ISSN 1330-3651
UDC/UDK 620.178.1:[543:624.423]

INVESTIGATION OF THE MATERIAL CHEMICAL COMPOSITION INFLUENCE ON ARTILLERY WEAPONS BARREL HARDNESS

Mirko Jakopčić, Krešimir Grilec, Dragutin Lisjak

Original scientific paper
The weapon barrel is exposed to strong thermal, mechanical and chemical effect of the powder gasses and the projectile. That causes the appearance of the intensive wear process of the barrel bore. In this paper the analysis of the samples' chemical composition is performed, the metallographic structure of the samples' material is imaged, the possible modification of the barrel bore surface is tested and the hardness over the samples cross section was measured. The hardness of the barrel material is one of the essential factors which contribute to increased barrel's wear resistance. Therefore, modelling of HV5 hardness as a function of the chemical composition of materials was conducted. Determined correlations should allow an easier selection of the wear resistant barrel material as well as the material of other parts of the artillery weapons, with the need to establish a small number of influential parameters, without carrying out extensive tests.

Keywords: *chemical composition, correlation, hardness, material, weapon barrel*

Istraživanje utjecaja kemijskog sastava materijala na tvrdoću cijevi topničkih oružja

Izvorni znanstveni članak
Cijev oružja izložena je jakom toplinskom, mehaničkom i kemijskom djelovanju barutnih plinova i projektila. To uzrokuje intenzivne procese trošenja kanala cijevi. U ovom je radu provedena analiza kemijskog sastava uzoraka, snimljena je njihova metalografska struktura, provjerena je moguća promjena površine kanala cijevi i izmjerena je tvrdoća materijala po poprečnim presjecima uzoraka. Tvrdoća materijala jedan je od bitnih faktora koji doprinose povećanju otpornosti na trošenje, pa je provedeno modeliranje procjene tvrdoće HV5 kao funkcije kemijskog sastava materijala. Utvrđene korelacije trebale bi omogućiti lakši izbor materijala cijevi i drugih dijelova topničkih oružja utvrđivanjem manjeg broja utjecajnih faktora, bez potrebe provođenja opsežnih ispitivanja.

Ključne riječi: *cijev oružja, kemijski sastav, korelacija, materijal, tvrdoća*

1 Introduction

The firing process is a quite strong and dynamic process which takes place in the weapon barrel. It has a compound tribological effect on the weapon barrel: thermal, mechanical and chemical processes affect the barrel. A large heat quantity is developed by powder burning, and both powder gasses and barrel material are heated by this heat energy. High flame temperature propellants may produce combustion gasses at temperatures as high as 3700 K. Peak gas pressure may reach up to 700 MPa. 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, 3].

Typically, the bore temperature at the origin of the bore rifling reaches 600 ÷ 1200 °C within few milliseconds of exposure to hot propellant gases. Heat transfer may be 500 MW/m^2 [4]. The peak bore temperature of a gun may reach up to 1800 K a few milliseconds after it is fired [2], and the melting point of the gun steel is 1720 K [5].

In accordance with the above mentioned, the firing process causes the existence of many wear mechanisms in the barrel at the same time: abrasion, erosion, adhesion, fatigue and tribocorrosion.

The ballistic life of the barrel is stated by the determined rounds number and it amounts up to 20 thousands rounds with equivalent full charge [1, 3]. It is characteristic for weapon systems that they perform their firing tasks much more intensively in war-time than during peace. It means that the available barrel resource is much more rapidly spent in the war than in peace. During piece time, weapon systems are long-term conserved and stored in the reserve, or they are employed at combat training areas for the purpose of training, test firing and similar. Therefore, prescribed maintenance procedure and operations have to be regularly performed in peace too. That requires inspection, repair, as well as replacement of the parts in certain circumstances.

The lack of necessary parts happens often, especially after war period and intensive use of the weapon. There are no required parts in the reserve, it is not possible to purchase them and the construction documentation of those weapons is not available. In that case the missing parts must be constructionally defined, which requires the knowledge of their functional role within the weapon system, their well-defined dimensions and shape, the process and quality of the surface processing and, last but not least, determined material for their production.

It is substantial at material characterization to determine the type of material, its metallographic structure and essential mechanical features, to determine implemented procedures of the heat treatment, as well as possibly applied chemical and physical processes of the surface engineering.

