing so. The actual results of the analysis may vary. Results may either approve the change, but oftentimes, just a partial change of e.g., 1/3 is sufficient. Other times, additional filtration, dehydration or adding additives may be recommended.

For our experiment, we chose an industrial crane AEROGRIP equipped with 4 individual gripping arms. The source of the power for the gripper is a small, separate HPU, each located on every gripper. Through hydraulic hoses, these HPUs power hydraulic cylinders located on the top of every gripping arm from the triple gear pump located in the tank on the bottom of the crane. The flow of oil is regulated through directional control valves. A drawing of the HPU is shown in Figure 1.

Fig. 1 Crane HPU
Obr. 1 Hydraulický agregát žeriavu

In the case of HPU analysed in this article, the manufacturer advised an oil cleanliness check every 6 months as written in the HPU user manual shown in Figure 2. Oil replacement is advised only after the oil quality is truly poor.

For our experiment, we chose the Parker iCount Oil Sampler (IOS) portable particle monitor to measure basic impurities in hydraulic oil shown in Figure 1. It is a self-contained system, equipped with a laser particle detection counter, battery, oil pump and internal memory with a website generator. Cleanliness can be measured regularly or continuously. The measurement of solid particles takes place using devices working on the principle of a laser. IOS uses light dimming technology. The measured liquid flows between the laser source and the evaluation device. Contaminants in the fluid interrupt the light beam and transmit the image to the photodiode cell, where the resulting change in light intensity leads to a directly proportional change in electrical output. The processor then evaluates the number of particles contained in the sample, and as a result, the liquid is assigned to a cleanliness level according to ISO or NAS standards, see specification at Table 1. Proven laser detection technology guarantees accurate, repeatable, reproducible results and real-time detection of particles down to 4 microns in size. The data is immediately displayed, saved or downloaded to an external device for analysis, further processing or archiving. (Parker, 2015). We will evaluate the measurements according to the ISO system, which expresses the number of particles in a given size range with the use of code values according to ISO 4406:2021.

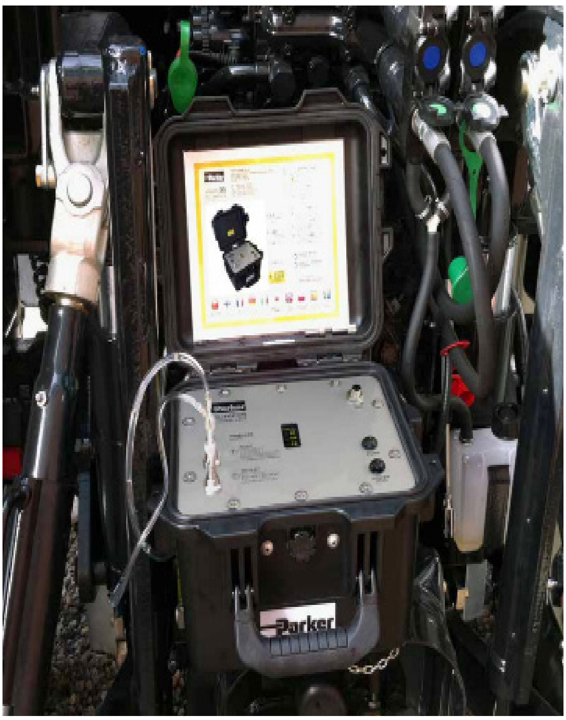

Fig. 2 Portable particle detector Parker IOS
Obr. 2 Prenosný časticový detektor Parker IOS (Parker 2015)

Table 1 Specification of measuring device (Parker 2015)
Tabuľka 1 Špecifikácia meracieho zariadenia

Feature	Specification
Product start-up time	10 s minimum
Measurement period	default 30 s run time; 15 s data logging time
Reporting interval	onboard data storage every second; output via RJ45 connection
Principle of operation	laser diode optical detection of actual particulates
Working pressure	0,25 – 35 MPa
Working viscosity	1 – 300 $mm^2.s^{-1}$
Flow range through IOS	40 – 140 $ml.min^{-1}$; controlled 60 $ml.min^{-1}$ by IOS´s internal pump
Ambient storage temperature for unit	-40 °C to +80 °C
Operating temperature for unit	-30 °C to +80 °C
Operating humidity range	5 %RH to 100 %RH
Oil operating temperature	+5 °C to + 80 °C
Moisture sensor	Linear scale within the range 5 %RH to 100 %RH

As the HPU is equipped with a Parker gear pump, type PGP511B0140, Parker directional control valves, type D1VW002CNJW and cartridge valves type DSH101CR from Parker, we are going to use their guidelines for setting the limit values of hydraulic oil cleanliness as shown in Table 2.

