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Article

Cold rolling of steel strips with metal-working coolants

Anatoly P. Avdeenko [1], Vladimir A. Fedorynov [2], Predrag V. Dašić [3,*], Raul Turmanidze [4], Mykhailo V. Fedorynov [5], Svetlana A. Konovalova [6], Konstantin S. Burmistrov [7], and Nikolay V. Toropin [8]

[1] Donbas State Engineering Academy, Akademichna 72, 84313, Kramatorsk, Ukraine; chimist@dgma.donetsk.ua
[2] Donbas State Engineering Academy, Akademichna 72, 84313, Kramatorsk, Ukraine; vladimir.fedorinov@dgma.donetsk.ua
[3] Faculty of Strategic and Operational Management (FSOM), 11000 Belgrade, Serbia; dasicp58@gmail.com
[4] Georgian Technical University (GTU), 0175 Tbilisi, Georgia, inform@gtu.ge
[5] Donbas State Engineering Academy, Akademichna 72, 84313, Kramatorsk, Ukraine; amm@dgma.donetsk.ua
[6] Donbas State Engineering Academy, Akademichna 72, 84313, Kramatorsk, Ukraine; chemistrydgma@gmail.com
[7] Ukrainian State University of Chemical Technology, Gagarin Avenue 8, 49005, Dnipro, Ukraine; kkssburm@gmail.com
[8] Ukrainian State University of Chemical Technology, Gagarin Avenue 8, 49005, Dnipro, Ukraine; toropin.nv@gmail.com
* Correspondence: dasicp58@gmail.com; Tel.: +381-60-6926690

Abstract: The efficiency of cold sheet and strip rolling of steels and non-ferrous metals in the main depends on the quality of the technological lubricant and its cost. In this regard, it is important to develop new compositions of effective metal-working coolants (MWC) having low cost and providing the maximum reduction in the friction coefficient. We developed and tested the new compositions of the MWC on basis of chicken fat, and mono- and diglycerides and their esters of boric acid synthesized from the wastes of sunflower oil production. The MWC were tested in DSEA on laboratory rolling mill 100x100 with a roll diameter of 260 mm during steel 08Kp rolling. The efficiency of the coolants was determined by the factor of metal stretch forming λ and the coefficient of friction μ in the deformation zone which was found by forward slip method. We found the metal-working coolant with 100 % concentration of boric acid esters of mono- and diglycerides is the most effective in steel rolling. Thus the new MWC on basis of boric acid esters of mono- and diglycerides synthesized from the wastes of sunflower oil production can be recommended for use in rolling of structural steels on account of availability, high efficiency, and a low cost.

Keywords: metal-working coolants (MWC); steel rolling; coefficient of metal rolling-out; friction coefficient; sunflower oil

1. Introduction

The efficiency of cold sheet and strip rolling of steels and non-ferrous metals in the main depends on the quality of the technological lubricant [1–4]. The research results presented in this article is the continuation of the cycle of our works [5-10] related to the search of new metal-working coolants (MWC) which can effectively reduce a friction level on the contact surfaces of metal and tool in metal forming. First of all it relates to production of cold-rolled plates and strips of ferrous and nonferrous metals and as well as the production of long products by metal drawing and pressing in a cold state.

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Earlier we found the MWC containing 30% of boric acid esters of mono- and diglycerides based on sunflower oil are the most effective [10]. We also noted the enough high efficiency, availability, and low cost of the MWC with chicken fat.

2. Materials and Methods

The task of the first stage was to study the MWC with the increased content of boric acid esters of mono- and diglycerides based on sunflower oil (from 30% up to 60%) (Table 1), and the new coolant compositions with chicken fat (Table 2).

The test results are shown in Table 3.

Table 1. Compositions of new metal-working coolants (MWC) on the base of boric acid esters for metal rolling

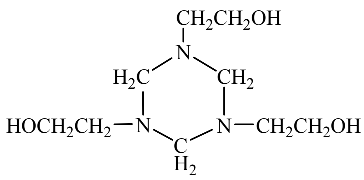
Composition number	Components, %			
	Boric acid esters of mono- and diglycerides based on sunflower oil *	Industrial oil	Chlorinated paraffin wax XP-470	Calcium stearate
№ 5	30	30	20	20
№ 19	40	20	20	20
№ 20	50	10	20	20
№ 21	60	-	20	20
№ 27	80	-	10	10
№ 28	100	-	-	-
№ 25	MWC of Ilyich Iron and Steel Works **			
№ 29	Mono- and diglycerides based on sunflower oil, 100%			

Notes. * These components were synthesized in Ukrainian State University of Chemical Technology (Dnipro, Ukraine). ** As MWC comparison we used coolant «Universal-1TC» developed and used in Ilyich Iron and Steel Works (Mariupol, Ukraine), TU U23.2-31023384.002–2004.

