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ANALYSIS OF WEAR RESISTANCE OF METALLIC-REINFORCED POLYURETHANE RESIN COMPOSITES FOR SHEET METAL FORMING

ABSTRACT

The paper presents the results of testing the wear resistance and coefficient of friction (COF) tools made of SikaBeresin® F50 polyurethane resin intended for dies and punches for the cold sheet metal forming process. Seven sets of composite tools (rotating rings) additionally reinforced with waste metallic powders from Al and Cu alloys (5-20% by volume) from the dry cutting process of pipes and rods were tested. Wear resistance tests and determination coefficient of friction were carried out using the T-05 block-on-ring tribotester. The tests were performed for heat and corrosion resistant sheets made of nickel alloy AMS5599 (Inconel 625), iron alloy AMS5510 (321) and aluminum alloy sheets AMS4026 (6061-T4). Composite tools with the addition of 20% aluminum powder (A+B+C+20%Al) tested with a specimen of steel alloy AMS5510 and nickel alloy AMS5599 were characterized by the lowest wear resistance. In each case, the composite rotating ring without reinforcements was characterized by the lowest coefficient of friction. The use of Cu powder reinforcements in each case had a positive effect on increasing wear resistance. The best wear resistance of 0.011% was obtained for composite rotating ring with the addition of 10% copper powder paired with specimen of nickel alloy AMS5599 sheet.

Keywords: *sheet metal forming dies; composite tools; stamping tool; wear resistance; polyurethane resin tool*

INTRODUCTION

Specialized tool steels are often used for sheet metal forming (SMF) into die and punch elements. Due to the requirements regarding wear resistance and shape stability, SMF tools are most often made of tool steels additionally heat or surface treated [1]. The technological processes used to manufacture steel tools for stamping die parts are time-consuming and costly. Specialized equipment such as grinders, CNC lathes and milling machines or EDMs are used to process tool steels. Nowadays, manufacturing companies are forced to look for new technological possibilities for producing tools for the sheet metal forming proces [2]. As an alternative to steel tools, elastomeric and composite materials are becoming more common and developed [3,4]. Implementation of epoxy resin-based materials for sheet metal forming processes is estimated to be 1950 [1]. Initially, tools based on epoxy resins were used for

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easily formable sheets, for example from aluminum alloys. Over time, the development of polymeric materials for SMF processes has made it possible to shape materials from high-strength steels [5]. Further development of polymeric materials such as epoxy and polyurethane resins found wider application in prototyping tools for die and stamp components for sheet metal forming [6-8]. Kuo et al. write about the widespread use of epoxy resin-based composite tools for plastic sheet metal forming in the automotive and aerospace industries [3]. Technologies for manufacturing tools from composite materials can significantly reduce the time and optimize the cost of tool manufacturing. Compared to the production of metal tools used in metal forming processes such as stamping and bending, it is estimated to reduce manufacturing costs by up to 77% [9]. An important aspect for metal and composite tools is control of wear, which ensures high quality production of shaped sheet metal products [10]. Research of Schmoeckel et al. show the effect of the shaped material in contact with the die and punch on the exploitation life of the tools used [11].

The wear resistance of composites based on polyurethane and epoxy resins can be improved by using suitable materials for reinforcements such as: SiC [12. 13], ZrO_2 [14], $CaCO_3$ [15], TiO_2 [16], CaO [14] or powder of aluminium [17]. Kuo et al. present the possibilities of improving wear resistance and reducing the costs of tools making from composite based on epoxy resin with additive of 30% wt. ZrO_2 for metal forming sheet from aluminium alloys [18, 19]. By adding ZrO2, the authors achieved a 44% increase in wear resistance. Wetzel et al. used TiO_2 and $CaSiO_3$ fillers to increase the wear resistance of die from the epoxy resin [20]. Burmistrov et al. in their work improved mechanical properties by adding potassium polynitrate [21]. Mohamed et al. in their study show an increase in wear resistance for composite tools with SiO_2 addition. Studies show the effect of SiO2 content and particle size on improving wear resistance [22]. The effects of metallic and non-metallic reinforcements on friction and wear resistance were also studied by Khattab et al. [23]. Nassar et al. in their work showed an increase wear resistance in dry friction by adding SiC particles of 6 to 18% by weight to samples based on epoxy resin. The composite with 18% SiC reinforcements had highest wear resistance [24].