The study in this paper was performed on materials of three artillery weapons, which have been in service for several decades: gun 76 mm, mortar 120 mm and anti-aircraft gun 20 mm. The test samples were prepared by cold cutting of the mentioned weapons barrels. Materials of the artillery weapon barrels are quenched and tempered steels, which must have the following properties: high strength and yield stress, well fracture toughness, required hardness and high resistance to the impact loads and friction, homogeneous structure without non-metallic inclusions, high resistance to chemical activity of the powder gasses and atmosphere and high impact energy [6, 7].

Chemical composition was carried out for materials of the weapon barrels. Test samples were prepared for metallographic imaging and imaged and the measurement of the material hardness was also done. In accordance with metallographic images and values of the measured hardness, and in accordance with the continuous cooling transformation (CCT) diagrams of the tested steels, it was established that the barrels' material is quenched and tempered steel.

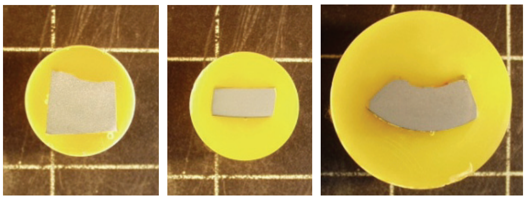
An important final part of this paper shows statistical modelling of the material hardness estimation as a dependent variable, depending on the content of the alloying elements as independent variables. The identified features and the intensity of correlations should provide for easier choice of the barrels' materials and other artillery weapon parts, without implementation of the extensive and detailed testing.

2 Test samples preparation

The test samples (Fig. 1) have been made of the barrel's material taken from the following three artillery weapons:

- field gun 76 mm,
- mortar 120 mm and
- antiaircraft gun 20 mm.

The samples were obtained from the barrels by cold cutting, thus retaining the metallographic structure and hardness of the material.



c) b) c)

Figure 1 Test samples of the artillery weapon barrel materials
a – field gun 76 mm, b – mortar 120 mm, c – antiaircraft gun 20 mm

The cross-section surfaces of the test samples were prepared for metallographic analysis. They were grounded and polished and subsequently corroded by NITAL. The test samples were prepared for metallographic imaging and imaged in the Metallographic Laboratory at the Faculty of Mechanical Engineering and Naval Architecture in Zagreb.

3 Analysis of the material chemical composition

Chemical composition of the barrel sample materials was analysed on the device SPECTRUMAT 750, LECO, in the Laboratory for Material Analysis at the Faculty of Mechanical Engineering and Naval Architecture in Zagreb. The results of the chemical composition analysis are presented in Tab. 1.

Table 1 Chemical composition of the test samples

Sample	Chemical composition / %							
	C	Si	Mn	P	S	Cr	Ni	Mo
a)	0,36	0,32	0,82	0,011	0,018	1,01	1,20	0,21
b)	0,28	0,38	0,59	0,014	0,006	2,70	-	0,45
c)	0,29	0,18	0,69	0,017	0,036	1,30	2,33	0,03

By comparing chemical composition of the samples with DIN 17006 and [8], it has been determined that the barrel material are heat treated steels as follows:

- sample a – steel 36CrNiMo4,
- sample b – steel 32CrMo12,
- sample c – steel 28NiCrMo5-5.

Therefore, tested steels are alloyed with chromium, nickel and molybdenum or chromium and molybdenum respectively.

The Defence Standard 10-13/3 issued by the British Ministry of Defence specifies materials, methods of testing and other requirements for the design and manufacture of forgings for the production of weapon barrels. The chemical composition data which are determined by that norm for 3 % nickel-chromium-molybdenum steel are shown in Tab. 2.

It is obvious that steels of the test samples contain the same percentage of carbon that the above mentioned military standard defines, while other chemical elements in the samples' material are present nearly equally. Some differences result from the fact that the standard in table 2 is British while the tested barrel was produced in East Europe.

According to the same standard, quenching temperature of the steel from Table 2 is 830 ÷ 910 °C.

Table 2 Chemical composition of the steel forgings for weapon barrels [7]

Chemical composition / %									
C	Si	Mn	P	S	Cr	Mo	Ni	V	Al
0,25-0,45	0,10-0,35	0,20-0,70	0,015 max	0,006 max	0,70-1,20	0,40-0,70	2,70-3,30	0,25 max	0,02 max

4 Metallographic analysis and hardness of the barrel material

The metallographic images of the samples' cross-sections are shown in Fig. 2. The homogeneous structure of the tempered martensite can be seen in this figure.