Table 2. Compositions of new metal-working coolants (MWC) with chicken fat

Composition number	Components, %		
	Chicken fat	Emulsifier*	Antibacterial additive**
№ 17	100	–	–
№ 22	92	5	3
№ 23	87	10	3
№ 24	82	15	3
№ 26	SP-3***		

Notes. * The diethanolamide of sunflower oil acids was used as emulsifier. ** Antibacterial additive evolves formalin because it is a condensation product of formalin and monoethanolamine and its formula is



*** We used the lubricant SP-3 (GOST 5702-75) as MWC comparison.

All tests with MWC we carried out on industrial and laboratory rolling mill in Donbas State Engineering Academy (Figure 1) as well as in [10].

Annealed 08Kp steel rolling was carried out for samples with initial thickness of h_0 = 1.88…1.91 mm and width of b_0 = 39.90 mm. The rolling rate was 0.2 m/s. We used two cobbing levels: 1st level with $\varepsilon_{avg} \approx 18\%$ and 2nd level with $\varepsilon_{avg} \approx 46.5\%$. Before rolling we laid MWC on the strip. Before each pass we thoroughly cleaned rollers.

To compare the results obtained for new MWC we carried out rolling without MWC (dry samples in dry rollers), with MWC № 5 and № 17 which was studied in work [10], and with MWC № 25 used in Ilyich Iron and Steel Works (Mariupol, Ukraine) as MWC for cold rolling of steel strips.

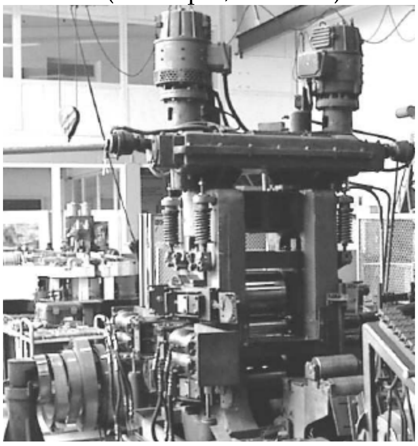


Figure 1. A working stand of the industrial and laboratory rolling duo-mill of 260x200 in DSEA

Table 3. Experimental data of 08Kp steel cold rolling with various MWC (l_0 = 200 mm, l_b = 150 mm, D_f = 260 mm)