The coefficient of friction for sheet metal forming tools can be controlled, among other things, by selecting appropriate tool materials. In article K. Żaba et al. present the results of the effect of non-metallic and metallic reinforcements in the form of glass fibers and aluminum powder on the change of coefficient of friction. The authors showed effect of applied force and the metallic and nonmetallic reinforcements for the change of coefficient of friction [17]. Kirkhorn et al. in research, they presented the effect of surface quality on the coefficient of friction. They showed that the condition of tool surface preparation significantly affects the increase in the coefficient of friction. As the roughness increases, the coefficient of friction increases [25]. Murtagh et al. in their research showed the effect of the orientation of carbon fiber reinforcements in the composite on the coefficient of friction. Frictional force was lower for reinforcements oriented at 90° to the slip direction [26]. Kumar et. al. showed the effect of carbon nanotube/glass fiber additives on improving the performance properties of the obtained composites [28-30].

The article presents the results of tribological tests of new composite tools based on polyurethane resin, reinforced with waste materials from copper and aluminum powders. Aluminum and Copper alloy reinforcements are the post-production waste of ERKO sp. z o.o. sp. k. from the processes of manufacturing components for use in the power and aerospace industries. New materials for stamping tooling include composites consisting of polyurethane resin and mineral filler additionally reinforced with aluminum and copper powder of 5 to 20% by volume of the composite. Tribological properties were tested using the T-05 block-on-ring tribotester. The measurements were carried out at ambient temperature with progressive motion in a dry sliding contact.

MATERIALS AND METHODS

Wear resistance and coefficient of friction were determined during the tests for samples from alloys Ni- AMS5599, Fe- AMS5510 and Al- AMS4026. Sheets of these alloys are the main materials used in ERKO's cold forming processes. Parts from this alloys are common used materials in the aerospace industry for, among other things, such structural components as: bracket, sleeve half – reinforcing tube, elements for ventilation duct, exhaust gas intake components and more. The properties of the tested materials are comply with the standards Aerospace Material Specification (AMS) which are controlled by SAE's aerospace materials committees. SAE International is a global organization of more than 128,000 engineers and related technical experts in the aerospace, automotive and commercial-vehicle industries which is responsible for supervision AMS specification where we can find among others chemical composition and mechanical properties materials. Table 1 shows chemical composition tested materials. Table 2 shows mechanical properties tested materials. Materials used during aerospace production must meet minimum requirements of the AMS specifications for each alloys. Suppliers should have in internal database actually revision of AMS specification for each materials which is used during production. Parameters included in Table 1 and 2 have been confirmed according to AMS specification and based on the Certificate of Conformance documentations (CofC) provided from approved sources by companies such as: Pratt&Whitney, GE Aero, Hamilton Sundstrand or Colins Aerospace. Purchasing materials from approved sources gives the parts supplier confidence in the compliance of the purchased raw materials.

Table 1. *Chemical composition tested alloy materials AMS5599, AMS5510 and AMS4026*

	% by weight												
	C	Mn	Si	P	S	Cr	Mo	Nb	Fe	Co	Ti	Al	Ni
AMS5599 AMS SPECIFICATION	0-0.10	0-0.50	0-0.50	0-0.015	0-0.015	20.00-23.00	8.00-10.00	3.15-4.15	0-5.00	0-1.00	0-0.40	0-0.40	Remainder
AMS5599 CofC***	0.04	0.30	0.17	0.007	0.001	22.27	8.25	3.44	4.53	0.06	0.19	0.22	Remainder
	C	Mn	Si	P	S	Cr	Ni	Ti	Mo	Cu	N	-	Fe
AMS5510 AMS SPECIFICATION	0-0.08	0-2.00	0.25-1.00	0-0.04	0-0.03	17.00-19.00	9.00-12.00	0-0.07	0-0.75	0-0.75	0-0.10	-	Remainder
AMS5510 CofC	0.015	1.84	0.53	0.026	0.0001	17.27	9.18	0.16	0.39	0.39	0.008	-	Remainder
	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	OEE*	OET**	-	-	Al
AMS4026 AMS SPECIFICATION	0.40-0.80	0-0.70	0.15-0.40	0-0.15	0.80-1.20	0.04-0.35	0-0.25	0-0.15	0-0.05	0-0.15	-	-	Remainder
AMS4026 CofC	0.55	0.44	0.24	0.01	0.98	0.16	0.01	0.06	-	-	-	-	Remainder

