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AN EXPERIMENTAL TECHNIQUE FOR STUDYING THE BEHAVIOR OF HIGH-STRENGTH STEEL UNDER STATIC PUNCHING

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Summary. *High-strength steels are widely used in the defense and civil industries. During operation, high-strength and armored steels are subjected to extreme static and dynamic loads. Material specimens or full-scale structures testing at such loads is a very complex and expensive process. Therefore, numerical calculation methods are commonly used to assess their strength. To determine the parameters of these models as an express method, it is reasonable to use tests that are similar in nature of the loading, deformation, and failure to full-scale or standard ones, but which are cheaper and easier to perform in the laboratory conditions. One of the key properties of high-strength steels is their resistance to penetration by various types of armor-piercing strikers. To simplify the testing procedure and minimize materials consumption, static and dynamic punching methods have been developed. A set of experimental and numerical investigations on the deformation of various specimens from high-strength steels has been made under static and dynamic load conditions, in particular, plate specimens punching (punches of different shapes) by the G. S. Pisarenko Institute for Problems of Strength of the NAS of Ukraine. This paper presents the experimental procedure and equipment for the investigation of the materials' behavior under static punching. High-strength steel plate specimens have been tested on an upgraded servohydraulic machine Instron 8802 using three types of punches: flat, spherical, and conical. It is established that the diagram describing the spherical punching is the most informative, while the diagram showing the conical punching is less informative. The nature of the specimen fracture is consistent with the results of field tests in the barrier penetration by armor-piercing strikers. The obtained results are in good agreement with the known literature data and can be used to validate the results obtained by numerical simulations.*

Key words: *high-strength steel, static punching, plate specimen, punching diagram, flat punch, spherical punch, conical punch.*

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Introduction. High-strength and armored steels have become popular in both the defense and civil industries. They are used in the manufacture of load-bearing and protective structures of various combat vehicles, as well as in the protective elements of civilian vehicles, structures, etc. During operation, high-strength and armored steels are subjected to extreme static and dynamic loads, including high-speed shock or explosion loads, which can destroy the material. Testing of the material specimen or full-scale structures at such loads is a very complex and expensive process due to the complexity and cost of manufacturing and processing of specimens, the need for high-tech experimental equipment, as well as high cost of high-strength materials. Therefore, numerical calculation methods are widely applied [1, 2]. The Garson-Tvergaard-Needleman model (GTN) [3–5], Johnson-Cook [6, 7], and other models are employed. The parameters of these models are determined from experimental and numerical investigations.

To determine the parameters of these models as an express method, it is reasonable to use tests that are similar in nature of the loading, deformation, and failure to full-scale or standard ones, but which are cheaper and easier to perform in the laboratory conditions. It can

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facilitate the obtaining of reliable data for numerical calculations of complex tests or determine the strength of actual structures using numerical methods.

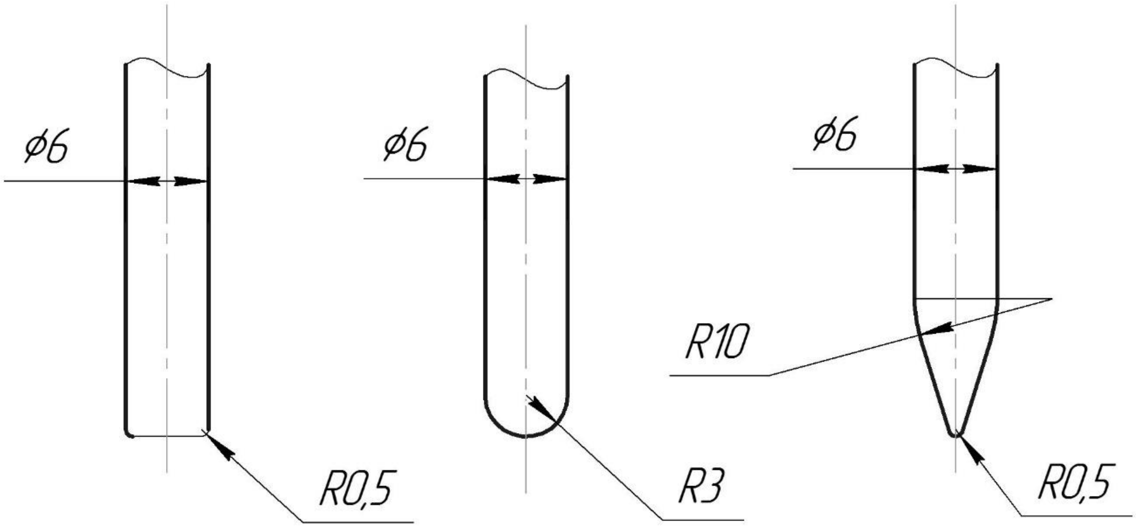
One of the key properties of high-strength steels is their resistance to penetration by various types of armor-piercing strikers. The shape of the striker's head and its hardness regarding the barrier are the main factors that affect the penetration. Static and dynamic punching test methods with low (up to 20 m/s) and average (20–300 m/s) load speeds [8, 9] are used to develop the calculation models of high-strength materials by minimizing materials consumption and simplifying the test procedure.

