ISSN 1330-3651
UDC/UDK 620.178.1:623.423

INFLUENCE OF ARTILLERY WEAPON BARREL SUPERHEAT ON ABRASION WEAR RESISTANCE OF MATERIAL

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Original scientific paper

This paper studies the influence of the artillery weapon barrel superheat on abrasion wear resistance of material. The firing process has a compound mechanical, thermal and chemical effect on the barrel. Many wear mechanisms exist in the barrel in firing conditions: abrasion, adhesion, fatigue and tribocorrosion. This paper presents the procedure and the results of abrasion wear experiment. Some test samples were previously tempered and air cooled. The abrasion test samples were made of the heat treated steel 42CrMo4. Wear resistance is represented by the sample mass loss during the wear process. The test results show that unheated samples exhibit higher wear resistance in comparison with heated samples. A significant material wear increase of 43 % is shown in the samples which were heated at 900 °C. Conclusively, the test results show that excessive fire causes the weapon barrel to superheat and the material wear resistance to significantly decrease.

Keywords: *abrasion wear, fire rate, superheat, weapon barrel*

Utjecaj pregrijavanja cijevi topničkog oružja na otpornost prema abrazijskom trošenju materijala

Izvorni znanstveni članak

U ovom se radu istražuje utjecaj pregrijavanja cijevi topničkog oružja na abrazijsko trošenje materijala. Proces opaljenja ima složeno mehaničko, toplinsko i kemijsko djelovanje na cijev oružja. Višestruki mehanizmi trošenja javljaju se u cijevi tijekom opaljenja: abrazija, adhezija, umor površine i tribokorozija. Rad prikazuje postupak i rezultate ispitivanja abrazijskog trošenja. Neki od ispitnih uzoraka su prethodno zagrijavani i hlađeni na zraku. Ispitni uzorci su izrađeni od čelika 42CrMo4. Otpornost na trošenje je predstavljena gubitkom mase uzoraka tijekom trošenja. Rezultati istraživanja pokazuju da nezagrijavani uzorci imaju veću otpornost na trošenje u usporedbi sa zagrijavanim uzorcima. Značajan porast trošenja materijala od 43 % u odnosu na nezagrijavane uzorke ostvaren je kod uzoraka koji su prethodno zagrijavani na 900 °C. Zaključno, rezultati istraživanja pokazuju da režim paljbe ne smije biti prekoračen, jer on dovodi do pregrijavanja cijevi i do smanjenja otpornosti materijala na trošenje.

Ključne riječi: *abrazijsko trošenje, cijev oružja, pregrijavanje, režim paljbe*

1 Introduction
Uvod

The firing process is a strong and dynamic process which takes place in the weapon barrel. During this process the powder burns intensively and a great quantity of hot powder gasses are produced. The high pressure of the powder gasses enables the projectile to move to the barrel mouth. The projectile movement through the barrel lasts for about 0,01 second and in this time the projectile reaches the maximum muzzle velocity v_0 of up to 1800 m/s [1, 2].

Figure 1 *View of grooved barrel bore*
Slika 1. *Pogled na ožljebljeni kanal cijevi*

Grooves of the barrel bore are fabricated with a definite twist angle (Fig. 1). Therefore, the projectile attains both the translational and the rotational motion at the coming out from the barrel mouth (Fig. 2).

A large heat quantity is developed by powder burning, and both the powder gasses and the barrel material are heated by this heat energy. High flame temperature propellants may produce combustion gasses at

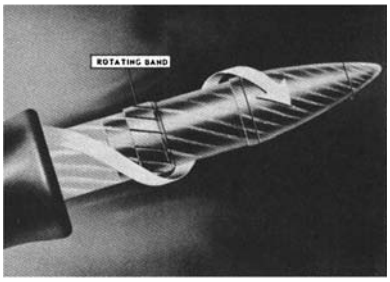

Figure 2 *Projectile rotation at the moment of coming out from barrel mouth* [3]
Slika 2. *Rotacija projektila u trenutku izlaza iz usta cijevi* [3]

emperatures as high as 3700 K. Peak gas pressure may reach up to 700 MPa [1, 4].