MWC number	h_0, mm	h_1, mm	Δh, mm	ε, %	L_1, mm	λ	l_1, mm	α, rad	S, %	γ, rad	μ
MWC based on boric acid esters											
1st level of cobbing ($\varepsilon_{avg} \approx$ 17.82%)											
Dry*	1.89	1.55	0.34	18.00	246	1.230	154.25	0.05	2.83	0.018	0.0995
5	1.91	1.56	0.35	18.30	247	1.235	153.20	0.05	2.13	0.018	0.0895
19	1.91	1.57	0.34	17.80	247	1.235	152.85	0.05	1.90	0.015	0.0626
20	1.90	1.56	0.34	17.90	248	1.240	152.19	0.05	1.46	0.013	0.0521
21	1.89	1.55	0.34	18.00	248	1.240	151.76	0.05	1.17	0.012	0.0481
25	1.89	1.57	0.32	16.90	245	1.225	153.44	0.05	2.29	0.017	0.0783
2st level of cobbing ($\varepsilon_{avg} \approx$ 46.84%)											
Dry*	1.91	1.13	0.78	40.84	369	1.845	160.00	0.08	6.67	0.024	0.1003
5	1.89	1.01	0.88	46.56	396	1.980	155.00	0.08	3.33	0.016	0.0668
19	1.90	0.96	0.94	49.47	389	1.945	154.49	0.09	2.99	0.015	0.0676
20	1.89	0.98	0.91	48.15	391	1.955	153.98	0.08	2.65	0.014	0.0616
21	1.91	0.96	0.95	49.74	415	2.075	151.25	0.09	0.83	0.008	0.0548
25	1.88	1.01	0.87	46.28	376	1.880	156.19	0.08	4.13	0.018	0.0729
MWC based on chicken fat											
1st level of cobbing ($\varepsilon_{avg} \approx$ 18.91%)											
Dry*	1.89	1.54	0.35	18.52	249.00	1.245	154.73	0.05	3.15	0.019	0.1045
17	1.89	1.53	0.36	19.05	252.00	1.260	153.38	0.05	2.25	0.016	0.0696
22	1.89	1.52	0.37	19.58	251.00	1.255	153.60	0.05	2.40	0.017	0.0783
23	1.88	1.53	0.35	18.62	251.00	1.255	153.32	0.05	2.21	0.016	0.0696
24	1.89	1.52	0.37	19.58	251.00	1.255	153.77	0.05	2.29	0.016	0.0696
26	1.88	1.54	0.34	18.09	248.00	1.240	154.66	0.05	3.11	0.019	0.1045
2st level of cobbing ($\varepsilon_{avg} \approx$ 46.43%)											
Dry*	1.90	1.02	0.88	46.32	375.00	1.875	158.25	0.08	5.50	0.021	0.0944
17	1.89	1.00	0.89	47.09	386.00	1.930	153.90	0.08	2.60	0.014	0.0616
22	1.89	1.00	0.89	47.09	383.00	1.915	154.60	0.08	3.07	0.015	0.0641
23	1.91	1.00	0.91	47.64	385.00	1.925	154.81	0.08	3.21	0.016	0.0668
24	1.88	1.01	0.87	46.28	379.00	1.895	155.11	0.08	3.41	0.016	0.0668
26	1.88	1.05	0.83	44.15	363.00	1.815	158.25	0.08	5.50	0.021	0.0844

Note. * Rolling without MWC.

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Working rolls from 9X steel had diameter of 260 mm. A hardness of forming surfaces of roll body was 80HS, a roughness was 0.63 microns.

The efficiency of MWC was determined by comparing the reduction ratios in rolling of the same samples without MWC (dry) and with MWC when initial roll opening S_0 was fixed [10; 11]. It is known the more effective MWC promotes the decrease of pressing force and stand springing. Therefore in this case when the initial roll opening S_0, thickness h_0, and width b_0 of samples are invariable the metal redaction increases. That let us estimate an efficiency of MWC. In thin flat-sample rolling the widening is practically absent (it is less than 1%), and the ratio of the thicknesses h_0 and h_1 is equal to reduction ratio λ for the strip in pass, that is $h_0/h_1 = \lambda$. Therefore, to improve the accuracy we estimated the redaction level in each case with reduction ratio λ calculated as a ratio of the distance between the initial marks previously applied on the strip before rolling (l_0 = 200 mm) and the distance between the same marks after rolling (l_1), that is $\lambda = l_1/l_0$ [10].

In this work to determine the friction coefficient μ for the tested MWC we used the forward slip method [12].

It is known the speed of forward motion of the strip exiting from the rollers is higher than the surface speed of rollers. This phenomenon is called the forward slip [11].

The forward slip is determined by the formula:

$$S = (V_1 - V_f)/V_f = V_1/V_f - 1, \tag{1}$$

where V_1 is the start strip speed and V_f is the surface speed of rollers.

In practice the forward slip is determined by kern method. For this the small indentation is punched on the body of roller on the distance l_b along circular arc. These marks leave the tracks on the strip, and the distance between these tracks l_1 is longer from forward slip.

Hence it appears

$$S = (l_1 - l_b)/l_b = l_1/l_b - 1, \tag{2}$$

where l_1 is the distance between the tracks on the strip and l_b is the distance between marks on the body of roller along circular arc.

Indeed, for a time t $l_b = V_f t$, and $l_1 = V_1 t$, so $V_f = l_b/t$, and $V_1 = l_1/t$.

Theoretically the forward slip in symmetrical rolling can be determined considering the position of the neutral section. In thin strip rolling when the roller radius R_f is much bigger than the strip thickness h_1 in exit from deformation zone the forward slip can be calculated by the Dresden formula [11]:

$$S = \frac{R_f}{h_1}\gamma^2, \tag{3}$$

where γ is neutral angle.

If we know the forward slip and use the forward slip method we can approximately determine the average value of the friction coefficient.