*OEE- other elements, each
**OET- other elements, total
*** CofC- certificate of compliance

Table 2. *Mechanical properties tested alloy materials AMS5599, AMS5510 and AMS4026*

	Yield Strength, MPa	Ultimatum tensile Strength, MPa	Elongation, %	Hardness
AMS5599 AMS SPECIFICATION	min. 414	min. 827	min. 30	N/A
AMS5599 CofC	498	956	54	74 HR30TW
AMS5510 AMS SPECIFICATION	min. 172	483-689	min. 40	N/A
AMS5510 CofC	267	619	62	60 HR30TW
AMS4026 AMS SPECIFICATION	min. 207	min. 110	min. 16	N/A
AMS4026 CofC	283	189	21	79 HR15TW

SikaBeresin® F50 and mineral filler RZ30150 The polyurethane resin has a low setting temperature of 36°C and is an odourless mixture. These parameters directly affect the user's safety, which is why we decided to use this material for testing tools. Polyurethane resin SikaBeresin® F50 (component A isocyanate + B polyol) was used to make the rotating ring with mineral filler RZ30150 (component C- powdered aluminium hydroxide Al(OH)3) and reinforcements from Al and Cu alloy powders obtained by recycling technologies after the dry-cutting process of rods and tubes at ERKO. The use of filler in the form of aluminum hydroxide (Al(OH)3) has a positive effect on reducing casting shrinkage. This ensures a high level of tool mapping relative to the casting mold. The aim of this study was to verify the impact of the use of reinforcements in the form of aluminum and copper powder, which are waste materials after the cutting process at ERKO. Their particular impact is presented in the presented results. The density of the composite mixture without metallic reinforcements was 1.75 g/cm3 (composition of component A+B+C in proportion 100g(A)+50g(B)+180g(C)). Based on data sheet of SikaBeresin® F50 and in own research were determined composite ratio. Composite samples with 5, 10 and 20% by volume of Al and Cu powder as rotating ring for wear resistance tests were cast into silicon molds. The silicone molds were made from MM922 molding silicone. It is a two-component silicone composition that cures at 20-23°C. After mixing and casting into the mold, the mixture was vented using a vacuum pump. The purpose of venting was to get rid of air. The silicone molds reached their mechanical functionality after 72h. An example of a silicone mold is shown at Fig. 1.

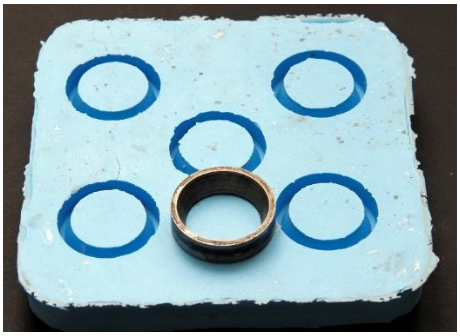
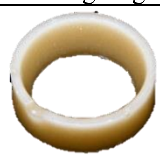


Fig. 1 Silicone mold for making composite rotating ring

Table 3. *Samples of composite rotating rings used for wear resistance tests*

Composition of the composite	Rotating rings		
A+B+C			
A+B+C+5, 10, 20 % Al. powder			
A+B+C+5, 10, 20 % Cu powder			

Composite rotating rings of 49.5 +/- 0.1 mm diameter without reinforcements and with metallic reinforcements in the form of aluminum and copper powders are shown in Table 1. The composite rotating rings after casting into the mold, were vented using a vacuum pump to eliminate air bubbles from the mixture. The material thus prepared was left for 24 hours. It was then subjected to annealing in an furnance at 60°C by 12 hours. Under these process conditions, the composite used achieves the highest mechanical properties.

The wear resistance test and the determination of the coefficient of friction were carried out on the T-05 block-on-ring tribotester. The test was conducted at ambient temperature with progressive movement in dry sliding contact. The principle of the tester is shown at Fig. **2**.

The specimens from sheet of Ni- AMS5599, Fe- AMS5510 and Al- AMS4026 alloy mounted in a holder, which is equipped with a hemispherical insert to ensuring good contact and even force distribution during test between the tested sample and composite ring.

Table ***4*** shows condition of wear resistance test.