The origin of rifling is the point at which heat transfer from hot propellant gasses to the barrel surface is the greatest. Typically, the bore temperature reaches 600-1200 °C at this place within few milliseconds of exposure to the hot propellant gases. Heat transfer may be 500 MW/m^2 [5].

The peak bore temperature of a gun may reach up to 1800 K a few milliseconds after it is fired [4], and the melting point of the gun steel is 1720 K [6].

While burning a higher powder amount, the quantity of powder gasses increases. Therefore, the muzzle velocity of a projectile also increases (Fig. 3).

At high temperatures, chemical species from the propellant gas include the main products of propellant combustion: CO, CO_2, H_2, H_2O and N_2, and a small quantity of dissociated atomic species [5, 8]. These species create a very aggressive atmosphere in relation to the barrel material.

The powder gasses also contain solid particles: soot particles and unburned powder grains. Because of the

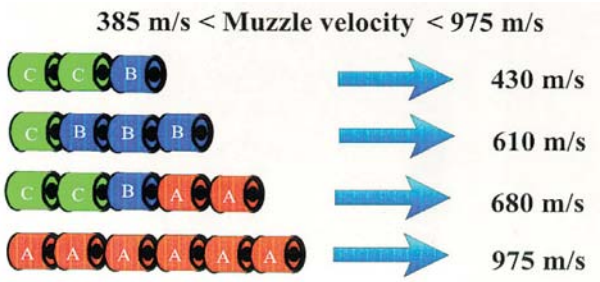

***Figure 3** Influence of powder amount on muzzle velocity of projectile* [7]
***Slika 3.** Utjecaj količine baruta na početnu brzinu projektila* [7]

strong turbulent streaming of the pressed powder gasses, these particles are moving with high speed in the barrel bore and hit the bore surface. In this way, both the erosive and abrasive barrel wear caused by the solid particles appears. Furthermore, because of very high speed, the particles penetrate into the material surface and form corrosion centres.

At the same time, the contact pressure between both the centring and rotating band of the projectile and the bore surface appears. The rotating band is cut into the grooved barrel profile. So, the high contact pressure as well as the strong sliding force appear on the contact surfaces between the projectile bands and the bore surface when firing. In these firing conditions, the centring and specially rotating band contribute significantly to adhesive and abrasive wear of the bore surface. The sliding friction energy transforms into a significant quantity of heat energy too.

The barrel heating is not uniform over the transverse section: the bore surface is heated the most, but the material layers in the direction of the barrel's outer surface are colder. In this way, the outer layers of the material do not enable the thermal dilatation of the inside warmer layers. So, thermal stress increases in the direction of the barrel bore surface. Finally, this stress may cause the appearance of micro surface cracks.

Fig. 4 shows the simulated results of the inner and the outer surface temperature under natural air cooling.

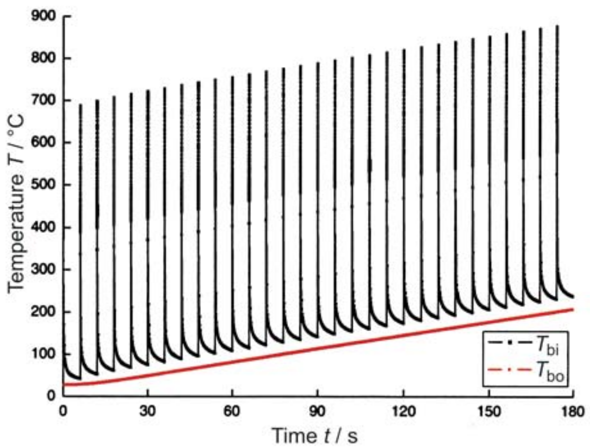

***Figure 4** Inner (T_{bi}) and outer (T_{bo}) surface temperature under natural air cooling* [9]
***Slika 4.** Temperatura unutarnje (T_{bi}) i vanjske (T_{bo}) površine kod normalnog hlađenja zrakom* [9]

It is observed that the inner surface temperature fluctuated sharply, whereas the outer surface temperature changed slightly. Also, the heat transfer process in the gun barrel is always transient.

