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Sensitivity analysis of factors affecting for the engraving of rifle projectile

J M Li^{1,2},W M Yan^{1,2},D B Lu^{1,2},Sh Wang^{1,2},Y J Qu^{1,2}.

¹ Science and Technology on Transient Impact Laboratory, Beijing, 102202, China;

² No.208 Research Institute of China Ordnance Industries, Beijing 102202, China.

Email:lijinming51818@163.com.

Abstract: In order to study the primary and secondary relationship between the factors affecting the engraving resistance of one small-caliber rifle projectile, quasi-static push tests were carried out for jacket material by H90 copper and copper clad steel projectile in three kinds of gun barrels with different structures and the corresponding changes of the engraving resistance were obtained and analyzed. At the same time, numerical simulations were carried out for constant high-speed extrusion. Quasi-static test and dynamic simulation results were analyzed, the order of the factors affecting the peak of engraving resistance under quasi-static is the yield strength of jacket>free stroke> engraving length>rifle number> lead, and the factors affecting the peak of extrusion force under high-speed is engraving velocity>yield strength of jacket>free stroke> engraving length >rifle number>lead. It is also found that the relative steady engraving resistance value is close 60% of its peak value under quasi-static, while the same value under high-speed is between 1/8 and 1/6 of the peak value, the results of force peak are basically quite.

1. Introduction

In the process of modern small arms design, the interaction between the projectile and the weapon system has been paid more and more attention. The process of the projectile engraving into and through the barrel takes place in the initial stage of the interaction between the projectile and the gun, which is related to the matching state between the projectile and the barrel, meanwhile has an impact on the combustion state of the propellant behind the base of the projectile, that is to say, the engraving process plays a crucial role on determining the ballistic performance and projectile stability. It is different from the band contacting with the barrel during the projectile squeezed into the bore in the cannon launching process, that when taking place in the launching process of the small arms, the cylindrical body of the projectile acts directly with the inner wall of the barrel. The interaction between the projectile and the barrel holds the key factor restricting the barrel life and the ballistic performance. Hence, it is extremely important to investigate the engraving process of the projectile into and through the barrel to improve the barrel life and firing accuracy, which can provide reference for the design of gun-barrel and bullet [1.2].

There have been previous studies about the engraving process in the field of firearms, Joseph South [3] and Jeff Siewert [4] had tested the process of M855 5.56mm and M80 7.62mm projectiles, respectively. S. Deng [5] have carried out numerical simulation research on the interior ballistic process in the barrel for 9mm pistol projectiles, the calculated results are very close to the test data in terms of the muzzle velocity, rotation speed and the projectile deformation. Fan Lixia et al. [6] studied the

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process of 7.62mm lead core projectile into the barrel, analyzed the deformation characteristics of the jacket and the lead core before and after the engraving process, and the residual stress of the projectile after the extrusion engraving process, however the barrel was regarded as a rigid body in the study, and the engraving time of the projectile was up to 0.2s, which was greatly different from being less than 1msthat reported in other studies, which is hard to convince researcher to accept it with the accuracy of the calculation. Hou Wenwei et al. [2] studied a small caliber rifle projectile and carried out the push testing on H90 copper jacket bullet and copper clad steel projectile, and obtained the corresponding extrusion force changes of different projectiles, at the same time, the finite element simulation was carried out, but the parameters such as the barrel structure were not explained, and it was questionable the rationality of the displacement time curve imposed by the simulation. Zhou Xiangxiang [1] designed a quasi-static and dynamic push experiment system for a small caliber bullet, and carried out the push test, comparing the difference of interior ballistic parameters between the dynamic push experiment and the numerical simulation calculation under different free travel, from the experimental results, proving the correctness of the numerical simulation research on the projectile engraving under different free travel, but it is without necessary premise for the conclusion that the peak value of dynamic engraving resistance was about the conclusion is one fifth of the peak value of quasi-static engraving resistance.

Most of the studies have not fully explained the sensitivity of factors affecting the engraving resistance, and the relationship between quasi-static and dynamic engraving process. In this paper, the research on the engraving process of the rifle projectile under quasi-static and high-speed was carried out, and the sensitivity of various factors affecting the engraving force is analyzed. This work proposed the basis with mechanism, in essence, to reveal the interaction between projectile and barrel in the process of engraving.

2. Resistance under quasi-static condition

2.1. Quasi-static push test

In this paper, one universal material experimental machine (SANS-PowerTest_D00C) is used to carry out the quasi-static push test. The barrel of velocity measuring ballistic gun is used in the test, and a set of the quasi-static push test device is designed by shortened it (shown in figure 1). The experimental device is shown in figure 2. In the experiment, the universal material machine provides the squeeze force, and its built-in force sensor feeds back the squeeze force in real time and provides the ability to obtain the load vs. time [8].





