On Fracture Criterion of Titanium Alloy under Dynamic Loading Conditions

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Abstract

One of the most important factors in ensuring the adequacy of the mathematical modeling of limiting states of structures is the choice of the material local fracture criterion and accurate determination of its parameters. The paper discusses some traditional approaches to the construction of local failure criteria of metals under dynamic loading, methods of their parameters identification, as well as the development of these approaches on the example of impact penetration problem. The work focuses on the possibility of modeling viscous and brittle types of fracture within a single deformation type criterion, while the dependence of fracture strain on the stress triaxiality ratio can became complicated and nonmonotonic. The quality of the considered criteria is determined by comparing the results of virtual simulation with the data of full-scale experiments that implement various types of stress state and failure mechanisms. The results of full-scale and virtual compression, tension and penetration dynamic tests of the titanium alloy samples are given. Virtual experiments were conducted using nonlinear LS-DYNA® code.

Keywords: *Failure of metals, impact, penetration, experiment, simulation, material models.*

Introduction

The work focuses on the problem of ballistic penetration of thick metallic plates, since it implements various types of stress state and fracture nature.

In formulating and solving the problem of impact penetration a characteristic set of geometric and material factors inherent in most nonlinear problems of the dynamic strength need to be considered. The most important of these are dynamic hardening, thermal softening, large plastic strain, possible material discontinuity due to local failure, dynamic contact boundaries. Depending on the rate of occurring impact dynamic deformation processes, the role of these factors is different, which can lead to significant simplifications of impact problem formulation. The most challenging for mathematical modeling is the range of relatively slow dynamic processes of deformation (10^2 - 10^4 s^{-1}), when the quasi-static, on the one hand, and hydrodynamic, on the other hand, approaches, are unacceptable. Because of the complexity of an adequate problem formulation, rigorous analytical solution technique for the impact penetration problems have no significant development, so nowadays experimental and semiempirical computational methods are predominantly used for this purpose.

Failure criteria for metals

Today, the most common method for solving the impact penetration problems is the direct three-dimensional computer simulation, using a characteristic set of physical-theoretical models of material behavior, local failure criteria, and contact algorithms. Below we shall not consider in detail the choice of constitutive relations and set of contact conditions, and will focus on the problem of choosing the most appropriate failure criterion. We only note that various modifications of plastic flow theory, taking into account the dynamic and thermal factors, are traditionally considered as the defining relations, and the laws of dry and viscous friction are accepted at the contact boundaries. Until recently, the simple deformation failure criterion on the constant ultimate effective plastic strain was the most widely used in engineering practice for solving impact problems. This approach allows accurate determination of the residual projectile velocity, but does not describe some qualitative effects that occur in metal barrier penetration process, such as the plug formation, petal fracture pattern, the presence of large plastic deformation in the vicinity of the damage region. In recent years the criteria that take into account the dependence of ultimate plastic strain on the type of stress state are increasingly being used when solving such problems. For example, Johnson-Cook material model [1] implements the failure criterion based on the exponential dependence of ultimate plastic strain on the stress state triaxiality variable, equal to the ratio of hydrostatic pressure to the equivalent stress. The use of this model allows describing some of the above mentioned qualitative phenomena. Further development of this approach is the transition from the universal curve to a single experimentally determined fracture surface, constructed according to the results of diverse tests that implement the various combinations of triaxiality and Lode angle values[2-3]. This approach is most intensively developed at present, but significant weakness is the need for numerous experiments.

Another attitude is the use of microstructural phenomenological approaches. In [4] the Gurson material model was used to describe the fracture of metals under dynamic loading conditions. Gurson model [5] suggests that the structural failure under intense stresses occurs due to nucleation and growth of microvoids in the bulk material. As the main model parameter the function f, defining the concentration of voids in the local volume at a time, represented as the sum of shares of existing and emerging voids is introduced. The growth of existing microvoids is determined by the volumetric plastic deformation increment and the nucleation of new voids is considered from the viewpoint of the probabilistic approach and is given by a Gauss distribution. Local failure of material occurs at a critical value of f. As an additional failure criterion for a given range of triaxiality values the Johnson-Cook failure criterion is introduced. The dependence between stresses and strains is determined by the associative flow rule with the specific plastic potential.