In accordance with all the above mentioned, the firing process has a compound tribological effect on the weapon barrel: mechanical, thermal and chemical processes affect the barrel. It is obvious that many wear mechanisms exist in the barrel in these conditions at the same time: abrasion, adhesion, fatigue and tribocorrosion [8], so that an increase in the barrel heat level probably changes the wear resistance of the material.

This paper presents the procedure and the results of abrasion wear experiment. The barrel material of a chosen artillery weapon was tested. Some test samples were not tempered previously, but others were tempered at 600 C, 700 C, 800 C and 900 C and air cooled. It is similar to the superheating and cooling of the barrel during intensive firing.

The influence of the weapon barrel superheat on the abrasion wear resistance of the material will be shown in the analysis of the obtained experimental results.

2
Test samples preparation
Priprema ispitnih uzoraka

The chemical composition analysis and the measurement of material hardness were carried out for barrels of some artillery weapons: a field gun, an antiaircraft gun and a mortar. It was established that the material of each barrel was quenched and tempered steel [8]. The test samples used for the investigation presented in this paper were made of soft annealed 42CrMo4 steel (Fig. 5).

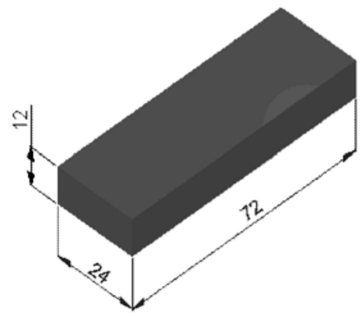

***Figure 5** Test sample for abrasion wear*
***Slika 5.** Ispitni uzorak za abrazijsko trošenje*

The chemical composition of the test samples is shown in Tab. 1.

***Table 1** Chemical composition of test samples (42CrMo4)*
***Tablica 1.** Kemijski sastav ispitnih uzoraka (42CrMo4)*

Chemical composition, %	C	Si	Mn	Cr	Ni	Mo
	0,41	0,20	0,75	1,05	-	0,23

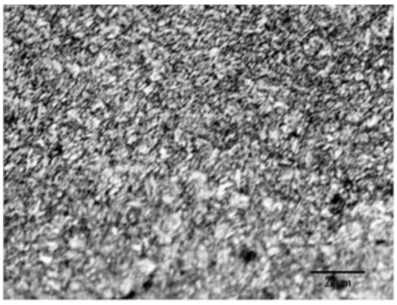

***Figure 6** Metallographic image of quenched and tempered sample (42CrMo4)*
***Slika 6.** Metalografska snimka poboljšanog uzorka (42CrMo4)*