The martensite represents the microstructure of the hardened steel, as a result of the austenitic transformation. It means that the barrel steels were heated to the austenitic range. Besides, the sample steels contain sufficient percentage of carbon, which provides them with good hardenability.

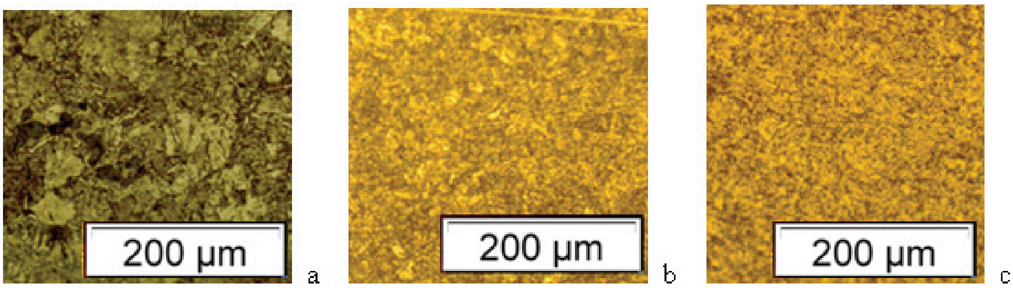


Figure 2 Metallographic images of the weapon barrel materials samples a-36CrNiMo4 (gun 76 mm), b-32CrMo12 (mortar 120 mm), c-28NiCrMo55 (antiaircraft gun 20 mm)

Also, metallographic images of the test samples show that no process of surface engineering modifying was applied.

Hardness measurement of the test samples was done in the Laboratory for mechanical testing of the materials at the Faculty of Mechanical Engineering and Naval Architecture in Zagreb. The measurement results are uniform across the cross section surface of the samples, and they are presented in Tabs. 3a, 3b and 3c.

Table 3a Surface hardness of the test sample **a** (steel 36CrNiMo4)

Sample **a**: gun				Material: 36CrNiMo4		
Measur. No.	Measurement direction: 1 (left)			Measurement direction: 2 (right)		
	Distance from the outer edge (mm)	Indentation diagonal (mm)	Hardness HV5	Distance from the outer edge (mm)	Indentation diagonal (mm)	Hardness HV5
1	0,25	0,207	216	0,35	0,213	204
2	1,25	0,208	214	1,35	0,212	206
3	2,25	0,211	208	2,35	0,206	219
4	3,25	0,211	208	3,35	0,209	212
5	4,25	0,208	214	4,35	0,207	216
6	5,25	0,202	227	5,35	0,205	221
7	6,25	0,204	223	6,35	0,204	223
8	7,25	0,198	236	7,35	0,210	210
9	8,25	0,200	232	8,35	0,201	229
10	9,25	0,198	236	9,35	0,201	229
11	10,25	0,200	232	10,35	0,198	236
12	11,25	0,200	232	11,35	0,199	234
	Mean	0,204	223	Mean	0,206	219

Table 3b Surface hardness of the test sample **b** (steel 32CrMo12)

Sample **b**: mortar				Material: 32CrMo12		
Measur. No.	Measurement direction: 1 (left)			Measurement direction: 2 (right)		
	Distance from the outer edge (mm)	Indentation diagonal (mm)	Hardness HV5	Distance from the outer edge (mm)	Indentation diagonal (mm)	Hardness HV5
1	0,25	0,176	299	0,15	0,179	289
2	1,25	0,174	306	1,15	0,173	310
3	2,25	0,173	310	2,15	0,172	313
4	3,25	0,172	313	3,15	0,173	310
5	4,25	0,173	310	4,15	0,177	296
6	5,25	0,179	289	5,15	0,176	299
7	6,25	0,185	271	6,15	0,179	289
	Mean	0,176	299	Mean	0,176	299

Table 3c Surface hardness of the test sample **c** (steel 28NiCrMo5-5)