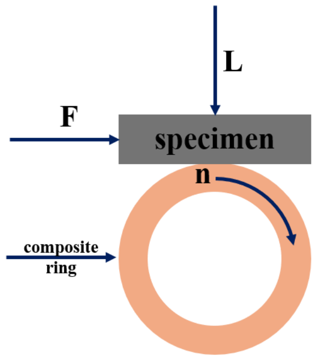


Fig. 2. Diagram of test using T-05 tribometer [27]

Table 4. *Condition of wear resistance test*

	Dimension of tested specimen (l x w x t)*, mm	Dimension of composite ring, mm	Rotational speed, rpm	Load, N	Sliding distance, m	Ambient temperature, °C	Sliding conditions
AMS5599	20x4x1	49.5	136	50	50	20	without lubricant
AMS5510	20x4x1	49.5	136	50	50	20	without lubricant
AMS4026	20x4x2	49.5	136	50	50	20	without lubricant

*l, w, t- length, width, thickness

The measure of wear resistance is the weight loss of the tested material with respect to the friction path and the applied load. The weight loss expressed in grams was determined according to the formula 1, while the mass loss in percentage according to the formula 2.

$$\Delta m = m_i - m_f \tag{1}$$

$$\Delta m = \frac{m_i - m_f}{m_i} 100\% \tag{2}$$

where:

$m_i - initial\ mass\ of\ the\ sample,$

$m_f - final\ weight\ of\ the\ sample.$

During the tribological test, the friction force F was recorded continuously, which was used to determine the coefficient of friction μ according to the formula 3.

$$\mu = \frac{F}{F_N} \tag{3}$$

where:
$F - friction\ force,$
$F_l - load\ force.$

RESULTS AND DISCUSSION

Composites with 5, 10, 20% of reinforcement contents of Al and Cu metallic powders were tested (Table 5). Their wear resistance and coefficient of friction measured by comparing the wear force and load under technically dry friction conditions were determined on the tested composites. The tests were carried out at ambient temperature and at a humidity level of 30%. Tribological tests were carried out using composite rotating ring with the surface as delivered, without any special treatment to reduce roughness. The premise was to obtain the working surface of the tool without additional finishing. The obtained samples were characterized by roughness Ra of 0.599, 1.409, 0.376 μm suitable for rotating ring without reinforcements, with the addition of 10% Al. powder and 10% Cu powder. Roughness of rotating ring have important impact for wear resistance and coefficient of friction. Effect of condition surface of rotating rings on wear resistance and coefficient of friction were presented on Figure 3 and 4.

Based on the tribological results obtained, the wear resistance and coefficient of friction were determined for each composite tested. Using formula (2), the wear resistance of the tested composite materials was determined. Coefficient of friction μ was obtained by formula (3). Table 5 shows obtained results of wear resistance. The highest wear resistance for AMS5599 and AMS 4026 sheets was obtained for the composite with the addition of 10% Cu powder. In the case of AMS5510 sheet for a composite with the addition of 20% Cu powder. Wear resistance was 0.153, 0.074 and 0.405%, respectively. Table 6 shows obtained results of coefficient of friction μ. The lowest friction coefficient in each case was obtained for the rotating ring without reinforcements. The coefficient of friction μ for the AMS5599 was 0.050, for AMS5510 0.075 and for AMS4026 0.128.

Table 5. *Results of wear resistance for the tested composites. Results presented in %*

	A+B+C	A+B+C+5% Al	A+B+C+10% Al	A+B+C+20% Al	A+B+C+5% Cu	A+B+C+10% Cu	A+B+C+20% Cu
AMS5599	0.101	0.029	0.153	0.217	0.116	0.011	0.025
AMS5510	0.244	0.050	0.137	0.405	0.164	0.244	0.037
AMS4026	0.128	0.023	0.074	0.097	0.104	0.022	0.033

Table 6. *Results of coefficient of friction μ for tested composites*

	A+B+C	A+B+C+5% Al	A+B+C+10% Al	A+B+C+20% Al	A+B+C+5% Cu	A+B+C+10% Cu	A+B+C+20% Cu
AMS5599	0.050	0.179	0.271	0.465	0.280	0.088	0.080
AMS5510	0.075	0.178	0.258	0.413	0.300	0.258	0.247
AMS4026	0.137	0.156	0.215	0.361	0.219	0.243	0.293