Impact penetration problem is characterized by different thermomechanical states. The most significant parameters of these states that affect the fracture criterion are triaxiality ratio, strain rate and temperature with characteristic values of -1 to 1 for triaxilaity, 500 to 5000 1/s for strain rate. In this paper, states, characterized by the triaxiality values in the range [-0.7, -0.5] were reproduced in the verification (full-scale and virtual) experiments on tension and fracture of smooth cylindrical specimens by the Kolsky method. Triaxiality range [0.3, 0.5] was simulated in the verification experiments on compression and fracture of cylindrical specimens. To obtain the material response in the remaining cases impact tests were used. Within the comparison of full-scale and virtual tests results various quantitative and qualitative characteristics were evaluated, such as impactor residual velocity, plug mass and velocity, shape and number of cracks - in ballistic tests, elongation (contraction) of the sample, the contraction in the neck, the nature of fracture - in tension and compression test.

Full-scale dynamic tests

In order to investigate failure of titanium alloy under dynamic loading conditions, different series of experiments were carried out. Dynamic full-scale tests were conducted in the Institute of Mechanics of the Nizhny Novgorod State University and consisted of SHB and ballistic impact tests. The SHB tests included compression and tension experiments with different types of specimens. A series of SHB tests on tension and compression of pseudo-α titanium alloy VT20 specimens at normal and high temperatures were conducted. Main experimental results are as follows:

1. Increasing the temperature to 270 C leads to a decrease in the yield of 30% in tension and compression.
2. Diagram obtained in compression is at 30% above the diagram obtained in tension.
3. In tensile tests elongation at the grips was 24% and 29% at room and high temperature respectively, and the specimen contraction in the neck was 63% and 71%.

Compression tests

Dynamic compression tests were carried out on specimens of pseudo-α titanium alloy VT20. Strain rate was varied from 860 to 6000 1/s. Tests were conducted at 20 и 270 C temperatures.

Experimental results are shown in figures 1-3 below.

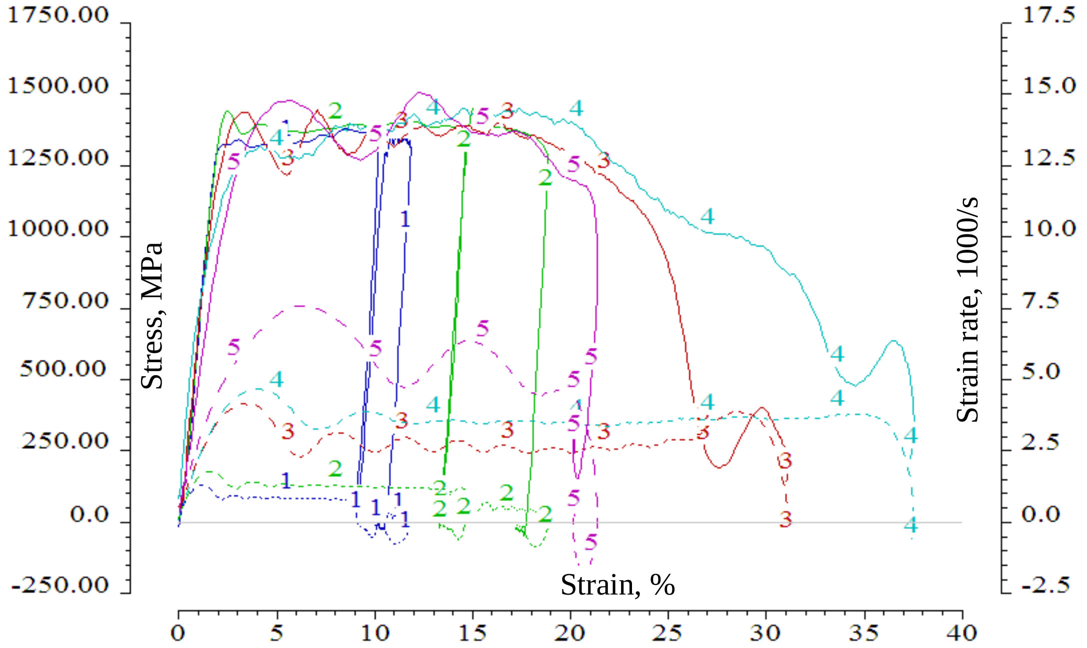


Figure 1. Compression dynamic test results. Strain rate dependency.