Table 2 Limits values of oil cleanliness for chosen hydraulic elements (Parker 2015)
Tabuľka 2 Limitné hodnoty čistoty oleja pre vybrané hydraulické prvky

Hydraulic elements	Required purity class according to ISO	Recommended filtration (µm)
Gear pumps	19/17/14	10
Directional control valves	18/16/13	10
Cartridge valves	18/16/13	10

After the measurement, the hydraulic oil of an unspecified brand, type ISO VG 46 was filtered using the mobile filter cart Parker 10MFP240SA10QBVPI1 shown in Figure 4 fitted with a 40 µm synthetic pre-filter and 10 µm fine micro-glass filter which can be replaced with a water removal filter. The effective volume of every HPU is 150l and in total, 4 HPU tanks were filtered over the time span of 2 hours each.

Detailed specifications of the filter cart can be found in Table 3. This particular equipment was chosen because filtering was carried out on the spot, at the factory premises. The portable filter cart is an ideal way to quickly and efficiently filter, check and transport lubricating liquids into tanks, or to clean existing systems. In addition to particle removal, residues of water can be removed when pumped through the filter cart with the above-mentioned special filter inserts made of polymer, which has a very high affinity for free water. Once water comes into contact with the material, it is captured and removed from the system. The portable filter cart also uses two large-capacity filters for higher filtered oil flow, longer service life and better system protection. The first stage – the inlet filter, captures larger particles, while the second stage – the outlet filter, captures fine particles or removes water. Oil pumping is ensured by a robust industrial gear pump. Similar filter carts are good practice examples of portable, cost-effective solutions to protect the machine's hydraulic system from damage that may be caused by contamination from either used or also from new oil. (Parker, 2019)