It has been observed that metallic reinforcements in the form of Cu and Al powders from waste materials after the dry-cutting process added to the produced composites improve wear resistance. Based on the literature analysis in the presented works, the authors in each case confirm the increase in wear resistance after the use of metallic and non-metallic reinforcements [11-24]. Kuo et al. an increase of 44% in wear resistance was obtained by adding 30% ZrO2 to the epoxy resin [18]. They also observed the optimal effect of the addition of ZrO2 on the functional properties of the composite. For a ZrO2 filler content of 50%, they obtained lower wear resistance compared to a composite with 30% ZrO2 content during forming a sheet of aluminum alloy EN-5052. Wetzel et al. in the presented research, improvements wear resistance were obtained by adding a TiO2 and CaSiO3 to composite tools [20]. Similar to the work of Kuo et al. they showed a relationship between the optimal reinforcement content of a composite and wear resistance. In the presented research, a similar phenomenon was observed regarding the optimal content of metallic reinforcement in the form of Al or Cu powder. The wear resistance of the AMS4026 aluminum alloy sheet was highest for the addition of 10% Cu powder and was 0.022%.
Depending on the AMS 5599, AMS5510 and AMS4026 sheet specimens tested and the use of different types and contents of metallic powders on composite rings, it is possible to significantly improve wear resistance (Fig. 3).

Fig. 3a presents the obtained results of wear resistance tests for AMS5599 sheet and composite rotating ring without and with metallic reinforcements. Wear resistance tests on a pair of AMS5599:composite ring specimens showed the lowest values for the composite with metallic reinforcements with added Cu powder content 10% - A+B+C+10%Cu. The wear resistance was 0.011%. The highest wear resistance was observed for the A+B+C+20%Al composite, which was 0.217%. The wear resistance for the A+B+C+10%Cu composite is more than 1970% higher than A+B+C+20%Al composite.

Wear resistance test results for AMS5510 sheet and composite rotating ring without and with metallic reinforcements are shown in Fig. 3b. Tests of wear resistance sample AMS5510:coposite ring specimen showed the lowest values for the composite with the addition of 20% Cu powder - A+B+C+20%Cu. The wear resistance in this case was 0.037%. The highest wear resistance was observed similarly to the AMS5599 sheet sample for the A+B+C+20%Al composite rotating ring, which was 0.405%. In this case, the wear resistance for the A+B+C+20%Cu composite is more than 1000% higher than A+B+C+20%Al composite.

Fig. 3c shows the results of wear resistance tests for AMS4026 sheet and composite samples without and with metallic reinforcements. Tests of wear resistance in the AMS4026:coposite ring specimen showed the lowest values similarly to the AMS5599 sheet specimen for the composite with the addition of Cu powder content 10% - A+B+C+10%Cu. The wear resistance in this case was 0.022%. The highest wear resistance was observed for the composite without metallic reinforcements- A+B+C, which was 0.128%. The wear resistance for the A+B+C+10%Cu composite is more than 550% higher than for composite A+B+C.

The addition of metallic reinforcements in the form of copper and aluminum powder to composite samples used in tribological tests based on polyurethane resin increase the coefficient of friction μ. A similar phenomenon was observed in work K. Żaba et al.

Composites without reinforcements had the lowest coefficient of friction. They observed effect of addition of reinforcements in the form of glass fibers increased the coefficient of friction [17].