Figure 2. test device.

The punch pin of the test translates at a known displacement rate forces the projectile into and through the barrel, controls the rate of engraving and the structural diagram of the projectile is shown in [2]. The barrels with different lead, rifling number and different free travel are selected to reduce for the test, and the structural diagram is shown in figure 2. Among them, the projectile is made of two kinds of jacket materials which are described in [2], copper-clad steel(CCS) and H90 copper(H90), and the barrel

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is made of three kinds of structures, which are expressed in Q1, Q2 and Q3 for the convenience of description. The parameters and results are shown in table 1.

No.	Jacket materia l	engravin g speed / mm / min	engraving length / caliber	Lead / calibe r	Free stroke / caliber	Rifling numbe r	Yield strength / MPa	engraving resistance /N	Barre 1 code
1	CCS	6	1.1897	30.69	1.552	4	358	3240	Q1
2	CCS	9	1.1897	30.69	1.552	4	358	2708	Q1
3	CCS	20	1.1897	30.69	1.552	4	358	3578	Q1
4	CCS	50	1.1897	30.69	1.552	4	358	4018	Q1
5	CCS	100	1.1897	36.21	0.607	6	358	3796	Q2
6	CCS	300	1.1897	36.21	0.607	6	358	3437	Q2
7	CCS	300	1.1897	41.38	1.724	4	358	4213	Q3
8	CCS	50	1.1897	41.38	1.724	4	358	3778	Q3
9	CCS	9	1.1897	41.38	1.724	4	358	2920	Q3
10	H90	50	1.3379	30.69	1.552	4	112	3793	Q1
11	H90	300	1.3379	30.69	1.552	4	112	3776	Q1
12	H90	100	1.3379	36.21	0.607	6	112	3448	Q2
13	H90	300	1.3379	36.21	0.607	6	112	6509	Q2
14	H90	9	1.3379	41.38	1.724	4	112	3316	Q3
15	H90	50	1.3379	41.38	1.724	4	112	3454	Q3
16	H90	300	1.3379	41.38	1.724	4	112	3594	Q3

Table 1. Experimental	scheme and	results.
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2.2. Test results and discussion

The engraved vestige by riflings of the projectile after the quasi-static push test is shown in figure 3. During the test, the push rod makes the projectile to move along the axis of the barrel, and the projectile is deformed by the extrusion of the bore and the rifling. During the engraving process, the projectile material undergoes the transition from elastic deformation to plastic deformation, and the plastic deformation shape is affected by the size and structure of the rifling. When the engraving process is completed, the cylindrical section of the projectile formed the vestige shown in figure 3.

In the test, the engraving resistance- displacement curve as shown in figure4 is obtained. Taking the engraving process of CCS projectile into the Q2 barrel as an example, the development trend of the engraving resistance changing with the displacement is explained. As the forcing cone is tapered, the engraving resistance increases gradually from zero at the beginning. When the projectile passes through the roller groove, the engraving resistance decreases slightly due to the retraction of the projectile diameter, as shown in point A, the engraving resistance continues to rise after passing through the roller groove. When the cylindrical section of the projectile is completely squeezed into the rifling, the engraving resistance reaches the maximum. As shown in point B, when the projectile continues to squeeze, the engraving resistance begins to decline. When the engraved vestige of the projectile is completely formed, the resistance of the projectile mainly changes into the force between the projectile and the rifling, and the deformation force caused by embedding (the force to overcome the deformation of the projectile material) disappears. When it reaches point C, the engraving resistance gradually becomes relatively stable. When the cylindrical section of the projectile starts to extrude the barrel, the engraving resistance begins to decrease, as shown in point D.Each scheme in the test conforms to the overall trend shown in figure 4, but the coordinate values of each point are different.

3500 Z 3000 resistance 2500 2000 engraving 1500 1000 500

Figure 3. Egraved vestige of projectile.



30 displacement (mm)

20

It can be seen from the range diagram of the engraving resistance of different schemes under different engraving speeds in figure 5 that the dispersion of the engraving resistance obtained in the quasi-static push test of the projectile is very large, and the sample size is insufficient. For CCS projectiles, the average engraving resistance is positively correlated with the overall engraving speed. In O2 and O3 barrels, when the engraving speed exceeds 50 mm/min, the change of the engraving resistance is relatively gentle. In Q1 and Q3 barrel, when the engraving speed of H90 projectile exceeds 50 mm/min, the variation of the engraving resistance is relatively gentle, but in Q2 barrel, the engraving resistance increases rapidly with the increase of the engraving speed.



Figure 5. Relationship between engraving speed and engraving resistance in different schemes.