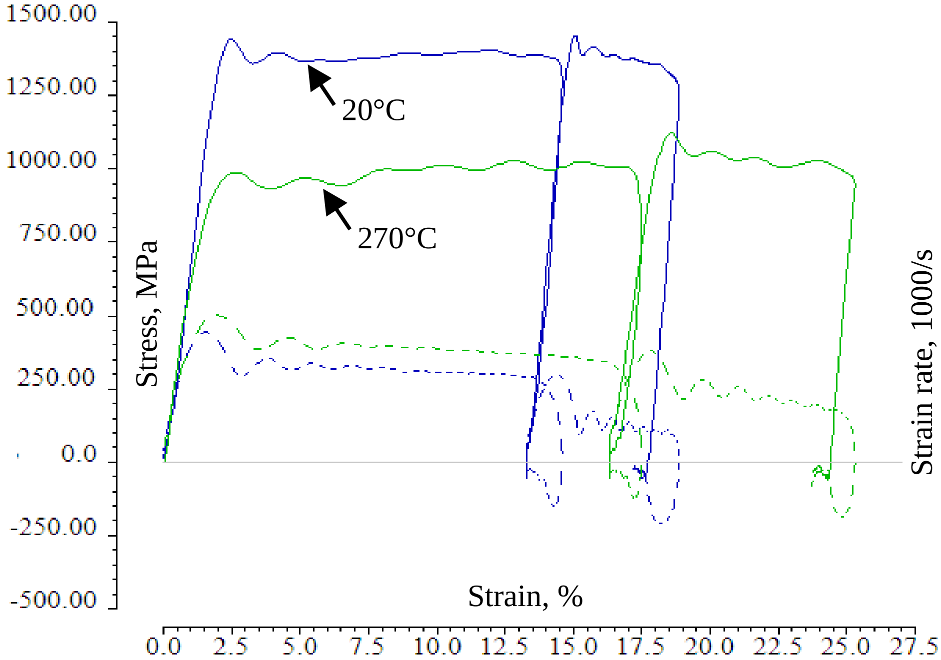


Figure 2. Compression dynamic test results. Temperature dependency.