Sample **c**: antiaircraft gun				Material: 28NiCrMo5-5		
Measur. No.	Measurement direction: 1 (left)			Measurement direction: 2 (right)		
	Distance from the outer edge (mm)	Indentation diagonal (mm)	Hardness HV5	Distance from the outer edge (mm)	Indentation diagonal (mm)	Hardness HV5
1	0,35	0,181	283	0,4	0,186	268
2	1,35	0,182	280	1,4	0,184	274
3	2,35	0,181	283	2,4	0,181	283
4	3,35	0,181	283	3,4	0,182	280
5	4,35	0,182	280	4,4	0,180	286
6	5,35	0,181	283	5,4	0,182	280
7	6,35	0,180	286	6,4	0,182	280
8	7,35	0,182	280	7,4	0,183	277
9	8,35	0,183	277	8,4	0,187	265
10	9,15	0,186	268	9,4	0,186	268
	Mean	0,182	280	Mean	0,183	277

The uniform hardness across the sample surfaces, as well as homogeneous martensite structure shows that no modification of the material surface has been realized on the barrel bore.

In accordance with the CCT diagram of the tested steels, the quenching and tempering of steels were realised by material heating at 860 °C and oil cooling. The CCT diagram of 36CrNiMo4 steel is shown in Fig. 3.

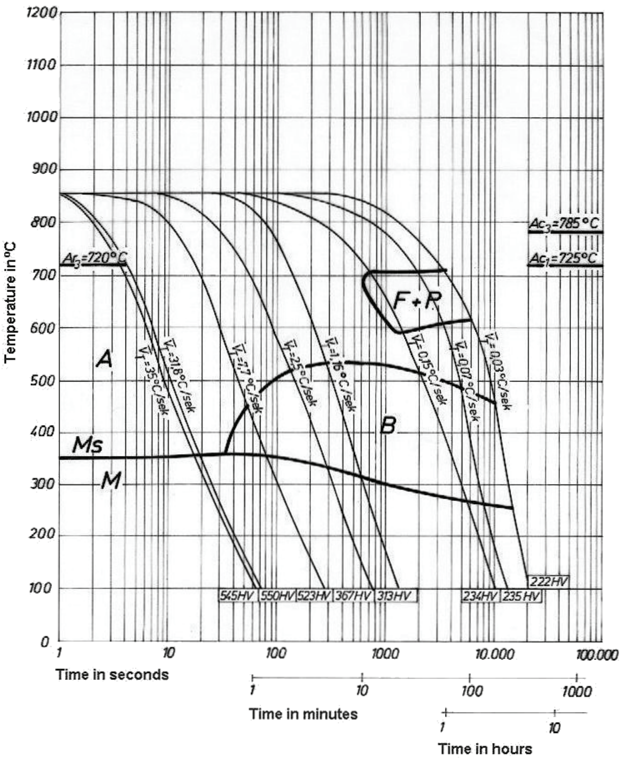


Figure 3 CCT diagram of 36CrNiMo4 steel [8]

According to tempering diagrams of the tested steels, the barrel material hardness (Tabs. 3a, 3b and 3c) was obtained by heating at 600 °C for two hours [8].

5 Modelling of HV5 hardness estimate by multivariable stepwise regression

Generally, multivariable regression (MR) is applied to estimate the dependent variable *Y* (in this paper, the hardness HV5) depending on one or more independent variables *X* (in this paper, elements of the chemical composition: C, Si, Mn, P, S, Cr, Ni, Mo) [9].

The so-called "Forward Stepwise" algorithm was included in the MR-model of the analysis in this paper. That algorithm by exclusion of the independent variables *X*, which have no effect on the dependent variable *Y*, leads to improvement of the MR-model estimates of the dependent variable *Y*.

The algorithm works so that at each iteration it estimates the impact significance of two or more independent variables in relation to the output, i.e. the dependent variable. If the last included independent variable has no significant effects on the dependent variable, it is excluded from further analysis. Tab. 4 shows the results of the multivariable stepwise regression modelling.

Table 4 Showing results of the multivariable stepwise regression modelling

Dependent variable: HV5
Independent variables: C Si Mn P S Cr Ni Mo
Stepwise regression:
Method: forward selection
P-to-enter: 0,05
P-to-remove: 0,05
Step 0:
0 variables in the model. 58 d.f. for error.
R-squared = 0,00 % Adjusted R-squared = 0,00 % MSE = 1235,64
Step 1:
Adding variable C with P-to-enter =0
1 variable in the model. 57 d.f. for error.
R-squared = 90,52 % Adjusted R-squared = 90,35 % MSE = 119,183
Step 2:
Adding variable Mo with P-to-enter =0,000253103
2 variables in the model. 56 d.f. for error.
R-squared = 92,55 % Adjusted R-squared = 92,29 % MSE = 95,3135

