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ELECTROMAGNETIC LAUNCHER AVIATION GUN OF THE FUTURE

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Abstract

The electromagnetic rail launcher is a type of high-energy weapon that uses a strong magnetic field to project missiles. To create this field, a current pulse source is needed to provide sufficiently high voltages and currents. The study thoroughly examines the principle of electromagnetic operation of the rail launcher, with particular emphasis on how to achieve the highest electromagnetic field strength. The analysis has been subjected to the source of the impulse current and the tendency of their development in the near future. The subject of the appropriate rails selection and their mutual arrangement has been touched up to attain adequate strength against the harmful effects associated with the flow of high currents. Considerations have been taken to protect the rails from the harmful effects of large-scale current flows, and the topic of the projectile itself to the electromagnetic field was raised. The rapid development of technology over the last few years indicates that high-energy weapons will be the basic weapon of all types of forces in the near future. The development of electromagnetic railroads requires the solution of many mechanical problems and harmful phenomena.

Keywords: *electromagnetic rail launcher, electromagnetic railgun, electromagnetic field, magnetic field, pulse source, missiles, rails system, compulsator, magnetic materials*

1. Introduction

Modern aspirations for technological advancement over potential opponents have led to the development of many new weapons systems. In spite of many years of research, at the present aircraft mounted cannons continues to project bullets using the energy generated by physicochemical changes in the powder charge [1]. The rapid development of technology is likely soon to resign from the long-running classic propulsion system for high energetic configurations. The use of electromagnetic fields to project high-speed bullets has been of interest for a long time for the armies of many countries. The electromagnetic propulsion projector uses the power of the strong electromagnetic field obtained during the current flow. They are divided into coil articulating systems in the Gaussian system and rail systems. In the electromagnetic railgun development of the propulsion unit, there are also a number of significant difficulties. Those are necessary for the wider dissemination of such weapons. One of the important factors is the need to achieve high induction of the electromagnetic field. The electromagnet system can be used to increase it. Another very serious problem in the design of the electromagnetic field is the need to protect the rails from the harmful thermal and mechanical effects of the resulting plasma during the high current flow at the contact surface of the rails with the projectile. An important issue is the construction of the projectile itself, which must be a good conductor at the same time and have the appropriate ability to destroy targets.

2. Construction and operation principle of electromagnetic rail launcher

The electromagnetic rail launcher consists of an electric power generator, an impulse current source and a rail system. The source of the impulse current may be a battery of capacitors or a compulsator. The rail system and the materials for their construction are selected in the way to maximize the electromagnetic field induction.

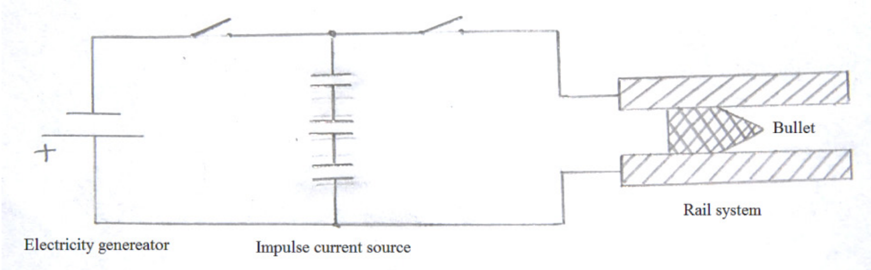

Fig. 1. Schematic drawing of electromagnetic rail launcher [source: own study]

2.1. Operation principle

The electromagnetic shield works by applying the magnetic field to the conductor through which current flows. The source of the magnetic field in the electromagnetic cannon is parallel to the rails through which the current flows at a given intensity. The bullet acts as a conductor, connecting the rails to each other and thus closing the electrical circuit. Electromotive force (SEM) is induced by electrodynamic force in the field of the magnetic flux in the projectile, which has an opposite sign for the flowing current. In the circuit, the current is reduced by the effect of the induced voltage.