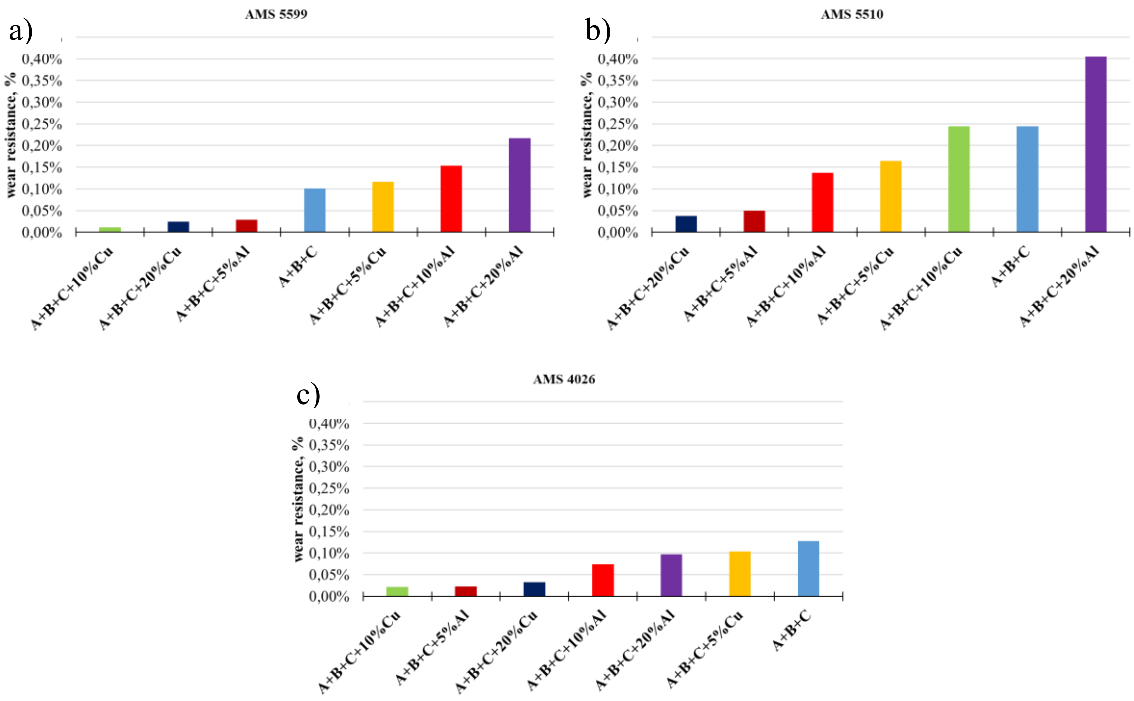


Fig. 3. Results of wear resistance for the tested composites. Results presented in %

Based on the obtained results, a relationship was observed between the amount and type of metallic reinforcement used on the increase in the coefficient of friction for the tested samples for alloys from AMS5599, AMS5599 and AMS4026 sheet. In each case, composites without metallic reinforcements had the lowest coefficient of friction. COF μ rotating rings without reinforcements is within the friction range of sliding materials or materials with lubricant. The results coefficient of friction for the composite ring tests with the addition of 20% aluminum powder (A+B+C+20%Al) for each sheet were the highest (Fig. 4). Rotating ring with the composition A+B+C+20%Al had the lowest wear resistance which directly affects the increase in roughness and COF. Kirkhorn et al. observed a similar effect for metal tools with higher roughness [26]. Addition of aluminum powder with increasing its proportion in the composite for all rotating rings causes decrease coefficient of friction. This is effect of adhesive action of metallic reinforcements in the form of Al powder at the friction node composite ring:sample.

Fig. 4a presents the obtained results coefficient of friction for sheet AMS5599 using different configurations of metallic reinforcements in the form of Cu powder and Al composite based on SikaBeresin® F50 resin. The lowest coefficient of friction μ=0,05 was obtained for the composite without metallic reinforcements- A+B+C. The highest coefficient of friction in the AMS5599 sheet specimen:composite ring pair was characterized by the composite with the addition of 20% Al- A+B+C+20%Al powder. The coefficient of friction in this case was μ=0,465. Observed increase more than 900%.

The results COF tests for AMS5510 sheet samples are presented in fig. 4b. The lowest coefficient of friction at μ=0,075 characterized by a composite without metallic reinforcements - A+B+C. The highest coefficient of friction was observed for the composite with the addition of 20% Al- A+B+C+Al20% powder, which amounted μ=0,413. In this case COF increase more than 550%.

Fig. 4c presents results COF for specimens AMS4026. The lowest coefficient of friction at μ=0,137 characterized by a composite without metallic reinforcements - A+B+C. The highest coefficient of friction was observed for the composite with the addition of the 20% powder of Al- A+B+C+Al20%, which was μ=0,361. COF was increase more than 260%.