3. Sensitivity analysis of factors affecting the engraving resistance

From the 1.2 test data, it can be found that due to the particularity of projectile structure and barrel structure, it is difficult to separate a single variable to analyze the impact of the engraving resistance. The structural parameter change of projectile is not a single variable. It is difficult to find out which parameter variable is the main factor that affects the engraving resistance from the test data. Therefore, using the grey relational analysis method, in the incomplete data information, for each factor to be analyzed, after a series of data processing, we can find the correlation between each factor and find out the main contradiction in the sequence of random factors, and point out which factor is the main

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influencing factor. Through the grey relational analysis, the primary and secondary relations of the factors that affect the quasi-static engraving resistance can be obtained [9].

The maximum engraving resistance obtained by quasi-static push test is taken as the reference sequence, recorded as $y_j(k)$, when j = 1, which is expressed as the maximum engraving resistance. The engraving speed, the ratio of engraving length / caliber, the ratio of lead / caliber, the ratio of free stroke / caliber, rifling number and yield strength of jacket were taken as the comparison sequence, and recorded them as $x_i(k)$, when i = 1,2,3,4,5,6, respectively indicating the engraving speed, the ratio of engraving length / caliber, the ratio of free stroke / caliber, rifling number and yield strength of jacket were taken as the comparison sequence, and recorded them as $x_i(k)$, when i = 1,2,3,4,5,6, respectively indicating the engraving speed, the ratio of engraving length / caliber, the ratio of lead / caliber, the ratio of free stroke / caliber, rifling number and yield strength of jacket material. Among them, k is equal to the number of samples, representing 16 different schemes. In order to ensure the accuracy of the calculated Grey relational degree, it is necessary to make these data dimensionless, and the scheme and results of dimensionless pre selection analyses are shown in table 1. The data in table 1 are analyzed with reference to literature [10], and the grey incidence matrix is obtained, as shown in table 2.

Table 2. Grey incidence matrix

	<i>x</i> ₁	<i>x</i> ₂	<i>x</i> ₃	<i>x</i> ₄	<i>X</i> ₅	x ₆
У1	0.6771	0.9587	0.9542	0.9650	0.9561	0.9724

The order of the values in the grey incidence matrix is the grey relational order [9]. By analyzing the data in the grey incidence matrix, it can be concluded that for the same caliber the grey relational order of the maximum engraving resistance in the quasi-static engraving r process is the yield strength > free stroke / caliber > engraving length / caliber > number of rifles > lead / caliber > engraving speed, that is to say, the order of the influence degree of the factors affecting the maximum engraving resistance under quasi-static engraving process. Among the factors that affect the maximum engraving resistance, the yield strength of the jacket material and the free stroke length of the barrel have the greatest influence on the maximum engraving resistance, while the engraving speed has the least influence.

4.Numerical simulation of high speed engraving

4.1. Numerical simulation model

In the initial stage of interior ballistics, the projectile breaks away from the restriction of the cartridge case mouth, and is pushed into the barrel by the propellant gas. When the projectile is completely squeezed into the rifling, the instantaneous velocity of the projectile is deemed to reach about 100m/s. In this paper, the numerical simulations of the engraving process at the constant speed of 80, 90, 100, 110 and 120 m / s are carried out, and the comparison between the numerical simulation and the low speed (quasi-static) engraving resistance is carried out to obtain the basic data for the study of the dynamic engraving resistance [1].

In this paper, the finite element model is established according to the actual structure of the gun barrel and the projectile, as shown in figure 6 (taking the copper-clad steel projectile as an example), in order to ensure the accuracy of calculation, the projectile is encrypted by the local grid of jacket, the male line of rifle of gun barrel adopts two-layer grid as shown in the figure, and the grid of forcing cone and the beginning part of rifling is shown in the figure.

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Figure 6. Finite element model.

The projectile is in accordance with the quasi-static push test. When the projectile is squeezed, it has elastic-plastic deformation and high strain rate. Therefore, J-C model is used to define the material properties. The barrel is made of high-strength steel named 30simn2mova. Johnson-cook constitutive model is used for jacket and lead core in calculation. In order to improve calculation efficiency, simplified-Johnson-cook model is used for barrel and steel core. Shown in table 3 for material parameters used in numerical calculation [1,2].

Johnson cook model is as follows:

$$\sigma_{v} = (A + B\bar{\varepsilon}^{p^{n}})(1 + C \ln \varepsilon^{*})(1 - T^{*m})$$

Where $\dot{\varepsilon}_0$ is the reference strain rate, $T^* = (T - T_r)/(T_m - T_r)$ is imensionless temperature, T_r is room temperature and T_m is melting temperature. In the simplified Johnson cook model, the temperature term is removed, as follows:

$$\sigma_{\nu} = (A + B\bar{\varepsilon}^{pn})(1 + C\,ln\,\varepsilon^*)$$

Mat.	ho (g/cm ³)	G (GPa)	A (MPa)	B (MPa)	С	М	n
H90	8.8	51.1	112	505	0.425	1.09	0.31
CCS	7.92	77	358	235	0.28	1.03	0.014
Lead	11.35	7	14	18	0.135	1.68	0.685
Core	7.85	77	760	692	0.28	1.03	0.25029
Barrel	7.9	77	935	692	0.28	1.03	0.25029

Table 3. Material properties in numerical simulation.