According to the pattern of Dutch physicist Hendrik Antoona Lorentz, a conductor with a length of l through which the current of magnitude I, placed in the magnetic field of induction B constant force F acts. The permanent magnetic field is generated by the electric charges in the monotonous movement. The flow of electricity, which is also the movement of electrical charges, generates a magnetic field.

Lorentz force – the force acting on an electric charge particle moving in the electromagnetic field:

$$\vec{F} = \mathrm{q} * \vec{v} \times \vec{B} \text{ [N]}, \tag{1}$$

where:
F –force [N],
q –particle charge [C],
B –magnetic field induction [T],
v –particle velocity vector [m/s].

The rails, the projectile, and the current pulse constitute one electrical circuit. At the moment of current flow around the rails and projectile, a field of electromagnetic fields is created that induces electrodynamic forces seeking to extend the rails. Because the rails are fixed and remained stationary, the electromagnetic forces work on the only moving element, which is a bullet [7]. The bullet moves relative to a constant magnetic field (when supplied with DC) generated in the circuit because of a flow of current. As a result of this movement in the material, vortex currents are induced. This results in an induced magnetic field that counteracts the original magnetic field. Vortex currents have a detrimental effect on the efficiency of electrical appliances.

Electric circuit electrical parameters: system resistance, inductance, capacitors capacitance should be selected so that the duration of the current pulse starts when the bullet is inserted between the rails and the current has the highest amplitude at that moment and ends when the barrel is lowered [8]. At this point, the capacitors should be discharged and the current value should be close to zero. The best way to close an electrical circuit is to insert a bullet between the rails with a separate pneumatic system. This is a good solution to avoid problems with the initial acceleration phase. However, if a missile was inserted to the system before the current pulse was applied, the contact surfaces of the projectile and the rails would be welded before the greatest driving forces would have occurred which would reduce the efficiency of the device and the outlet velocity. There are various methods of introducing and precipitating a projectile from the aforementioned pneumatic system, pyrotechnic systems or the use of a coil-driven system.

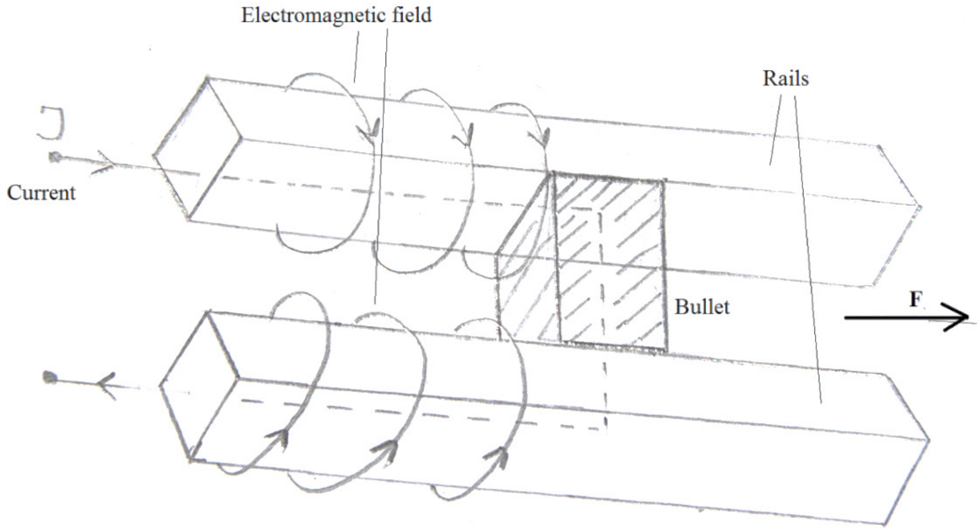

Fig. 2. Scheme of induction of electromagnetic field in rail launcher [source: own study]

3. Sources of impulse current

3.1. Capacitors

For powering a launcher, a source capable of storing a large amount of Energy is needed, which can give stored energy in a very short time in the form of a current pulse. Obtaining high-impulses is to discharge the capacitor in a circuit with low resistance. Limitation of impulse current consumption from the batteries resulting from the construction makes it impossible to use them as a power source. A good solution is to use capacitor banks, that is, single capacitors connected in parallel, in series or in a mixed manner to obtain adequate capacitance and a powerful impulse. It is important to accumulate high energy in the capacitor banks [5]. The maximum current that a capacitor can give when it is charged to a higher voltage does not change, but the higher the voltage, the better it will be able to transmit this impulse more efficiently through the load that is characteristic of the rail system. Capacitors are characterized by very high current efficiency, that is, the maximum value of current that can be obtained at a voltage drop not less than assumed. In our case, the capacitors can be discharged completely without fear of damage, which means that the charge accumulated in such system can be used impulsively in a very short time.