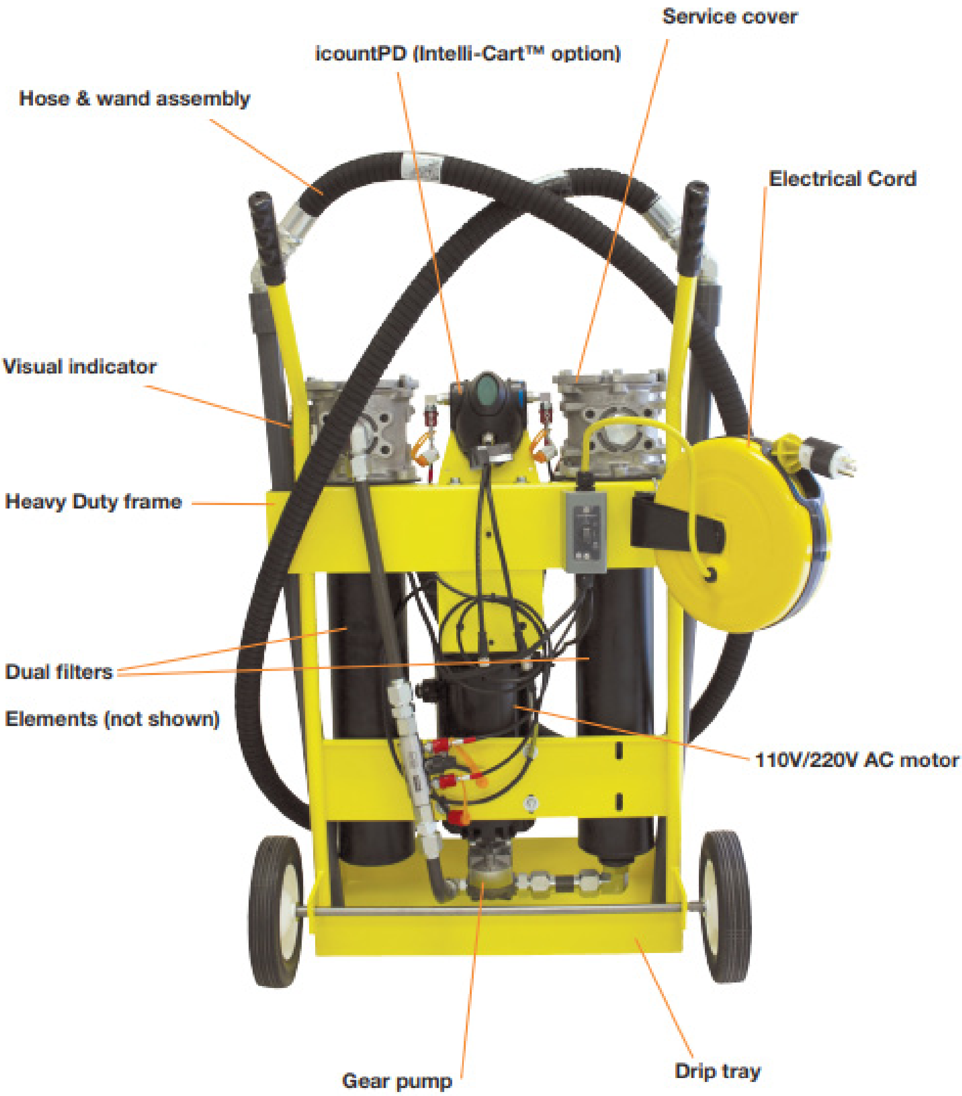

Fig. 3 Portable filter cart Parker MFP
Obr. 3 Prenosný filtračný vozík Parker MFP
(Parker 2019)

Table 3 Specification of filtration device (Parker 2015)
Tabuľka 3 Špecifikácia filtračného zariadenia

Feature	Specification
Maximum Recommended Fluid Viscosity	108 $mm^2.s^{-1}$ 0,85 specific gravity
Visual Indicator (outlet filter)	Visual differential type 3-band (clean, change, bypass)
Filter Bypass Valve Settings (Integral to Element):	Inlet – 0,02 MPa Outlet – 0,24 MPa
Operating Temperature	-40 °C to +66 °C
Electrical Service Required	110/220 V, 60/50 Hz, single phase, 10/5 A
Electrical Motor	0,6 kW at 3450 $r.min^{-1}$, open, drip-proof, thermal overload protection
Construction	Cart frame – Steel Filter head – Aluminium Filter bowl – Steel Hoses – PVC Wands – PVC
Dimensions	Height: 1034mm Width: 648mm Depth: 503mm
Weight	45 kg

RESULTS AND DISCUSSION

The oil cleanliness results prior to filtration and after filtration are presented in Table 4. In Figure 5, the final reading from the laser detector is shown. In the first column of the table, results after 6 months of operation of HPUs are shown. The oil is slightly contaminated with the contaminants most possibly originating from the outside environment and from the working of the system as such. Cleanliness levels show that oil is at the limit of usability from the gear pump, however, it is already too dirty for the operation of valves which work with much smaller tolerances and clearances in cavities (Šupák and Almášiová 2014). Oil cleanliness results after filtration shows noticeable improvements. All the values are in line with the manufacturer's guidelines, even with slight room for gradual degradation in the future. The next oil cleanliness check is to be planned in the next 6 months.

Condition monitoring of fluid power systems is emphasised by a number of authors like Hindman, Burton & Schoenau (2002), Tkáč et al. (2021), Hnilicová et al. (2021), Stachowiak and Batchelor (2013), Peťková (2012), Kučera and Aleš (2017), Krilek et al. (2019), Kopčanová et al. (2020). Further experiments can be made using vacuum dehydrator devices such as the one from Pall Corporation or Parker Hannifin. Apart from filtering oil from mechanical contaminants, these devices heat up the oil to safe temperatures and with the use of vacuum technology, capture the excessive moisture (free water contamination) in the hydraulic oil. This technology is great for hydraulic systems more prone to water contamination – such as the ones operating in the outside environment (Antala 2008). There is an interesting case study when conditioning of the used hydraulic oil is made for the US Air Force, with projected savings of $30 million a year (O'Sullivan, Seaman & Testerman, 1997) and (Werner & Madhavan, 1998). For electro-hydraulic actuators which are extremely sensitive to oil cleanliness, Samways propose a centrifugal by-pass filtration as an addition to conventional full-flow barrier media filtration (Samways, 1999). The final level is then the revitalizing of hydraulic oils which can be done with the help of specialized companies (Fluitec, 2021). In this process, however, the oil needs to be transported to a specialized facility for conditioning. This pays off when it comes to large volumes of highly contaminated oil.