Some experimental and calculation investigations on the deformation of the specimens of different configurations of high-strength steels under static and dynamic loads, namely, plate specimen punching penetration (various punches), have been performed at the G. S. Pisarenko Institute for Problems of Strength of the NAS of Ukraine.

This paper presents the investigation results required for the development of the experimental facilities and methods of investigation of the materials’ behavior under static punching.

Materials, Test Methods and Equipment. In the punching of the plate specimen, which is rigidly clamped in the special device, the process of its deformation by the punch of the certain shape is registered in the coordinates «load applied to the punch – depth of punching».

Figure 1 illustrates the geometry of the standard punch tips (flat, spherical, and conical) in punching the plate specimens of high-strength steel.



(a) (b) (c)

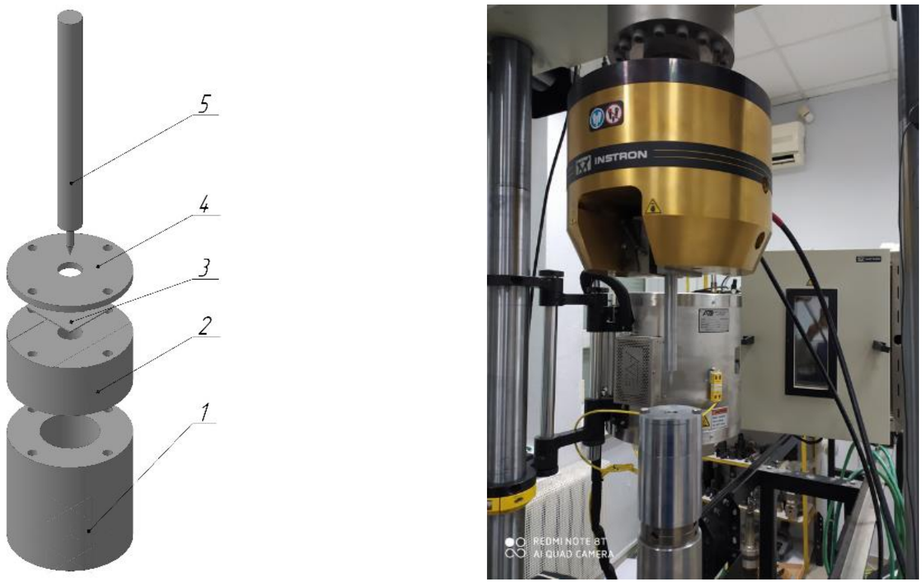
Figure 1. Standard punch tips: flat (a), spherical (b) and conical (c)

The method of plate specimens punching is similar to small punch test. Some investigations aimed at the design of equipment to perform disc micro-specimens punching within the macro-range of load forces [10] have been performed at the G. S. Pisarenko Institute for Problems of Strength of the NAS of Ukraine. Also, the authors have developed and improved new methods for determining the strength properties based on the results of such tests.

The plate specimens have a larger thickness as compared with the disc microspecimens. From the results of numerical simulation for the square-shaped plate specimens punching (with a side of 50 mm and a thickness of 1 mm) it is determined that the spherical punch (~ 14 kN) requires the largest load to fracture, whereas the conical one (~ 4 kN) requires the lowest load.

The laboratory setup UTM-20HT [10] for testing disk microspecimens is designed with a maximum load of 10 kN. Therefore, it is decided to use a servohydraulic machine Instron 8802, which allows one to ensure a rigid load on the specimen. This fact is of vital importance in the registration of the specimens' penetration depth during nucleation and crack growth in them. The certified digital control system, measurement of forces, deformations, and displacements makes it possible to plan the experiment. Moreover, licensed software allows one to register the selected experimental parameters in real-time and obtain all the required characteristics in the electronic form, which describe the material's behavior during deformation.