3.2. Compulsators

In order to give missiles with higher mass the right speed or to fire a series of smaller projectiles in a short period, a source of energy capable of storing a few MJ of energy is needed. The reduction in energy storage due to the overall dimensions of the current capacitors currently produced makes it impossible for them to be used in the construction of a rapid-fire ballistic canon. Researchers at the University of Texas at Austin have created a spinning machine with low impedance and high energy in the pulse. This technology has been successfully applied by the US Army for use in electromagnetic missile launchers. The first pulse was a rotating machine, which, at a rotational speed of 4800 rpm, could store 40 kJ of kinetic energy and deliver 1MJ energy pulses each with a pulse duration of 2 ms. The output voltage of this generator was 2 kV, which at the current of 1 MA gave a pulse of 2GW. The concept of new impulse power sources is fundamentally different from modern impulse currents, evolving to the topology of rotating fields and multi-phase operation modes.

Compulsator is a type of machine capable of storing energy in the form of kinetic energy and being capable of delivering it in a short pulse. Also known as FES (Flywheel Energy Storage). The principle of operation is to force the vortex by means of an external mechanical energy source, e.g. an engine connected to it by a mechanical or magnetic transmission, to give the maximum rotational speed of the rotor. The mass rotating at high speed has kinetic energy defined by the formula:

$$E = \frac{1}{2} * m * v^2 \text{ [J]}, \quad (2)$$

where:
m –rotor mass [kg],
v –rotor velocity [m/s].

At the moment of the "shot", the pulse generator is switched to an alternator of low conductivity, i.e. a low value of passive resistance, which quickly converts the kinetic energy of the spinning mass into a high current pulse with high voltage and current values. The impulse is then fed to the rails system. The low value of the alternator coil's conductance allows for immediate induction of an electric current, which makes the pulse generator an excellent source of impulse energy. As a result of energy conversion, the rotational speed of the pulse generator decreases, and therefore the amount of stored energy decreases [9].

By analysing the kinetic energy formula, it can be seen that the energy stored in the pulse generator depends on the mass of the rotor and the linear velocity raised to the square. Practical solutions for both mass and weight limitations, as well as rotor problems with evenly distributed mass, use lighter rotors to accelerate them to higher rotational speeds. Contemporary most advanced compulsators have a rotor made of carbon fibres suspended on magnetic rings that can achieve rotational speeds of 20,000 to 50,000 revolutions per minute. Maximum speed is reached after just a few minutes. Magnetic rings are used to minimize friction [5].

Rotations around the axis of the compass unit will be of a kind a gyroscope seeking to maintain a constant plane of rotation in space.

The formation of gyroscopic moments is caused by the action of centrifugal forces directed perpendicular to the actual axis of rotation. The direction of motion of the aircraft caused by the gyroscopic moment is always deviated by 900 in relation to the direction of the aircraft caused by the pilot or external conditions. To avoid the impact of the gyroscopic moments on the pulse generator and to reduce the forces present, the axis of the pulse generator with the axis of rotation of the Earth should be aligned. Continuous manipulation of the pulse generator on high-speed aircraft could cause many technical problems. Another interesting solution is to use two flywheels rotating in opposite directions at the same speed in the compulsator. In that case, momentums would be balanced and no gyro effects would occur. Unfortunately, if the speed of the wheels were even slightly different then the resulting forces would try to turn the pulse generator. A series of smaller wheels that rotate in different directions to reduce the force can also be used, but then the design of the pulse generator would be much more complicated.