Table 4 Oil cleanliness measurement results
Tabuľka 4 Výsledky merania čistoty oleja

	Oil cleanliness prior to the filtration	Oil cleanliness after the filtration
HPU 1	18/17/14	16/13/7
HPU 2	20/18/14	18/16/12
HPU 3	20/19/16	16/14/10
HPU 4	19/18/16	15/14/11

Fig. 5 Oil cleanliness results after filtration
Obr. 5 Výsledky merania čistoty oleja po filtrácii

CONCLUSION

The results of oil cleanliness measurements presented in Table 4 show significant improvement in oil quality. Even after 2 hours of filtration, oil cleanliness levels are within the cleanliness limits which are set by the hydraulic components manufacturer. Filtration was effective due to the well-designed, high-quality filters chosen for the experiment. It is important to remind the HPU filters also need to be changed after the filtration process. If not, the residual contamination kept in the filters might contaminate the filtered oil again. Condition monitoring devices, such as the laser particle detector used in our experiment are essential in this process. Without the knowledge of oil cleanliness level prior to, during and after filtration, one cannot effectively design the filtration process. Depending on the volume of contaminants, the right filters need to be chosen at the beginning of the process, while during the process, monitoring of the cleanliness level defines when the oil is clean enough to be safe for the hydraulic components to operate without excessive wear. Without such knowledge, one could fail the filtration process with the oil not being clean enough or the filtration process taking too much time. With the use of conditioning monitoring tools, the process can be optimised, so the cleanliness level achieved is just right for the specific application and the time of the service procedure is optimized to the shortest period possible. By doing so, we can ensure the machine will operate within the manufacturer's limits and that breakdowns caused by foreign particles are eliminated. With running on clean oil, the gradual wear of the components is also smaller, so the components shall operate for longer periods of time without leakages or failures. However, it is crucial these checks are carried out periodically, in reasonable time intervals (6 to 12 months maximum), otherwise, the multiplying volume of contaminants might reach the limits where the machine stops due to the breakdown or the oil is too dirty to be measured and filtered. On the other hand, when preventive maintenance is well planned, we can conclude that thorough filtration with the use of the filter cart and oil cleanliness levels verified with the use of condition monitoring tools proved to be an effective and sufficient maintenance measure to ensure proper oil cleanliness level without the need to change oil filling. Apart from financial savings for hydraulic oil and broken components, significant savings of resources can be achieved, in our case we speak about 600l of hydraulic oil bi-annually.

To sum up the findings, we can conclude the right design of HPU can save a significant amount of electrical energy, proper and consistent maintenance of HPU saves running costs, use of condition monitoring devices is especially helpful in preventing undesired wear of hydraulic components and unforeseen failures, well-designed filtration may extend the working life of hydraulic oil by 6 months thanks to the monitoring of oil cleanliness and save several hundred litres of hydraulic oil which would otherwise be replaced with the new one. Hence, filtering, monitoring and re-using of hydraulic oil have shown to be noteworthy initiatives to significantly decrease the environmental impact of any industrial company using HPUs in their machines.

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LITERATURE

ANTALA, J. 2008. Hodnotenie znečistenia oleja. Strojárstvo, vol.1, no 9, pp. 194-195.

BACZEWSKI, K. – SZCZAWINSKI, P. 2016. Investigation of the process of ageing of hydraulic oil during its use. In The Archives of Automotive Engineering – Archiwum Motoryzacji, vol 73, no. 3, pp. 5 – 18. *DOI:10.14669/ AM.VOL73.ART1*

DOWSON, D. 1998. History of Tribology. Hoboken: Wiley.

FITCH, J. C. 2001. Advancements in Fluid Analysis Technologies and Strategies for Hydraulic System Condition-Based Maintenance. In: Hydraulic Failure Analysis: Fluids, Components, and System Effects. West Conshohocken: ASTM.

FLUITEC, 2021. Revitalizing Hydraulic Oils – The Sustainable Future of Hydraulic Oils. https://www.fluitec.com/revitalizing-hydraulic-oils-the-sustainable-future-of-hydraulic-oils/

HINDMAN, J., BURTON, R., & SCHOENAU, G. (2002). Condition Monitoring of Fluid Power Systems: A Survey. SAE Transactions, 111, 69–75. http://www.jstor.org/stable/44718521

HNILICOVÁ, M. – TURIS, J. – HNILICA, R. 2021. Application of Multidimensional Statistical Analysis in Tribotechnical Diagnostics of Hydraulic Fluids in Woodworking Equipment. In Materials, vol. 14, 22 pp.