The surface to surface contact is used to define the contact between the outer surface of the projectile jacket and the inner bore of the barrel, and between the inner surface of the projectile jacket and the surface of the lead core. One end of the barrel is defined as the fully constrained state. A constant rate of loading was given the projectile to squeeze into the rifling. The data of contact energy, displacement and time can be obtained by numerical simulation that would provide the ability to calculate the engraving resistance.

4.2. numerical simulation results

Through the data processing of simulation results, the resistance curves at different constant high speeds are obtained as shown in figure 7.

From the overall trend of the curve, the greater the engraving speed is, the greater the resistance reaches the maximum moment first. Under the same barrel condition, the engraving of H90 projectile is generally greater than that of CCS rifle projectile, while engraving resistance is greater that of Q3 barrel under the condition of the synchronous projectile.

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Figure 7. Engraving resistance curve at constant high speed.

As the curve of engraving resistance vs time is basically the same as that of engraving resistance vs displacement, the obvious difference between the curve of engraving resistance obtained by high-speed extrusion and the curve of quasi-static engraving resistance obtained by figure4 are that the value of CD section (figure4) under quasi-static engraving is close to 60% of the peak value after relatively stable, while the value of CD section under constant high-speed engraving is between 1 / 8 and 1 / 6 after relatively stable, and the variation amplitude is obviously smaller than that of quasi-static engraving.

In terms of the peak value of engraving resistance, among the statistical peak values of quasi-static engraving resistance, the peak value of CCS projectile is the largest and the value is 4213N when it is squeezed into the barrel (Q3) with the ratio of lead / caliber of 41.38 at the speed of 300 mm / min. The peak value of H90 projectile is 6509N which is the largest when the it is squeezed into the barrel (Q2) with a lead / caliber of 36.21 at the speed of 300 mm / min. These two sets of values are higher than the results of constant high speed engraving in the numerical simulation, and the other values are similar to the numerical simulation results.

According to the method in reference 2, the maximum engraving resistance obtained by numerical simulation is taken as a reference sequence, which is expressed as the dynamic maximum engraving resistance. Taking the engraving speed, the ratio of engraving length / caliber, the ratio of lead / caliber,

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the ratio of free stroke / caliber, rifling number and yield strength of jacket material as the comparison sequence, carry out grey correlation analysis, and obtain the influence degree order of each factor affecting the maximum engraving resistance under constant high-speed, and grey correlation matrix, as shown in table 4.

Table 4. Grey incidence matrix							
	<i>x</i> ₁	<i>x</i> ₂	<i>x</i> ₃	<i>x</i> ₄	x 5	<i>x</i> ₆	
<i>y</i> ₂	0.8275	0.4143	0.3915	0.4963	0.3968	0.5671	

It can be seen that the order of grey relational degree is as follows: engraving speed > yield strength > free stroke / caliber > engraving length / caliber > rifling number > lead / caliber. The biggest influence on the peak value of engraving resistance under high-speed engraving process is engraving speed, which is different from quasi-static engraving process. For the same caliber, the order of grey relational degree is as follows: engraving speed > yield strength > free stroke > engraving length > rifling number > lead.

5. Conclusion

In this paper, the experimental studies of quasi-static and dynamic simulation of constant high speed were researched, the following conclusions are obtained:

1. The factors influencing the peak value of the quasi-static engraving resistance are ranked as yield strength > free stroke > engraving length > rifling number > lead > engraving speed. Among the factors influencing the peak value of the engraving resistance, the yield strength of the jacket material and the free stroke length of the barrel have the greatest influence on the maximum engraving resistance, while the engraving speed has the least influence, at the same time, it can be proved that the rationality and reliability of quasi-static push test.

2. The influence degree of each factor affecting the peak value of the engraving resistance under high-speed engraving process is ranked as the following: engraving speed > yield strength > free stroke > engraving length > rifling number > lead. The biggest factor affecting the peak value of the engraving resistance under high-speed engraving process is the engraving speed, which is different from the quasi-static engraving process.

3. Compared with the quasi-static engraving resistance curve, the obvious difference between the high-speed engraving resistance curve and the quasi-static engraving resistance curve is that the value of the relatively stable section of the static engraving resistance is close to 60% of its peak value, while the value between 1/8 and 1/6 of the high-speed engraving resistance curve is obviously smaller than the quasi-static engraving resistance curve. In terms of the peak value of the engraving resistance, the dynamic and quasi-static results are similar.

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