The undoubted advantage of the pulsators is their indifference to the changing temperatures and resistance to chemical damage typical for batteries. They are also less harmful to the environment. Another advantage is that by simply measuring the rotation speed it is possible to determine the exact amount of energy stored in the pulse. Compulsators have theoretically unlimited life due to the need for simple maintenance work such as replacement of bearings, etc. Most modern compulsators are sealed; and require no significant technical support and the use of magnetic bearings eliminates the problem of mechanical wear.

4. Construction of an electromagnetic cannon barrel

Current consumption from pulsed energy sources generates high currents in the busbar system. This results in various harmful physical phenomena affecting the individual components. As mentioned earlier, the flowing current tries to disengage the rails, and thus loads them mechanically. In order to prevent undesirable effects on long-term use of the parcel, the materials used for its construction should be adequately mechanically rigid but also produce a large induction of the magnetic field. The materials used have a certain resistance, which results in the creation of destructive thermal effects at the projectile. To avoid this, materials with good electrical conductivity should be used and the surface of the projectile to the rail should be as high as possible [6]. Around the rails, electromagnetic field should be formed with as much induction as possible, so the materials to build the rails should be carefully selected.

Some magnetic materials, such as ferromagnetics, produce a permanent magnetic field around them. Ferromagnetic is a material in which there are areas of permanent magnetization so-called magnetic domains. Ferromagnetism is one of the strongest forms of magnetism. Thanks to this phenomenon there permanent magnets exists. Ferromagnetics are materials of high magnetic susceptibility and therefore have the greatest importance in electrical engineering. Magnetic properties of anisotropic ferromagnetic materials may vary from point to point, whereas isotropic ferromagnetic properties have the same properties at each location [4]. Ferromagnetic amorphous alloy can be produced by rapid cooling of the molten alloy resulting in almost isotropic magnetic properties. When selecting the appropriate chemical composition and adapting the heat treatment processes, materials with low magnetic coercivity can be obtained with high relative magnetic permeability. Soft magnets are used to obtain high values of magnetic flux [4]. Soft ferromagnetic materials lose magnetization after removal of the magnetic field. They are used to build e.g. transformers to shape the magnetic field. Examples of ferromagnetic materials that can be used to build rails are iron, copper, cobalt, nickel, iron and nickel alloys, iron transition metals and rare earth metals, and many alloys and compounds.

When selecting soft magnetic materials, the following characteristics should be taken into consideration:

- high saturation induction,
- narrow hysteresis loop,
- easy magnetism – low field strength values for high induction,
- adequate electrical permeability.

The magnetic properties of the material are influenced by:

- production technology (e.g. rolling),
- alloy composition and its purity,
- Heat and mechanical treatment – Cold rolling is conducive to the formation of microcrystals in one direction (magnetic anisotropy).

One of the better commercially available rail construction materials appears to be a low carbon iron alloy with silicon. Electro-sheet plates made of this alloy have a high elastic limit, high fracture strength, and losses associated with vortex currents are small. Electrotechnical sheet is a kind of sheet with the properties of soft magnetic material. The alloy composition and production technology are so selected to achieve the best magnetic performance [2]. Iron is the main constituent of the alloy in excess of 93%. It is striving for the coal to be reduced to the smallest value. Silicon (the anisotropic sheet is about 3%) is used as the basic alloying additive. As the silicon content increases, the hardness of the material increases, but unfortunately, resistance and brittleness also increase [4]. With a content of 6.5%, silicon in the material there is almost zero magnetostriction, i.e. deformation of ferromagnetic magnetic field, which is very desirable. During current flow and magnetic field induction, the vortex currents earlier discussed that cause energy loss. To reduce this problem, the rails should be made of insulated folding plates. Magnetic soft materials that are likely to be replaced in the future by electrotechnical plates are metallic glass with an amorphous structure. They are obtained from iron or cobalt based alloys [3].

The shape of the rails, their length and the materials used to make them have a major influence on the magnetic field induced value.

The largest induction of the magnetic field occurs in rails in a double-fed DC system.