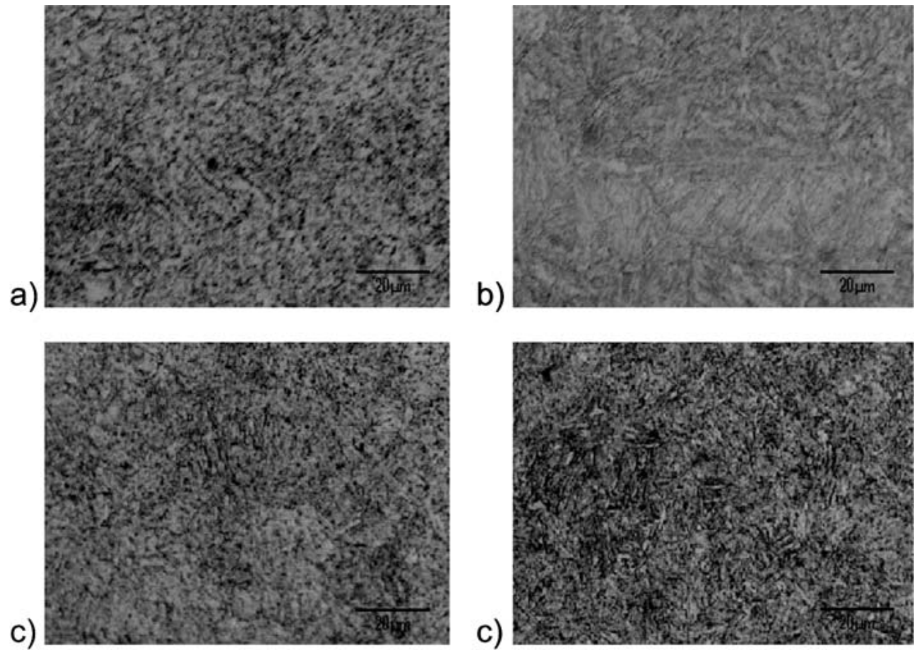

Figure 7 *Metallographic images of tempered and air cooled test samples*
a - sample tempered at 600 °C, b - sample tempered at 700 °C, c - sample tempered at 800 °C, d - sample tempered at 900 °C
Slika 7. *Metalografske snimke zagrijavanih i zrakom hlađenih ispitnih uzoraka*
a - uzorak zagrijavan na 600 °C, b - uzorak zagrijavan na 700 °C, c - uzorak zagrijavan na 800 °C, d - uzorak zagrijavan na 900 °C

The sample surfaces were previously ground and they have N6 quality because the bore surface has the same machining quality [10]. The hardness of 32±2 HRC was measured on the weapon barrel bore. To obtain this hardness, the samples were oil quenched at 860 °C and tempered at 600 °C for two hours [8].

One of the test samples was subsequently cross-sectioned and prepared for metallographic imaging. The cross-section surfaces were ground and polished previous to etching in nital. The metallographic imaging cross-section of the quenched and tempered sample is shown in Fig. 6.

The homogeneous structure of the tempered martensite can bee seen in the above figure.

The test samples were heated prior to the abrasion wear caused by the dry sand/rubber wheel method. Therefore, two by two samples were tempered at 600 °C, 700 °C, 800 °C and 900 °C over a period of one hour and air cooled. These are possible heating temperatures of the barrel bore surface which develop due to the intensive firing process or when the allowed rate of fire is exceeded.

One sample of every tempered group was cross-cut cold and prepared for metallographic imaging. The cross-sections of the samples were ground and polished and subsequently corroded with nital. The metallographic images of sample cross sections are shown in Fig. 7.

Hardness was measured on sample surfaces and the means of the measurement results are shown in Tab. 2.

Table 2 *Surface hardness of test samples*
Tablica 2. *Površinska tvrdoća ispitnih uzoraka*

Temperature of previously heating /°C	600	700	800	900
Mean hardness / HV1	495	476	397	412

In accordance with the metallographic images (Fig. 7) and the values of the measured hardness (Tab. 2) as well as in accordance with the CCT diagram of the 42CrMo4 steel (Fig. 8), the structure of the tempered martensite is kept by the material heating at 600 °C and 700 °C and air cooling.

The samples tempered at 800 °C and 900 °C maintain a uniform small-grained structure. However, with the obtained hardness of about 400 HV1, bainite may appear in the micro structure of the test steel as well as the ferrite-pearlite structure, along with the basic structure of martensite.

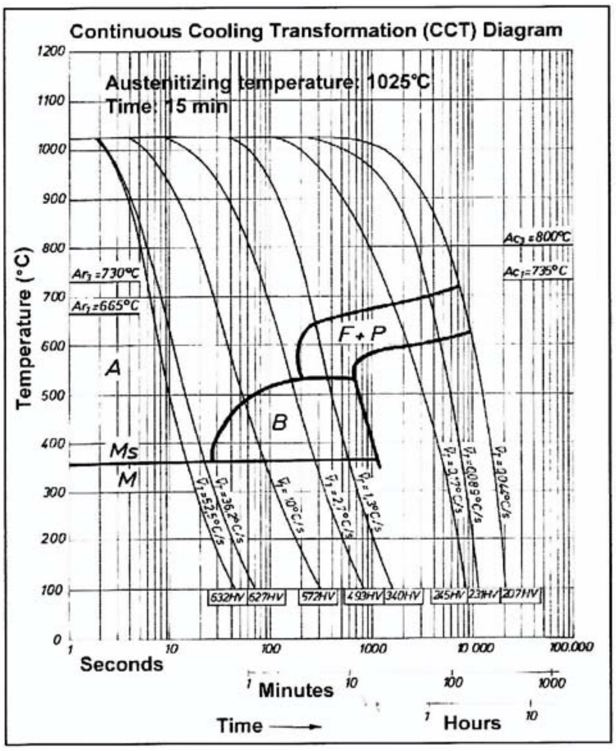

Figure 8 *CCT diagram of 42CrMo4 steel* [11]
Slika 8. *CCT dijagram čelika 42CrMo4* [11]