In this case the value of forward slip S is determined experimentally as an indicator of relative metal sliding on roller surface in exit from deformation zone in steady rolling. After this the value of neutral angle γ is calculated with help of Fink formula [12]:

$$\cos\gamma = \frac{D_f + h_1}{2D_f} + \sqrt{\left(\frac{D_f + h_1}{2D_f}\right)^2 - \frac{h_1}{D_f}(1+S)}, \tag{4}$$

where D_f is roller diameter.

For the same purpose it can be used the Dresden formula (3) simplified in the form:

$$\gamma = \sqrt{\frac{Sh_1}{R_f}}. \tag{5}$$

The angle γ found in this way is substituted into known Ekelund-Pavlov formula [12]:

$$\gamma = \frac{\alpha}{2}(1 - \frac{\alpha}{2\beta}), \tag{6}$$

which is used to find the friction angle β:

$$\beta = \frac{\alpha^2}{2(\alpha - 2\gamma)}. \tag{7}$$

The friction coefficient is determined by the equation (7) in consideration of equation (8)

$$\mu = tq\beta. \tag{8}$$

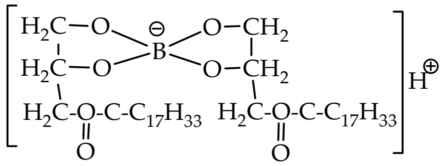
It should be taken into account the formulas (4-6) were obtained under the assumption of uniform height distribution of speed in deformation zone, that is, the hypothesis of "flat sections" was taken in their derivation. It is now established that the longitudinal velocities of metal particles have non-uniformly height distribution in deformation zone. Full decreasing of nonuniformity of speeds occurs only after exit of metal from zone of contact with the rollers. In this regard, the neutral section has generally curved form [13]. This important fact is not reproduced in the formulas (4–6). Therefore, the use of formulas (4–6) gives satisfactory results in relatively thin strip rolling when $l/h_{avg} > 3…4$ at plane deformation, that is $b_0/l > 5$, where l is the horizontal projection of the contact arc length of metal and rollers, h_{avg} is average height of strip in the deformation zone, b_0 is initial width of strip.

In this case, the use of these dependencies was justified.

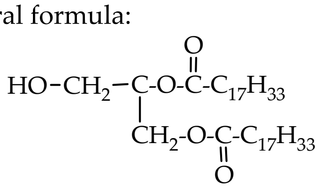
3. Results and Discussion

On the base of analysis of the experiments (see Table 3) it should be noted that in the MWC group based on boric acid esters (№ 5, 19, 20, and 21) the MWC № 21 has shown the best results in reduction ratios λ and friction coefficients μ for 1st and 2st levels of cobbing (for $\varepsilon_{avg} \approx 17.82$ % $\mu = 0.0481$, and for $\varepsilon_{avg} \approx 46.84$ % $\mu = 0.0548$). This coolant contained 60% of boric acid esters of mono- and diglycerides based on sunflower oil, that is, with an increase in the percentage of boric acid esters the MWC efficiency increased.

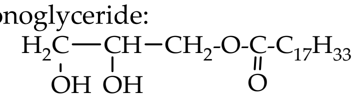
Boric acid ester of monoglyceride based on sunflower oil has the structural formula:



This is stable compound as opposed to boric acid ester of diglyceride. In this regard, in the product having a name "boric acid esters of mono- and diglycerides based on sunflower oil" the active components are the boric acid ester of monoglyceride based on sunflower oil and diglyceride based on sunflower oil with structural formula:



The feedstock in the synthesis of boric acid esters of mono- and diglycerides based on a sun-oil is a mixture of diglyceride and monoglyceride:



In previous study [10] the prospects of use of chicken fat as MWC was noted (MWC № 17 with 100% chicken fat).

In this work the compositions № 22, 23, and № 24 based on of chicken fat and containing very important components – an emulsifier and an antibacterial additive, that provide high performance,

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have shown good results (see Table 3), but slightly worse than composition № 21 based on boric esters.

In consideration of results described above we decided to increase the concentrations of boric acid esters of mono- and diglycerides based on sunflower oil up to 80% and 100% in MWC № 27 and 28. Also we decided to estimate the possibility of use of the feedstock (a mixture of monoglyceride and diglyceride) as MWC in steel rolling. This is MWC № 29.

Results of experiments are shown in Table 4.