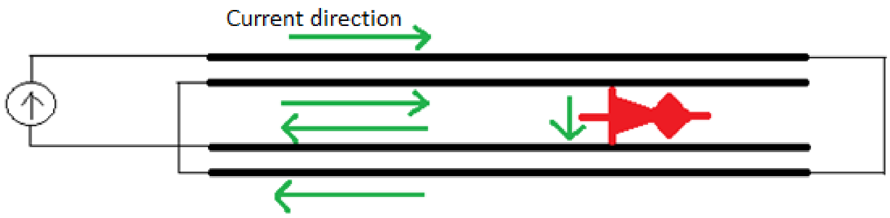

Fig. 3. Diagram of electrical rails connection in double system [source: Developed on the basis of: Electromagnetic guns – guns of the future]

The value of induction of rails in a double system depends on the distance between the pairs of rails in which the current flows in the same direction. When the distance between pairs of rails increases, the value of the induced field decreases.

The direct vicinity of the rails also affects the distribution of the induced magnetic field. As already mentioned, the current flowing through the rails loads them mechanically, striving to extend them. The housing to which the rails are attached must therefore be sufficiently resistant to the resulting stresses and should not interfere with the magnetic field. In this case, the guards should be constructed of non-magnetic materials such as fiberglass laminates, carbon composites, ceramics. However, there is a necessity to combine individual elements of the covers and this is usually done by means of compression screws. The material used to make the screws has little effect on the magnetic field distribution. For example, when feeding the busbar system and using carbon steel screws, the magnetic field induction in the slot slightly increases as opposed to non-magnetic screws such as stainless steel [3].

5. Field induction growth by using permanent magnets and electromagnets

The use of an additional source of strong magnetic field in such a way that the magnetic field lines will have the same direction as the magnetic field induced around the rails will cause the “addition” of the vectors, which in consequence will increase the induction of the magnetic field. Increasing induction will in turn increase the value of the propelling force of the projectile.

5.1. Permanent magnets

Permanent magnets can be used as an additional source of magnetic field. A permanent magnet is an element made of a ferromagnetic material that produces a solid magnetic field around it. In the permanent magnet, two magnetic poles are defined, the points in which the lines of the field produced by the magnet are concentrated. For permanent magnets, the magnetic moment is characteristic. This size determines the direction and value of the magnetic dipole. For example, the vector of the magnets field line has a return from the pole S to N. Because of the materials used to build the magnet can be distinguished, for example, neodymium magnets, samaro- cobalt, plastic and ceramic magnets.

The magnetic poles of the permanent magnet interact with the force defined by the formula:

$$F = \frac{\mu * q_{m1} * q_{m2}}{4\pi r^2} \text{ [N]}, \quad (3)$$

F –force [N],
M –magnetic permeability [(T × m) / A],
r –distance between poles [m],
q_{m1} i q_{m2} – “force” of individual magnetic poles (charges) [A × m].

Currently, the strongest produced permanent magnets (neodymium magnets) have a magnetic field strength of 1.15 T.

5.2. Electromagnets

Permanent magnets are a good source of magnetic field. Unfortunately, the induced field has a relatively small value. Magnets with a much higher magnetic field are needed to provide high acceleration. The ideal solution seems to be the use of electromagnets. An electromagnet is a device that generates a magnetic field at the moment the current flows through it. It consists of a coil (solenoid) wound on a ferromagnetic core. The core is mainly made of mild steel, not tempered. The current flowing through the coil generates a magnetic field that magnetizes the core, thus undergoing substantial amplification. To reduce the magnetic flux, electromagnets should be horseshoe shaped.

Due to the use of electromagnets, they are divided into positioning (lifting, pulling), holding and generating power (clutches, brakes). Electromagnets can be powered by DC or AC. Voltage and current in the alternating current varies sinusoidally, causing changes in the direction and magnitude of the magnetic flux over time. As a result, the electromagnetic force flashes from zero to a maximum of twice the frequency of the mains current. To reduce the energy losses caused by vortex currents, the cores of such electromagnets are made of insulated sheets. The solenoid wire should be insulated to prevent current flowing on the core surface. In electromagnets powered by DC, the magnetic flux is constant over time. This solves the problem of synchronizing the shooting at the moment of the highest value of the magnetic field, as is the case with alternating current. Such electromagnet should work impulsively, i.e. be turned on at the moment the shot is fired. This is due to the large amount of heat generated during the flow of current that can lead to the burnout of the coil.

