Shock imprint and rolling direction influence upon the breaking tenacity for 2P armor steel

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Abstract. The state of art in present literature shows that the breaking tenacity of a material is influenced by the integrity of the structure. Since armors used in aviation and to protect military vehicles are frequently impact loaded, through the contact between armor sheet and projectiles, or other foreign bodies, the authors have proposed to study the dependence between the breaking tenacity of 2P armor steel depending on the direction of the rolling of the armor plate, of the geometry (spherical imprint, pyramidal and linear imprint) and the depth of the deformation that results after impact. Tests were conducted upon CT (ASTM E-399) specimen type, using the critical factor of stress intensity during the state of planar strain.

1. Introduction
2P armor alloy is used in military fields while it resist without cracking hits of a large-caliber small arms bullets [1]. Due to its characteristics (survivability requirement and welding requirements [1]), this alloy is used for Light Armored Vehicles (APC, IFV) and also as aviation armor. For such applications steels with the upper allowable limit of carbon content (no more than 0.32%) are used [1].

A simple classification of armors can be made [2] considering three factors: depending on the role of the armor (passive armors or reactive armors and slide plates armors), or depending on the manufacturing solution (homogeneous armors or layered armors) and depending on the constructive solution (basic or removable armors).

According to the producers, chemical composition and mechanical proprieties values are given “for information purposes only” [1], presented in table 1 and table 2.

| Table 1. Chemical composition (ladle chemical analysis), (%), and (maximum value) [1]. |
| --- |
| Product name | C | Si | Mn | Cr | Ni | Mo | B |
| 2P (acc. to GOST) | 0.29 | 1.60 | 1.60 | 0.30 | 0.50 | 0.25 |

| Table 2. Mechanical properties [1]. |
| --- |
| Product name | HBW hardness (average), EN ISO 65061:2006 | Mechanical properties EN 10002-1:2004 minimum | Impact strength |
| 2P (acc. to GOST) | KV (-40°C) $R_n$ [MPa] min. [J]’ | A5 [%] | EN 100451:1994 |

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In order to achieve the goal of the paper, which is to determine the behavior of the 2P armor steel when the plate is damaged through shock by different corps with variable dimensions, the authors had to determine the precise values of the mechanical characteristics of the used steel.

2. Characteristics of the material

In order to obtain valid characteristics for the purpose of the paper, the authors have gathered the material characteristic curve on three specimens taken from 2P sheet with 6.8 mm thickness, manufactured at three different angles to the rolling direction: 0°, 45° and 90° (figure 1 - 3).

For the analyzed samples, simple traction test were carried-out, and an average thereof was made. The results are presented in table 3.

![Figure 1](image1.png) ![Figure 2](image2.png) ![Figure 3](image3.png)

**Table 3. Centralization of the characteristic mechanical properties of the tested specimens**

| Sample no. | Rolling direction [°] | Thickness “s” [mm] | Yield stress [MPa] | Fracture stress [MPa] | Axial extension [%] | Young modulus [■10^4 MPa] | Poisson ratio |
|------------|----------------------|--------------------|--------------------|----------------------|---------------------|-----------------------------|--------------|
| 1          | 6.8                  | 941                | 1358               | 0.2                  | 24                  | 0.26                        |              |
| 2          | 6.8                  | 955                | 1374               | 0.24                 | 21                  | 0.28                        |              |
| 3          | 6.8                  | 916                | 1440               | 0.22                 | 21                  | 0.24                        |              |
| Average    | 6.8                  | **937**            | **1391**           | **0.22**             | **22.3**            | **0.26**                    |              |
| 1          | 6.8                  | 1004               | 1490               | 0.11                 | 31.8                | 0.14                        |              |
| 2          | 6.8                  | 1009               | 1527               | **0.09**             | 22                  | 0.27                        |              |
| 3          | 6.8                  | 976                | 1523               | 0.23                 | 18.9                | 0.31                        |              |
| Average    | 6.8                  | **995**            | **1513**           | **0.14**             | **24.2**            | **0.24**                    |              |
| 1          | 6.8                  | 936                | 1483               | 0.1                  | 27.1                | 0.3                         |              |
| 2          | 6.8                  | 925                | 1476               | 0.11                 | 22                  | 0.29                        |              |
| 3          | 6.8                  | 950                | 1477               | 0.09                 | 19.8                | 0.27                        |              |
| Average    | 6.8                  | **937**            | **1479**           | **0.1**              | **22.9**            | **0.29**                    |              |
| Average    | 6.8                  | **956**            | **1461**           | **0.15**             | **23.1**            | **0.26**                    |              |

From figures 1 - 3, the breaking mode of the material can be observed, which presents an area of constriction with a small value before breaking. Figures 4 - 6 presents the characteristic curves gathered after tests on the three specimens sets.
3. Experimental plan; Apparatus

Determination of breaking tenacity (KIC) under plane strain condition can be made performing specific tests developed since this property is directly correlated with the designed material stress and with the estimated dimensions of the defects from structures [3]. Breaking tenacity values, are affordable for establishing a relationship between the amount of stress calculation (a) and the size of the crack defect (a) [3]:

\[ K_{ic} = f\left(\sigma\sqrt{\pi \cdot a}\right) \]  

with important indications about the limits of induced crack (on the defect). This type of test is among those meant to highlight the characteristics of resistance to crack initiation expansion [4]. Determining the breaking tenacity through the critical stress factor in terms of planar strain state, based on the interpretation of force - displacement diagram (figure 7), involves the analyze of the breaking tenacity value using the relationship obtained from elastic solution (2) [5].