Parameter	*Estimate*	*Standard Error*	*T Statistic*	*P-Value*
CONSTANT	535,257	11,3731	47,0634	0,0000
C	-889,631	34,8304	-25,5418	0,0000
Mo	31,1993	7,98284	3,90829	0,0003

Analysis of Variance:

Source	*Sum of Squares*	*Df*	*Mean Square*	*F-Ratio*	*P-Value*
Model	66329,6	2	33164,8	347,95	0,0000
Residual	5337,56	56	95,3135		
Total (Corr.)	71667,2	58			

R-squared = 92,5523 %
R-squared (adjusted for d.f.) = 92,2863 %
Standard Error of Est. = 9,76287
Mean absolute error = 7,84746
Durbin-Watson statistic = 0,951112 (*P-Value*=0,0000)

The output shows the results of fitting a multiple linear regression model to describe the relationship between HV5 and 8 independent variables. The equation of the fitted model is:

$$HV5 = 535{,}257 - 889{,}631C + 31{,}1993Mo. \quad (1)$$

Since the P-value in the analysis of variance table is less than 0,05, there is a statistically significant relationship between the variables at 95,0 % confidence level. The R-Squared statistics indicates that the model as fitted explains 92,5523 % of the variability in HV5. The adjusted R-squared statistics, which is more suitable for comparing models with different numbers of independent variables, is 92,2863 %. The standard error of the estimate shows a standard deviation of the residuals to be 9,76287. The mean absolute error of 7,84746 is the average value of the residuals. The Durbin-Watson statistics tests the residuals to determine if there is any significant correlation based on the order in which they occur in your data file. Since the P-value is less than 0,05, there is an indication of possible serial correlation at the 95,0 % confidence level. In determining whether the model can be simplified, it can be noted that the highest P-value on independent variables is 0,0003, belonging to Mo. Since the P-value is less than 0,05, that term is statistically significant at the 95,0 % confidence level.

Matching of the results of the experimental and regression model, achieved from the expression (1), is shown in Fig. 4.

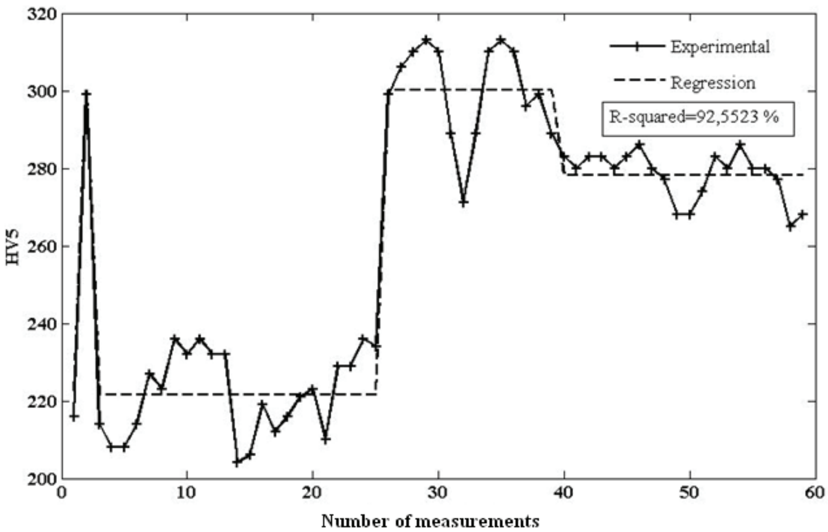


Figure 4 Matching on results of the experimental and regression model

According to the previous figure, a high coincidence of the experimental and regression model was obtained.

Modelling of the hardness estimates has shown that carbon and molybdenum contents achieve a very high correlation in the effect on hardness HV5 of the steel, as the dependent variable. The explanation for that is in the fact that the steel hardening depends on the proportion of carbon, which is contained in the proportion from 0,25 to 0,6 % in quenched and tempered steels. The hardenability of the steel turn depends primarily on alloying elements and their proportion, but also on dimensions of the parts and of the cooling reagents type [10].

High mechanical properties of the products, which include high yield and tensile strength, high fracture toughness and high impact energy, may be achieved by proper selection of both: the steel and the implemented heat treatment process. Those steel properties must be uniform throughout the cross section, what can be achieved only if the material is completely quenched and if the entire cross section has a uniform martensite structure.