Test samples were heat-treated in the Laboratory for Heat Treatment at the Faculty of Mechanical Engineering and Naval Architecture in Zagreb. Also, the samples were prepared for metallographic imaging and imaged in the Metallographic Laboratory and the tribological tests were performed in the Tribology Laboratory at the same Faculty.

3
Testing of abrasive wear and test results
Ispitivanje abrazijskog trošenja i ispitni rezultati

The abrasive wear test of barrel material was performed by modified "dry sand/rubber wheel" method, in accordance with the ASTM G 65-94 standard. The modification means that the sample mass loss was measured at the force load *F*=130 N, after 100; 500 and 1000 revolutions of the rubber wheel.

Testing parameters:

- abrasive: rounded quartz grain sand AFS 50/70
- number of rubber wheel revolutions: 100, 500 and 1000
- dimension of samples: 72×24×12 mm.

The macro image of the final worn surface is shown in Fig. 9.

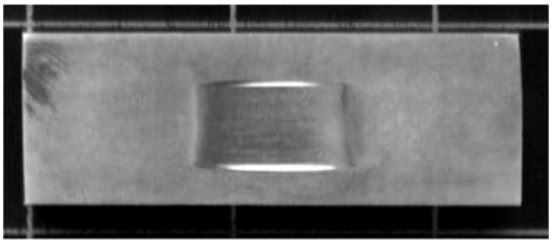

***Figure 9** Sample surface after abrasive wear*
***Slika 9.** Površina uzorka nakon abrazijskog trošenja*

The wear track is well marked in the Fig. 9. The test samples were abrasive worn on both sides, so that four wear cycles were done for every level of previous sample tempering. The mean values of the measured mass loss are shown in Tab. 3.

The data in Tab. 3 show that the heated samples exhibit more significant mass loss than unheated sample. The distribution of the sample mass loss is represented in Fig. 10.

A most significant influence of the barrel superheat on the increase of material wear can be seen in Fig. 10 if the temperature of previous sample heating was 900 °C.

For example, Fig. 11 shows typical gun bore wear at the origin of the barrel rifling.

Normal wear occurs at temperature between 900 and 1400 K, which is well below the melting point of the gun barrel steel. The melt erosion is many times faster and stronger than normal erosion so it leads to the abnormal wear of material.

***Table 3** Mass loss (g) in the abrasion wear*
***Tablica 3.** Gubitak mase (g) prilikom abrazijskog trošenja*

Previous sample heating, °C	Mass loss (g) after wheel rotation number					
	100		500		1000	
Unheated sample	0,0099; 0,0137; 0,0131; 0,0117		0,0647; 0,618; 0,0667; 0,0629		0,1149; 0,1102; 0,1088; 0,1127	
	mean value	**0,0121**	mean value	**0,0640**	mean value	**0,1116**
600	0,0180; 0,0171; 0,0124; 0,0148		0,0715; 0,0653; 0,0702; 0,0662		0,1307; 0,1094; 0,1261; 0,1055	
	mean value	**0,0156**	mean value	**0,0683**	mean value	**0,1179**
700	0,0154; 0,0112; 0,0129; 0,0177		0,0773; 0,0702; 0,0694; 0,0676		0,1322; 0,1283; 0,1159; 0,1136	
	mean value	**0,0143**	mean value	**0,0711**	mean value	**0,1225**
800	0,0182; 0,0204; 0,0129; 0,0141		0,0652; 0,0676; 0,0712; 0,0728		0,1353; 0,1316; 0,1188; 0,1284	
	mean value	**0,0164**	mean value	**0,0692**	mean value	**0,1285**
900	0,0224; 0,0220; 0,0195; 0,0197		0,0925; 0,0939; 0,0834; 0,0838		0,1637; 0,1572; 0,1662; 0,1520	
	mean value	**0,0209**	mean value	**0,0884**	mean value	**0,1598**