\[ K_{ic} = \frac{P_{Q}}{\sqrt{BW}} \left[ 29.6 \left(\frac{a}{w}\right)^{\frac{5}{2}} - 185.5 \left(\frac{a}{w}\right)^{\frac{3}{2}} + 655.7 \left(\frac{a}{w}\right)^{\frac{5}{2}} - 1017 \left(\frac{a}{w}\right)^{\frac{7}{2}} + 638.9 \left(\frac{a}{w}\right)^{9/2} \right] \]  

where PQ is the force as determined, B - thickness of the specimen, W - width of the specimen and a - crack length as determined (figure 8).

In order to obtain accurate results, several conditions has to be complained [4]:
- Use forms of specimens according to the standards;
- The dimensions of the specimen, especially the transverse one, has to be large enough so that the transverse contraction to the front of the crack to be minimal;
- The acuity of the practiced crack has to be close from the natural one. Therefore specimens are previously subject to varying loads, so a fatigue crack nuclease and spreads on a controlled length of 0.5-W (figure 9).
For each specimen set, the depth of deformation was ranging from 15% of the thickness (B) to 30% of the thickness, with an increment of 5%. To determine the force - displacement curve has been used a TIRA - test 2151 equipment made by Heckert company, with force cell, an Epsilon extensometer 3542-050M type with an opening area of 25 mm, specimens being controlled pre cracked through a fatigue testing machine of own manufacturing.

In order to establish the breaking tenacity of 2P armor alloy after an impact with a foreign material that can deform the body specific tests were carried-out. For this purpose five sets of specimens were created, labeled from P1 to P5, followed by the value of manufacturing angle to the rolling direction. Each set contained standard specimens, with spherical deformation (figure 10.a.) with pyramidal deformation (figure 10.b.) and linear deformation (figure 10.c.).
4. Results
After tests, it was possible to centralize the data in table 4.

| Sample       | KIC [MPa-m^1/2] |
|--------------|-----------------|
|              | Standard specimen | Ball imprint | Pyramid imprint | Longitudinal imprint |
| P1(0°)       | 167.8           | 186.16       | 146.66          | 165.65               |
| P1(45°)      | 163.7           | 181.31       | 144.06          | 161.90               |
| P1(90°)      | 168.5           | 187.04       | 148.28          | 166.45               |
| P2(0°)       | 167.1           | 185.58       | 148.05          | 165.26               |
| P2(45°)      | 163.5           | 181.49       | 143.88          | 161.20               |
| P2(90°)      | 168.2           | 186.40       | 147.02          | 166.35               |
| P3(0°)       | 168.1           | 186.59       | 149.93          | 166.75               |
| P3(45°)      | 167.4           | 185.71       | 149.31          | 165.56               |
| P3(90°)      | 167.9           | 186.37       | 149.75          | 166.05               |
| P4(0°)       | 167.2           | 185.29       | 148.14          | 165.96               |
| P4(45°)      | 163.8           | 181.52       | 145.14          | 162.11               |
| P4(90°)      | 168.4           | 186.62       | 146.19          | 166.55               |
| P5(0°)       | 167.9           | 186.47       | 146.75          | 166.25               |
| P5(45°)      | 165.7           | 183.63       | 146.82          | 163.78               |
| P5(90°)      | 168.1           | 186.59       | 147.93          | 166.25               |

A graphical analysis may offer a suggestive evaluation of the breaking tenacity dependence to the shape of the imprint and the rolling direction. Thus, in figure 11 the general dependence is presented, using all the tested specimens and all types of imprints.

![Figure 11. Variation of the breaking tenacity for standard and deformed specimens.](image)

It is obvious that the ball imprint had the effect of a hardening that conduces to an increase of the
breaking tenacity. For the pyramidal imprint, as well as for the longitudinal one, the imprint had cutted the fiber of the sample and the values of the breaking tenacity had registrated a major decrease (figure 12 and figure 13).

![Figure 12. Variation of the breaking tenacity for the specimens with longitudinal imprint.](image1)

![Figure 13. Variation of the breaking tenacity for the specimens with pyramidal imprint.](image2)

If the force of the impact increases and implicitly the footprint depth, damages appears in the intimate structure of the material (for longitudinal and pyramidal imprint - figure 12 and figure 13) and the breaking tenacity measured values decreases to 8% approx.

5. Conclusions
The impact of different bodies to an armor steel changes its mechanical properties, mainly breaking tenacity. If the imprint type conduces to a hardening process, the breaking tenacity may increase up to 7%. For the imprints that destroys the base material microstructure, by altering the characteristics of the plastic enclave in the direction of crack propagation the decrease of the breaking tenacity is up to 8%. In addition to dedicated methods in fracture mechanics, for the crack growth rate appreciation (KIC, DCVF, J integral etc.) should be considered the hydrostatic pressure of the material at the crack nose too and the incident angle under which the collision occurs with the foreign body.

The study is important especially for used for Light Armored Vehicles (APC, IFV) equipped with layered armors that can be stressed through impact by a foreign object, as projectiles are.
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