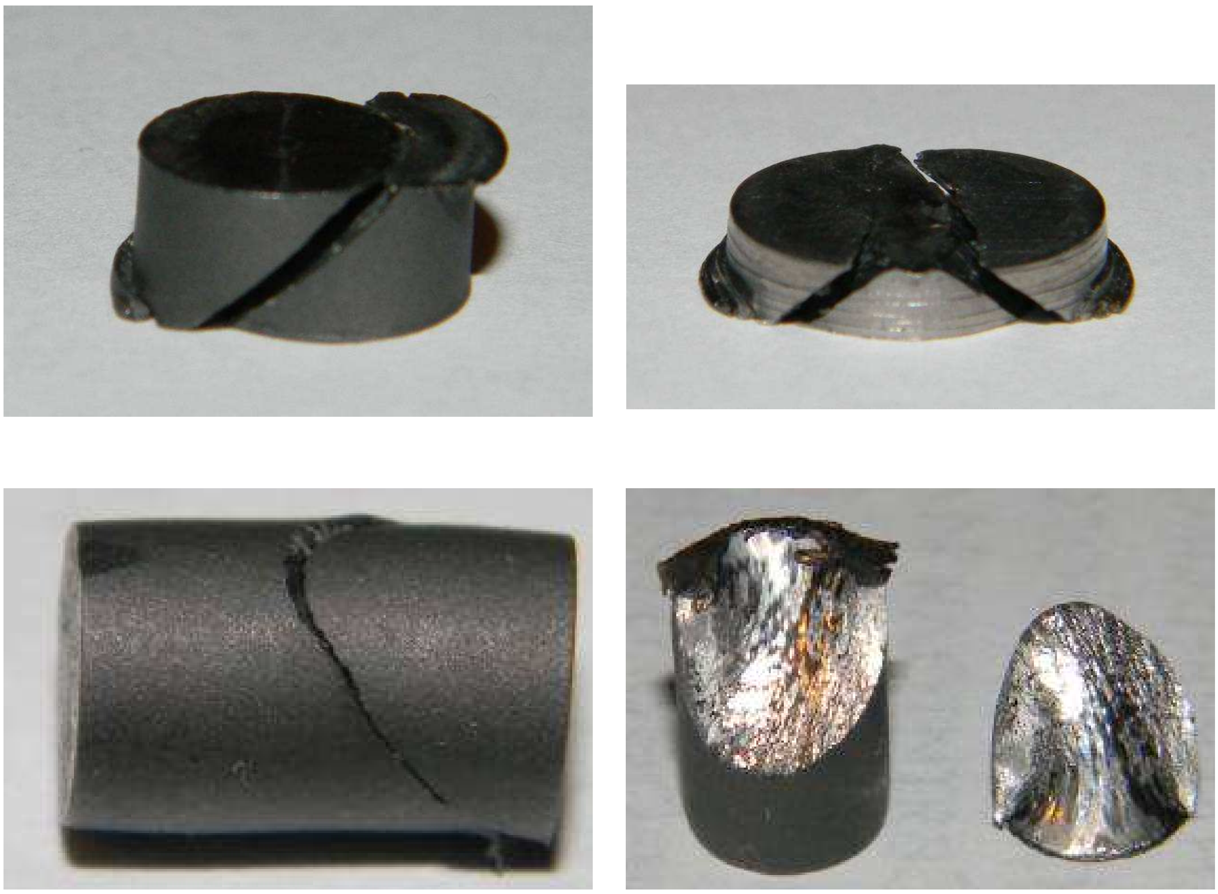


Figure 3. Cylindrical specimens after compression tests.

Tension tests

Tension tests were conducted at the strain rate range of 650-2300 1/s. Cylindrical and v-cut specimens were used. Test results for cylindrical specimens are shown in figure 4 for different temperatures and strain rates. Specimens after testing are shown on figure 5.

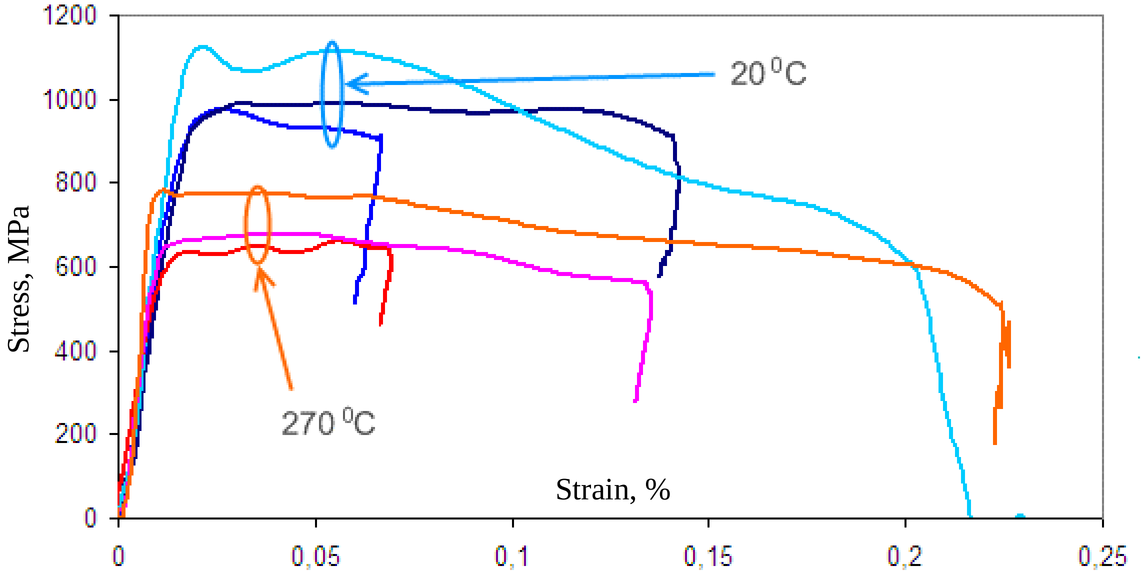


Figure 4. Tension test results.