The equipment (Fig. 2 a) was designed and produced for the plate specimens' punching. It ensures the reliable fixing and symmetrical positioning of the specimen relative to the force axis. Structurally, it consists of a base 1 attached to the lower grip of the machine, the lower 2 and upper 4 dies between which specimen 3 is installed, and the punch 5, which is attached to the upper grip of the machine. In lower 2 and upper 4 dies, grooves are made symmetrically to the force axis and perpendicular to each other for the specimen size. The depth of the grooves is less than half of the specimen thickness, which allows one to reliably push the specimen through the dies. This design of the device allows one to center the specimen relative to the load axis of the test machine. The parts of the device are attached through the holes using fasteners. The upper and lower grips of the Instron 8802 have been modernized to mount and center the device designed to punch the plate specimens (Fig. 2 b). The registration of the load applied to the punch, as well the punch displacement, is performed using the Instron 8802 gauges.



(a) (b)

Figure 2. Equipment (a) for punching: 1 – base; 2 – upper die; 3 – specimen; 4 – lower die; 5 – punch; and machine Instron 8802 (b)

The test method for the plate specimens punching was approved using the specimens made of a high-strength alloy steel sheet of special-purpose Armox 500T with a thickness of 3 mm. The specimens were cut out of sheet metal blanks with dimensions of 50 × 50 × 3 mm to 1 mm in thickness by grinding with cooling on both sides (Fig. 3).

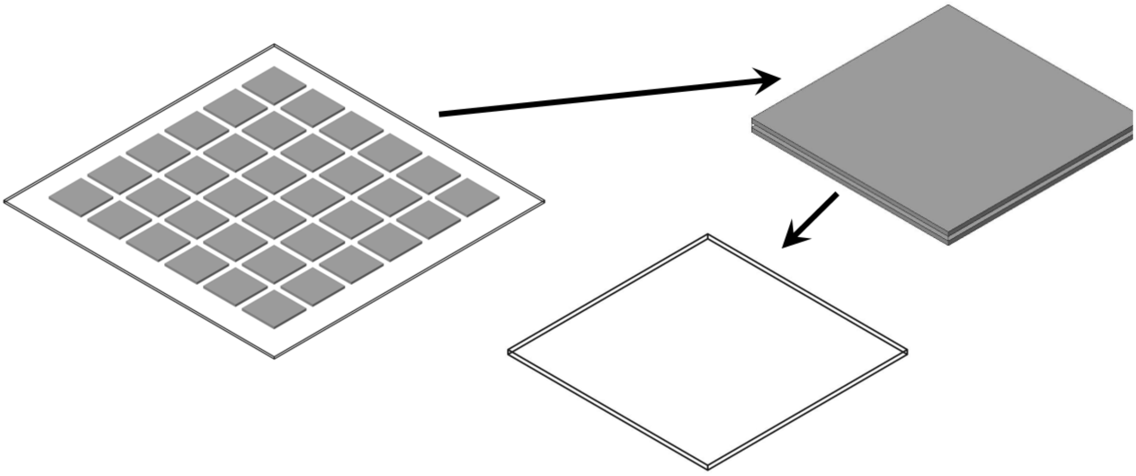
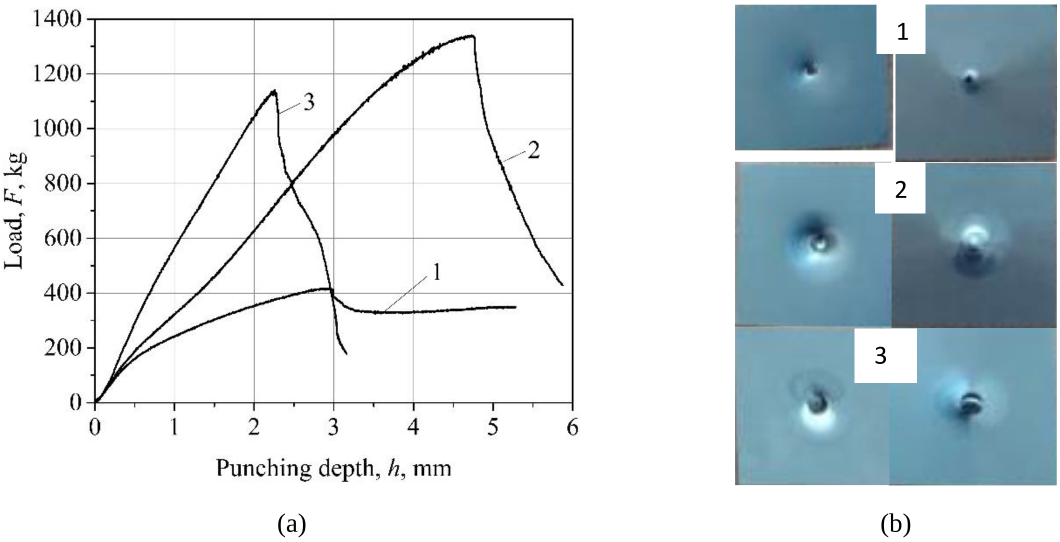