The metallographic images (Fig. 2) and the measured hardness (Tabs. 3a, 3b and 3c) of the test samples show that the barrel material is completely quenched. The molybdenum is often added together with the other alloying elements, and it significantly improves the steel hardenability and increases the impact energy. The effect of molybdenum provides the martensitic structure as well as the structure of the lower bainite, which also contributes to good mechanical properties of the quenched and tempered steel. The molybdenum is a strong carbide-former alloyed element and it provides the small-grained steel structure and wear resistance of the material. It also increases enduring strength at elevated temperatures. Molybdenum in combination with chromium and nickel, also provides very good hardenability [10].

The stated features of the carbon and molybdenum effect on the structure and construction strength of steel, individually and in combination with other alloying elements, justify their significant impact on hardness of the heat treated steels, what is shown in the performed modelling by multivariable stepwise regression.

6 Conclusion

This paper presents the research of the main parameters that determine the material of the artillery weapons barrel, and their impact on improving the wear resistance of the barrel material. Hardness is one of the important indicators of the material wear, so this paper investigates the influence of the alloying elements on hardness of the heat treated steels. Test samples were made by cutting the barrels of three artillery weapons: 76 mm field gun, 120 mm mortar and 20 mm antiaircraft gun. By chemical analysis it is shown that the tested materials are quenched and tempered steels: 36CrNiMo4, 32CrMo12 and 28NiCrMo5-5.

The metallographic cross section images of the samples showed a homogeneous tempered martensite structure. The results of the HV5 hardness measurement are uniform over the of the samples cross section. Those findings indicate that weapon barrel materials were quenched and high temperature tempered, without modifying the surface of the barrel bore.

Final modelling of the hardness estimate was implemented by multivariable stepwise regression, in order to determine the correlation of the chemical composition as independent variable on steel hardness as a dependent variable. Modelling has shown that carbon and molybdenum are steel chemical constituents which show a strong correlation with respect to material hardness. For the group which includes steels of the tested samples materials, the hardness of the material can be calculated mathematically on the base of the carbon and molybdenum content.

7 References

[1] Jakopčić, M. Temeljne značajke tribološkog procesa u cijevi topničkog oružja. // Zbornik MATRIB '99 / uredio Vinko Ivušić. Trogir, 1999.

[2] Sopok, S.; Rickard, C.; Dunn, S. Thermo-chemical-mechanical gun bore erosion of an advanced artillery system part one: theories and mechanisms. // Wear 258, 2005. p. 659-670.

[3] Tenkovski top 125 mm 2A46. // SSNO, Beograd, 1984.

[4] Lawton, B. Thermo-chemical erosion in gun barrels. // Wear 251, 2001. p. 827-838.

[5] Johnston, I. A. Understanding and Predicting Gun Barrel Erosion. // Weapons Systems Division, Edinburgh, Australia, 2005. p. 3-11.

[6] Pavelić, V. Specifične tehnologije u proizvodnji oružja. // MORH, Zagreb, 1995. p. 131-132.

[7] Steel Forgings for Guns. // Ministry of Defence-Directorate of Standardization, Defence Standard 10-13, Issue 3, Glasgow, August 1999. p. 17-19.

[8] www.F:\Ravne\steels\vcmo135.html. (12. 04. 2004.)

[9] Draper, N. R.; Smith, H. Applied Regression Analysis, Hoboken. // Wiley-Interscience, 1998. p. 307–312.

[10] Novosel, M.; Krumes, D. Posebni čelici. // Sveučilište Josipa Jurja Strossmayera u Osijeku, Strojarski fakultet u Slavonskom Brodu, Slavonski Brod, 1998. pp. 18-19, 150-154.

Authors' addresses

Mirko Jakopčić, doc. dr. sc.
Croatian Defence Academy "Petar Zrinski"
Ilica 256 B, 10000 Zagreb, Croatia
E-mail: mjakopc@yahoo.com

Krešimir Grilec, prof. dr. sc.
Faculty of Mechanical Engineering and Naval Architecture
University of Zagreb
Ivana Lučića 5, 10000 Zagreb, Croatia
E-mail: kgrilec@fsb.hr

Dragutin Lisjak, doc. dr. sc.
Faculty of Mechanical Engineering and Naval Architecture
University of Zagreb
Ivana Lučića 5, 10000 Zagreb, Croatia
E-mail: dlisjak@fsb.hr