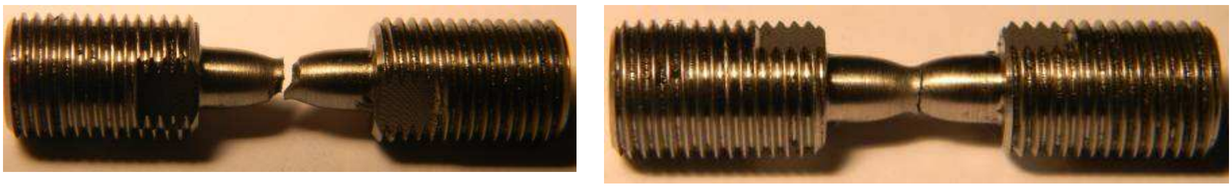
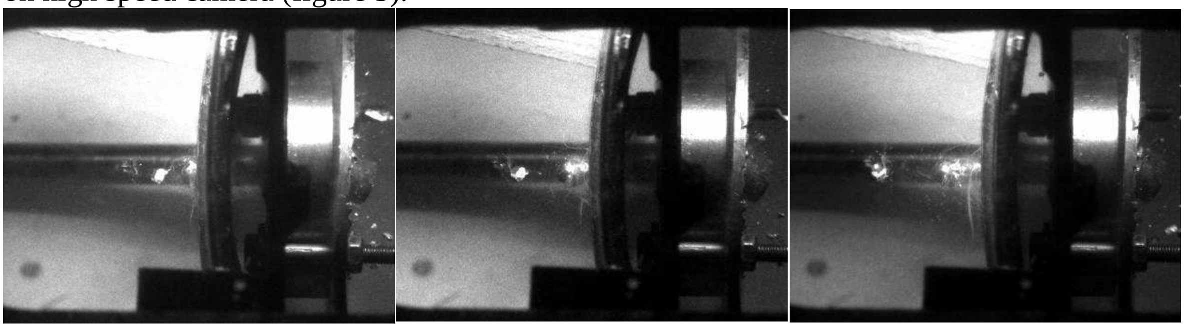


Figure 5. Specimens after tension.

Ballistic tests

Ballistic impact tests were conducted on curved titanium 2.5mm thick plates, cut from the turbojet fan case. 12mm steel balls were used as impactors. The impactor speed was varied from 250 to 350 m/s, with ballistic limit determined to be 290 m/s. The penetration process was filmed on high speed camera (figure 5).



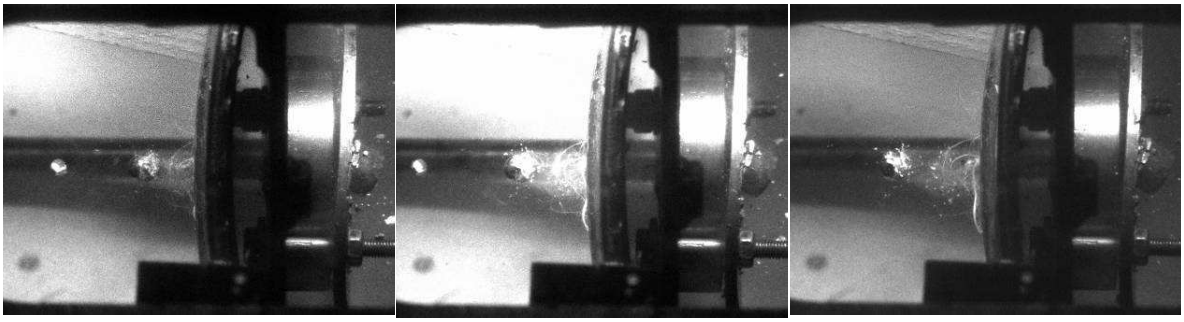


Figure 6. High speed photo of an impact penetration.

Analyzing the photos, the plug velocity and the impactor residual velocity were measured for each experiment.

Virtual experiments

Virtual experiments were conducted using nonlinear LS-DYNA code and consisted of the same series of tests that were made full-scale. Different material models were used with virtual simulations:

***MAT_024/*MAT_PIECEWISE_LINEAR_PLASTICITY** with simple failure criterion on effective plastic strain,

***MAT_224/*MAT_TABULATED_JOHNSON_COOK** with failure surface specified, and ***MAT_120_JC/*MAT_GURSON_JC.**

The stress-strain dependency for each model was given by series of curves at different strain rates which were obtained from the compression full-scale test results (figure 7).