Figure 3. The scheme of the specimen manufacturing procedure

Test Results. Figure 4a illustrates the punching diagrams. Figure 4b shows the external view of the fractured specimens. As seen from the presented results, specimen 1 after fracture by a conical punch is the least deformed in the load action plane, and the indentation place is of the pierced hole form. The deformation diagram is the least pronounced due to small forces during fracture. Specimen 2, after fracture by a hemispherical punch, is the most deformed in the load action plane having a convex downwards dent that ends with a crack, therefore, the diagram is more informative. Specimen 3, after fracture by a flat punch, is less deformed in the load action plane in comparison with the spherical one and has a punched-out round hole. The greatest load destruction was required when punching by a spherical punch, and the smallest – with a conical one. The value of the punching depth (at the beginning of the specimen destruction) had the smallest values via flat punching, and large ones – by a spherical punch. The nature of the specimens' destruction is consistent with the results of field tests in the barrier penetration by armor-piercing strikers.

The obtained test results are in agreement with the known literature data and are qualitatively similar to those given in [9].



(a) (b)

Figure 4. Punching diagrams (a) and plastic specimens with different punches (b):
1 – conical, 2 – spherical and 3 – flat

Conclusions. The experimental methods and equipment for the investigation of the materials’ behavior under static punching were developed. The high-strength steel plate specimens were tested on the modernized servo-hydraulic machine Instron 8802 using different types of punches. The obtained results are consistent with the known literature data and can be used to validate the results obtained in numerical simulations.

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РОЗРОБЛЕННЯ ЕКСПЕРИМЕНТАЛЬНОЇ МЕТОДИКИ ДОСЛІДЖЕННЯ ПОВЕДІНКИ ВИСОКОМІЦНОЇ СТАЛІ ПРИ СТАТИЧНОМУ ПРОДАВЛЮВАННІ

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Резюме. *Високоміцні сталі широко використовуються в оборонному й цивільному секторі промисловості. В процесі експлуатації високоміцні та броньовані сталі піддаються екстремальним статичним та динамічним навантаженням. Проведення випробувань зразків матеріалу або повномасштабних конструкцій при таких навантаженнях є дуже складним та дороговартісним процесом. Тому для оцінювання їх міцності в світовій практиці широко використовуються чисельні методи розрахунку. Для визначення параметрів розрахункових моделей в якості експрес-методу доцільно використовувати випробування, які за характером навантаження, деформування та руйнування є подібними до повномасштабних чи стандартних, але які дешевше й легше провести в лабораторних умовах. Однією із важливих властивостей високоміцних сталей є їхня стійкість при пробитті різними типами бронебійних ударників. Тому з метою розроблення розрахункових моделей високоміцних матеріалів, мінімізуючи при цьому об'єм використовуваного матеріалу для виготовлення зразків та спрощуючи процедуру проведення випробувань, в останній час розвиваються такі методи, як випробування на статичне та динамічне продавлювання. В Інституті проблем міцності імені Г. С. Писаренка НАН України було проведено комплекс експериментально-розрахункових досліджень деформування зразків різної конфігурації з високоміцних сталей в умовах як статичного, так і динамічного навантажень, зокрема, процесу продавлювання пластинчастих зразків пуансонами різної форми. В рамках даної роботи розроблено експериментальну методику та устаткування для дослідження поведінки матеріалів при статичному продавлюванні. Проведено випробування пластинчастих зразків із високоміцної сталі на модернізованій сервогідравлічній машині Instron 8802 із використанням трьох типів пуансонів: плоского, напівсферичного та конусного. Встановлено, що найбільш інформативною є діаграма продавлювання зразків напівсферичним пуансоном, а найменш інформативною – діаграма продавлювання конусним пуансоном. При цьому характер руйнування зразків є подібним до результатів полігонних випробувань при пробитті перешкоди бронебійними ударниками. Отримані результати добре узгоджуються з відомими літературними даними і можуть бути використані для валідації результатів, отриманих при чисельному моделюванні.*

Ключові слова: *високоміцна сталь, статичне продавлювання, пластинчастий зразок, діаграма продавлювання, плоский пуансон, напівсферичний пуансон, конусний пуансон.*

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