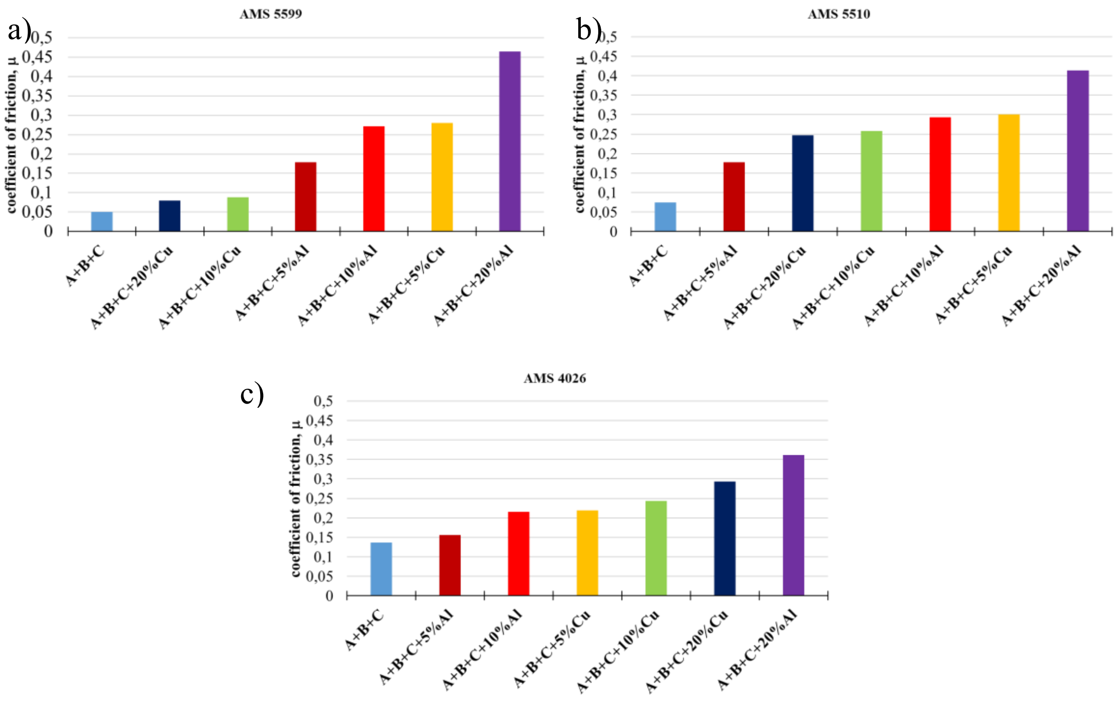


Fig. 4. Results of coefficient of friction μ for tested composites

The tested rotating rings materials belong to a very wide group of composite materials that are sensitive to the sample used in the tribological test. In the presented work, these are sheets made of Ni (AMS5599), Fe (AMS5510) and Al (AMS4026) alloys. By changing the chemical composition of composites, we are able to find favorable combinations coefficient of friction and wear resistance for die and stamp used for sheet metal forming processes.

CONCLUSIONS

The paper presents the results of testing the wear resistance and coefficient of friction (COF) composite tools made of SikaBeresin® F50 polyurethane resin intended for dies and punches for the cold sheet metal forming process.

- The addition of metallic reinforcements has a positive effect on increasing the wear resistance of the tested composite materials based on SikaBeresin® F50 polyurethane resin,

- The highest increase in wear resistance in the AMS5599 sheet specimen:composite ring pair was characterized by the composite with the addition of 10% copper powder- A+B+C+10%Cu. In this case, an increase in wear resistance of more than 1900% was observed compared to the composite A+B+C+20%Al,
- The addition of 10% Cu powder shows a sufficient effect on the wear resistance of the composite rotating ring. This is advantageous from an economic point of view, as the lower proportion of copper in the tested combinations with sample AMS5599 and AMS4026 is sufficient. In the case of sample AMS5510, the best wear resistance was obtained for the reinforcement of 20% copper powder,
- In each of the cases studied, the lowest coefficient of friction μ was obtained for composites without metallic reinforcements,
- The application of metallic reinforcements to the tested composites caused an increase in the coefficient of friction μ. For the AMS5599, AMS5510 and AMS4026 sheet specimens tested, the highest coefficient of friction was obtained with the composite ring A+B+C+Al20%. The coefficient of friction was respectively: μ=0.465, μ=0.413, μ=0.361,
- Metallic reinforcements used for composite tools for cold plastic forming of sheet metal offers the possibility of configuring different coefficients of friction and wear resistance in a single tool set (die:stamp) depending on the technological needs of the process.

Conflicts of interests

The authors declare that they have no competing financial interests or personal relationships that could have seem to influence the study reported in this paper.

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