It is also important to mention the existence of polarized electromagnets, i.e. those that have a magnetic flux produced by a permanent magnet regardless of the flowing current. Now of current flow, the stream is significantly strengthened.

The intensity of the induced field depends on the intensity of the current flowing through the coil and the number of turns of the coil. The greater the number of coils and the current the stronger the magnetic field. When the current stops flowing, the magnetic field disappears [3, 8]. Nowadays strongest electromagnets are made using superconducting coils. These coils are made of superconductive materials that do not show electrical resistance. The resulting magnetic field can reach values up to 1000 A/m. Reaching stronger magnetic fields with current superconductors is impossible because the properties of the superconducting materials are destroyed by a stronger magnetic field. The mass and dimensions of electromagnets made of superconductive materials are considerably smaller than the dimensions and mass in the case of permanent electromagnets. Unfortunately, most of the currently discovered superconductors achieve their properties at absolute zero temperature. Obtaining high temperature superconductors will certainly contribute to the spread of strong electromagnets. So far, we have managed to achieve stable superconductivity at 140 K and this limit is constantly increasing. One of the most powerful electromagnets currently produced is the Bitter electromagnet. It is made up of metal disks and insulating spacers located spirally. This results in proper cooling of the electromagnet and makes it sufficiently mechanically resistant to bursting magnetic forces. Magnetic field induction of this type of electromagnets reaches a value of 10-20 T, although there are static structures up to 35 T.

6. Rail protection coatings

As the electromotive forces tend to spread the rails by worsening the contact surface of the projectile, and the resulting destructive heat and erosion damage the guide surfaces, it is necessary to use sufficiently strong materials or make protective coatings on the projectile surfaces of the projectile barrel. In order to reduce wear and tear a suitable busbar limiting system can be applied while simultaneously maintaining the appropriate induction of the magnetic field. So far, the best effect has been achieved by using a double rail system as shown in figure [4].

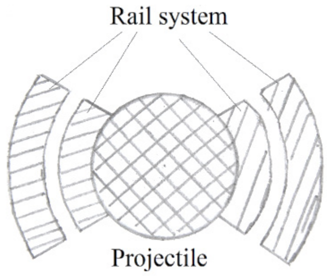

Fig. 4. Dual rail system with high magnetic field induction values [source: [8]]

Galvanic coatings are used to improve the surface properties of corrosion, abrasion or increase its hardness. The layer laid on the rail should not only be resistant to harmful effects, but also above all be a good conductor of electricity to maintain the proper induction of the magnetic field. The main process widely used today in deposition of coatings is the so-called anodizing. The films are obtained in an electrolyte in which the anode is a protected object, while the cathode is an electrolyte resistant material. During DC flow, metal ions adhere to the anode forming a coating. At the same time, the cathode, which is usually made of the same material as the built shell, dissolves, causing the ions to adhere to the anode. Choosing the right electrolyte depends on the coating you want to get. In sulfuric or oxalic acid solutions, hard coatings with high abrasion resistance and reduced coefficient of friction are produced. Electrolysis is carried out under specified conditions of current and voltage at constant temperature [2]. The galvanic method is used to deposit most metals in pure state but also as galvanic alloys. The protective action of galvanic coatings is related to the type of coating metal and substrate. It is required that the coating must characterized by fine crystalline structure, high adhesion to the substrate and tightness. The electrolysis element should be thoroughly purified and degreased beforehand. The properties of the resulting layer are affected by various factors such as temperature, concentration and type of electrolyte, current density or presence of impurities. With low current density, the growth of new embryos on the surface is slower than that of existing ones, which is conducive to the formation of thick coats. As the density increases, the rate of formation of new embryos increases, resulting in the desired fine coat. Examples of widely used coatings may be zinc coatings. Their widespread use is due to their low price, adequate protective properties, good adhesion and good plasticity.