Table 4. Experimental data of 08Kp steel cold rolling with MWC with high concentrations of boric acid esters of mono- and diglycerides based on sunflower oil (l_0 = 200 mm, l_b = 150 mm, D_f = 260 mm)

MWC number	h_0, mm	h_1, mm	Δh, mm	ε, %	L_1, mm	λ	l_1, mm	α, rad	S, %	γ, rad	μ
1st level of cobbing ($\varepsilon_{avg} \approx$ 19.60%)											
Dry*	1.89	1.54	0.35	18.52	247.50	1.237	154.50	0.05	3.00	0.019	0.1045
21	1.88	1.52	0.36	19.15	251.00	1.255	153.20	0.05	2.13	0.016	0.0596
27	1.88	1.51	0.37	19.68	251.00	1.255	153.10	0.05	2.10	0.016	0.0586
28	1.90	1.50	0.40	21.05	254.00	1.270	152.39	0.05	1.59	0.014	0.0569
29	1.91	1.53	0.38	19.89	253.00	1.265	153.80	0.05	2.53	0.017	0.0783
2st level of cobbing ($\varepsilon_{avg} \approx$ 49.88%)											
Dry*	1.89	1.04	0.85	44.97	376.50	1.883	158.00	0.08	5.33	0.021	0.0954
21	1.89	0.98	0.91	48.15	422.00	2.110	152.39	0.08	1.59	0.011	0.0552
27	1.88	0.89	0.99	52.66	435.00	2.175	150.53	0.09	0.35	0.005	0.0507
28	1.88	0.87	1.01	53.72	447.00	2.235	148.82	0.09	-0.79	0	0.0450
29	1.88	0.9	0.98	52.13	407.00	2.035	151.00	0.09	0.67	0.007	0.0533

Note. * Rolling without MWC.

As expected, MWC № 28 with 100% concentration of boric acid esters showed the highest results. It is indicate that the chlorinated paraffin wax XP-470 and calcium stearate, widely used in various compositions of MWC for steel rolling, have not influence on properties of MWC with boric acid esters of mono- and diglycerides based on sunflower oil.

It should be noted that on the 2st level of cobbing for the coolant № 28 the absolute reduction is practically maximum (Δh = 1.01 mm, ε_{avg} = 53.72 %) due to the high efficiency of this MWC and as a result the low value of friction coefficient (μ = 0.0450). This is evidenced by the negative value of the forward slip (S = -0.79%).

It indicates that the reserve of friction forces in deformation zone for rolling with this cobbing is exhausted due to the high quality of MWC because the lag zone extended to all length of deformation zone.

MWC № 29 with 100% concentration of mono- and diglycerides based on sunflower oil showed relatively high results. Therefore, the both diglyceride and boric acid ester of monoglyceride raise the reduction ratio of steel λ and reduce the friction coefficient μ.

In addition, we studied boric acid ethers of mono- and diglycerides based on sunflower oil waste (MWC № 30), mono- and diglycerides based on sunflower oil waste (MWC № 31), boric acid esters of mono- and diglycerides based on rapeseed oil (MWC № 32) and mono- and diglycerides based on rapeseed oil (MWC № 33) in two cobbing levels ($\varepsilon_{avg} \approx$ 19.7%) and ($\varepsilon_{avg} \approx$ 42.8%) (Table 5).

In the first level of cobbing we observed the smallest forward slip (S = 1.43%), that is the smallest coefficient of friction, for mono- and diglycerides based on rapeseed oil. In the second level of cobbing ($\varepsilon_{avg} \approx$ 42.8%) we found the insignificant reduction in the coefficient of friction for MWC № 30 and № 31, and more significant reduction in the coefficient of friction for MWC № 32 and № 33 in comparison with rolling without MWC. But these results cannot be called positive.

Due to the fact that MWC based on rapeseed oil (MWC № 32 and 33) reduced the friction coefficient, we also investigated 100% emulsion MWC based on boric acid esters of mono- and

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diglycerides of rapeseed oil (MWC № 34) and aqueous emulsions with MWC concentration of 30% (№ 35), 20% (№ 36), 10% (№ 37), 5% (№ 38), and 3% (№ 39) (see Table 5).

Emulsion MWC № 34 has the following composition:

- boric acid ester of mono- and diglycerides of rapeseed oil – 25%;
- industrial oil I-40 – 5%;
- emulsifier – 70%.