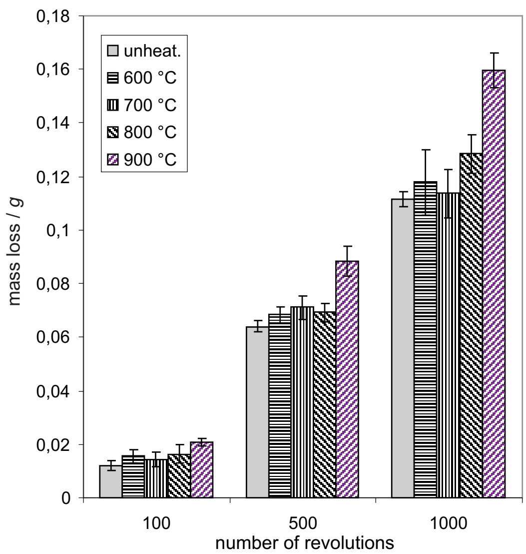

***Figure 10** Distribution of sample mass loss (mean value and standard deviation)*
***Slika 10.** Raspodjela gubitka mase uzoraka (srednja vrijednost i standardna devijacija)*

The rate of the gun barrel wear is one of the main factors limiting a gun's muzzle velocity and range. Therefore, adherence to the determined firing rate is very important to prevent the barrel from superheating and its consequent

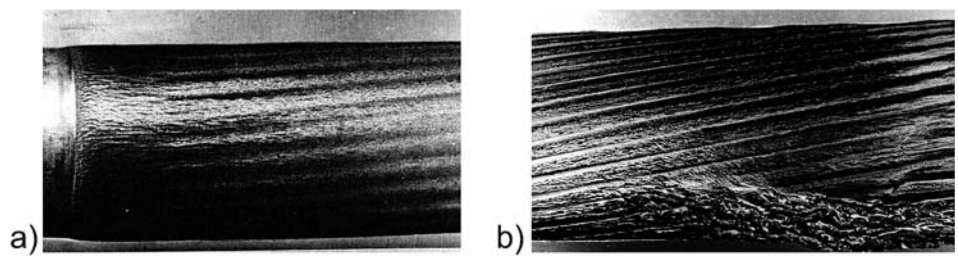

***Figure 11** Typical gun bore wear at the origin of rifling* [5]
a - normal wear, b - abnormal wear (melt erosion)
***Slika 11.** Tipična istrošenost kanala topovske cijevi* [5]
a - normalna istrošenost, b - prekomjerna istrošenost (erozija taljenjem)

intensive wear.

4 Conclusion
Zaključak

This paper studies the influence of the weapon barrel superheat on the intensity of abrasion wear. The test samples were made of the 42CrMo4 steel and quenched and tempered, so as to obtain similar metallographic and mechanical properties to the weapon barrel steel. Before testing, the samples were heated at 600 °C, 700 °C, 800 °C, and 900 °C over a period of one hour and then air cooled. One group of previously unheated samples was also tested.

The uniform structure of the tempered martensite is presented in metallographic images of the samples. The measured hardness on the sample cross-section surfaces is higher in the test samples which were tempered at 600 °C and 700 °C (495 HV1 and 476 HV1). Also, hardness is lower in the samples tempered at 800 °C and 900 °C (397 HV1 and 412 HV1). In accordance with the CTT diagram of the 42CrMo4 steel, a portion of bainite as well as a portion of ferrite perlite may be contained in the microstructure with the basic martensite.

The test results demonstrate that the unheated samples exhibit greater wear resistance in comparison with the heated samples, especially if the samples were previously heated at 900 °C. In comparison with the material loss of the unheated samples, the material loss increases 73 % during 100 revolutions of rubber wheel, 38 % during 500 revolutions of rubber wheel and 43 % during 1000 revolutions of rubber wheel if the heating level was 900 °C.

The test results have shown that the determined fire rate is very important to adhere to: the fire rate must not be exceeded because it causes the weapon barrel superheat and a significant decrease in the material wear resistance.

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