ISO 4406: 2021. ISO 4406:2021 Hydraulic fluid power — Fluids — Method for coding the level of contamination by solid particles.
KOPČANOVÁ, S. – SEJKOROVÁ, M. – KUČERA, M. – HNILICOVÁ, M. 2020. Wear of hydraulic system components assessment based on the analysis of hydraulic oil degradation degree. In Przemysel Chemyszny, vol. 99, no.9, pp. 1000 – 1004.
KRILEK, J. – KOVÁČ, J. – KUVIK, T. – DOBROTOVÁ, L. 2019. Analysis of hydraulic oil to drive band sawmill. In Scientific Bulletin of UNFU, vol. 29, no 10, pp. 89 – 92. ISSN 1994-7836.
KUČERA, M. – ALEŠ. Z. 2017. *Morphology Analysis of Friction Particles Generated in Tractor Transmission Oils*. In Acta Technologica Agriculturae, vol. 20, no.3, pp. 57–62.
LINKEDIN, 2023. How do you reduce the environmental impact of hydraulic power units? https://www.linkedin.com/advice/1/how-do-you-reduce-environmental-impact-hydraulic
MÁCHAL, P. et al. 2013. Design and verification of additional filtration for the application of ecological transmission and hydraulic fluids in tractors. In Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis, vol. 61, no. 5, pp. 1305–1311.
MAJDAN, R. et al. 2017. Filtration Systems Design for Universal Oils in Agricultural Tractors. In Tribology in Industry, vol. 39, no. 4, pp. 547-558.
MAJDAN, R. et al. 2019. Contamination of transmission and hydraulic oils in agricultural tractors and proposal of by-pass filtration system. In Agronomy Research, vol. 17, special issue 1, pp. 1107-1122.
O'SULLIVAN, D., SEAMAN, E., & TESTERMAN, L. (1997). Reusing Waste Hydraulic Fluid. The Military Engineer, 89(586), 53–54. http://www.jstor.org/stable/44550944
OSMANOVIC, A. - TRAKIC, E. - SARIC, B. - HADZISMAJLOVIC, M. – BECIROVIC, M. 2018. Diagnostics of hydrostatic power transmission on hydraulic excavators, using work fluid analysis. In Technics – Technologies – Education – Management : Journal of Society for Development of Teaching and Business Processes in New Net Environment in B&H, Vol. 13, No. 3, pp. 115 – 120. ISSN 1840 – 1503.
PARKER, 2015. icountOS: Accurate Condition Monitoring made Quick, Simple and Cost Effective.
PEŤKOVÁ, V. et al. 2012. Tribotechnika v teórii a praxi. Košice: Vienala, 2012. s. 366 s. ISBN 978-80-8126-0575.
SAMWAYS, A. L. (1999). Centrifugal Cleaning of Fluid Power Oils. SAE Transactions, 108, 267–278. http://www.jstor.org/stable/44723049
STACHOWIAK, G. - BATCHELOR, A. W. 2013. Engineering Tribology. 4. vydanie. Oxford: Butterworth-Heinemann.
ŠUPÁK, M. - ALMÁŠIOVÁ, J. 2014. Hydraulické mechanizmy. first ed. Bratislava: Metodicko-pedagogické centrum v Bratislave.
TKÁČ, Z. - ČORNÁK, Š. - KOSIBA, J. - JANOUŠKOVÁ, R. - MICHALIDES, M. - VOZÁROVÁ, V. - CSILLAG, J. 2021. Investigation of degradation of ecological hydraulic fluid. In Proceedings of the Institution of Mechanical Engineers: Part C – Journal of Mechanical Engineering Science (In press).
TOTTEN, G. E. - WILLS, D. K. - FELDMANN, D. G. 2001. Hydraulic Failure Analysis: Fluids, Components, and System Effects. West Conshohocken: ASTM.
WERNER, N., & MADHAVAN, P. (1998). Recycling Hydraulic and Lubricant Fluids. The Military Engineer, 90(590), 35–36. http://www.jstor.org/stable/44551045

Corresponding author:
Jakub Drmla, phone +421 948 777 493, e-mail: jdrmla@gmail.com