As emulsifier we used the composition:

- oleate of triethanolamine – 15%;
- preparation OC-20 – 8%;
- monoethanolamides of sunflower oil – 5%;
- isoamyl alcohol – 3%;
- bactericide – 0,2%;
- water – up to 100%.

Table 5. Experimental data of 08Kp steel cold rolling with various kinds of metal-working coolants (l_0 = 200 mm, l_b = 150 mm, D_f = 260 mm)

MWC number	h_0, mm	h_1, mm	Δh, mm	ε, %	L_1, mm	λ	l_1, mm	S, %	γ, rad
1st level of cobbing ($\varepsilon_{avg} \approx$ 19.7%)									
30	1.88	1.50	0.38	20	247.00	1.235	152.44	1.62	0.014
31	1.90	1.52	0.38	20	246.50	1.233	152.57	1.71	0.014
32	1.90	1.52	0.38	20	247.50	1.235	152.57	1.71	0.014
33	1.90	1.50	0.4	21	248.00	1.240	152.15	1.43	0.013
34	1.90	1.53	0.37	19	243.00	1.215	153.22	2.15	0.016
35	1.89	1.54	0.35	19	242.00	1.210	153.83	2.55	0.017
36	1.88	1.54	0.34	18	246.00	1.230	153.84	2.56	0.017
37	1.90	1.51	0.39	21	246.00	1.230	153.06	2.04	0.015
38	1.90	1.52	0.38	20	246.00	1.230	153.20	2.13	0.016
39	1.90	1.54	0.36	19	247.00	1.235	152.57	1.71	0.014
2st level of cobbing ($\varepsilon_{avg} \approx$ 42.8%)									
Dry*	1.90	1.14	0,86	45	328.00	1.640	158.00	5.33	0.022
30	1.88	1.05	0.83	44	352.00	1.760	155.34	3.56	0.017
31	1.88	1.05	0.83	44	350.00	1.750	155.52	3.68	0.017
32	1.89	1.02	0.87	46	363.00	1.815	153.99	2.66	0.014
33	1.90	1.03	0.87	46	362.00	1.810	153.77	2.51	0.014
34	1.89	1.13	0.76	40	327.00	1.635	158.80	5.87	0.023
35	1.90	1.20	0.70	37	316.50	1.583	159.50	6.33	0.024
36	1.90	1.13	0.77	41	330.00	1.650	158.50	5.67	0.022
37	1.90	1.10	0.80	42	334.00	1.670	157.00	4.67	0.020
38	1.89	1.12	0.77	41	338.00	1.690	157.00	4.67	0.020
39	1.89	1.13	0.76	40	336.00	1.680	157.00	4.67	0.020

Note. * Rolling without MWC.

In all cases we obtained negative results: a decrease in the friction coefficient was not observed. For MWC № 34, 35, and 36 we observed even an insignificant increase in the coefficient of friction in comparison with rolling without MWC. That may indicate a chemical interaction of coolant components with the metal surface of the rolls and rolled steel.

4. Conclusions

In steel rolling the metal-working coolant with 100 % concentration of boric acid esters of mono- and diglycerides based on sunflower oil is the most effective. It has been found that for the 2st level of cobbing (ε_{avg}=53.72 %) the absolute reduction is practically maximum (Δh=1.01 mm) when initial thickness of strip h_0 is 1.88 mm and roller diameter D_f is equal 260 mm. That is due to the high efficiency of this metal-working coolant and as a result the low value of friction coefficient (μ=0.0450). This is evidenced by the negative value of the forward slip (S=-0.79%). Relatively high results have been shown by mono- and diglycerides which are starting materials in the synthesis of boric esters. Diglyceride is part of boric esters; therefore it is possible to conclude that the diglycerides have a significant influence on properties of metal-working coolants based on boric esters.

Compositions of metal-working coolants based on chicken fat shown slightly lower results in comparison with compositions based on boric acid esters.

It should be noted the low efficiency of industrial metal-working coolants in steel rolling at conditions of this experiment: The coolant «Universal-1TC» developed and used in Ilyich Iron and Steel Works, and technological grease SP-3.

In brass rolling the MWC on basis of mono- and diglycerides are more effective than ones on basis of boric acid esters of mono- and diglycerides [14]. MWC composition containing 30 % of mono- and diglycerides is the most effective.

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