From the available materials, the use of a graphene coating seems to be a good solution to protect rails of the airplane electromagnetic launcher. Graphene is the latest work of nanotechnology in which carbon atoms form a layer only one nanometre thick. It has very unique properties. Through graphene, the current flows at very high speed, making it a very good conductor. Graphene, in addition to its excellent electrical conductivity, is also the most powerful yet exposed material, more than one hundred times stronger than steel, and it is very light, flexible, hard and has high thermal conductivity. Thin graphene flakes placed in the air immediately crumble or roll into rolls, so the graphene in nature is not in pure form. In order for the graphene, its properties, it should be placed on the appropriate substrate. Currently, silicon carbide, boron nitride, and copper are best for this role. The composite created now of projecting the bullet in the barrel, thanks to its elasticity, bends slightly and then returns to the original shape. One of the problems that accompany this technology is the difficulty in producing a graphene coating. There are currently several different methods of obtaining graphene. One of the most promising is the method developed by Poles called the "layer by layer" method of polyelectrolyte layering. It is based on electrostatic interactions that cause the attraction of non-unique loads. Production of the layer consists in placing a charged material on the substrate that has opposite charge. Attracting loads causes deposition of substrate molecules on the surface. The next step is to rinse the resulting composite to remove the unbound molecules, and then repeat the whole process until a suitable thickness is obtained. When graphene coating is being built, graphene oxide is usually used as the substrate, which is a nonconductive material with the intention of obtaining a conductive material, i.e., graphene [5, 6].

7. Construction of electromagnetic rail gun launcher missiles

The shape and materials used to build the missiles have a substantial effect on the resulting outgoing velocities, and significantly reduce the destruction of the surface of the rails. Structural solutions should provide the least loss of electrical contact between the projectile and the rails. In modern solutions, two solutions are used: fixed jumpers and brush jumpers.

There are also jumpers: Hybrid, Liquid and Plasma. The principle of the liquid jumper is to heat the jumper material before firing it to its melting point and bringing it to a liquid state. This solution minimizes the frictional forces that occur when the projectile moves and protects the rail surfaces from damage. Liquid jumper is the most promising way to increase the efficiency of electromagnetic propulsion.

It is also very important to choose the material itself for the construction of the conductive elements of the projectile.

An electromagnetic rail launcher should be made using several different materials in its various parts. The core is best made from very hard materials such as tungsten, depleted uranium to achieve the best possible firearm performance at armoured target. It is good to use composite materials to build the sabot, because of their high strength at low mass. It also should be remembered to use a well-conductive material in the last layer to allow for the generation of the projectile's electromagnetic field. An excellent solution seems to be the use of liquid jumper to increase the strength of the barrel and increase the number of shots fired before it needs to be replaced. One should also not forget to use the back of the missile core, which after the fire will put it into rotation. This will stabilize the flight path and get a smaller dispersion of missiles when hit on target.

8. Conclusion

The rapid development of technology over the last few years indicates that high-energy weapons will be the basic weapon of all types of forces in the near future. The development of electromagnetic railroads requires the solution of many mechanical problems and harmful phenomena occurring now of projectile firing. At present, the works are capable of dispelling the projectile to a speed that many times exceeds the speed of sound. The development of electromagnetic plots will give an advantage over potential opponent by reducing the cost of driving fire over long distances, as opposed to more expensive rocket systems. Great hopes make progress in the development of superconductors operating at room temperature, which will allow for a much stronger electric pulse, which in turn will allow even greater force acting on a projectile. One of the available solutions for increasing the produced force is the use of a cooling system, e.g. liquid nitrogen, which will reduce the resistance of the wires and this will result in higher currents with less electrical impulses. It is a good idea to develop cooled electromagnetic systems to provide an extra magnetic field that will allow even greater accelerating forces.

Visionaries see the wide scope of future use of Rail Gun systems. One of the ideas is to use a launcher to launch small satellites into low Earth orbits.

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