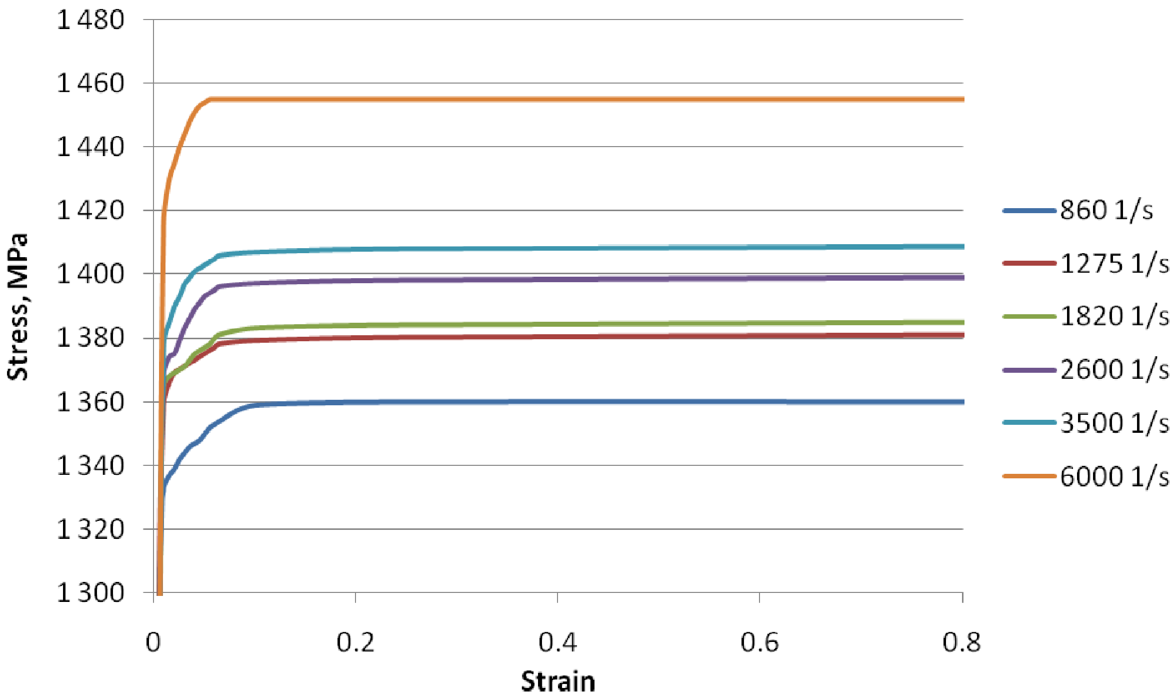


Figure 7. Stress-strain curves for different strain rates.

Failure criterion parameters of the models used were defined within the verification procedure of full-scale and virtual tests results comparison.

For ***MAT_024** there is no single criterion (effective plastic strain at failure) that describes all the series of experiments, so for each test the unique value of failure strain was used. For penetration tests the value of 20% gives the best result.

Failure surface obtained for ***MAT_224** as a result of verification impact penetration experiments is shown in figure 8. It shows the dependency of effective plastic strain at failure on triaxiality and Lode angle.

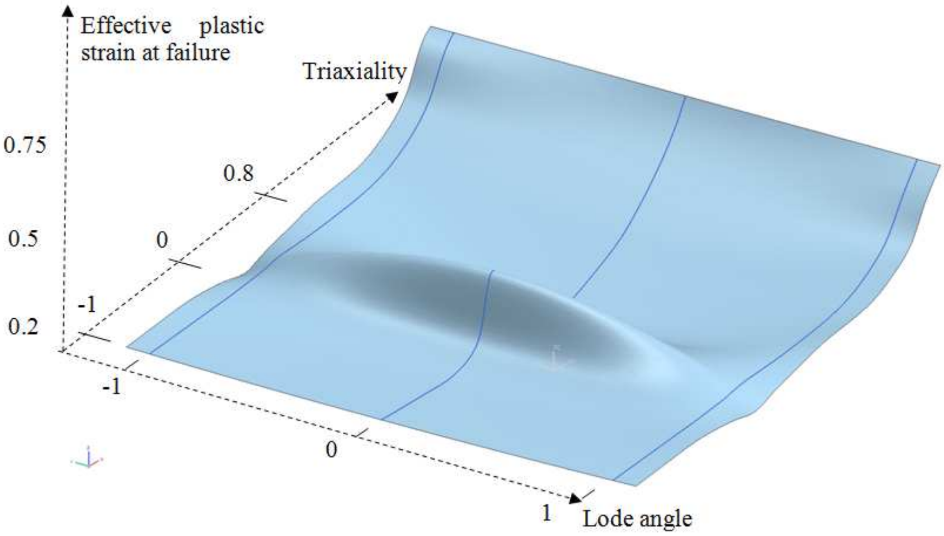


Figure 8. ***MAT_224** failure surface.

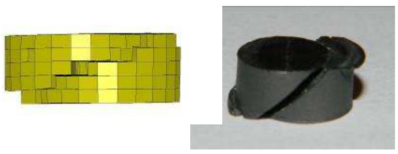
***MAT_120_JC** parameters used in virtual experiments are listed in table 1.

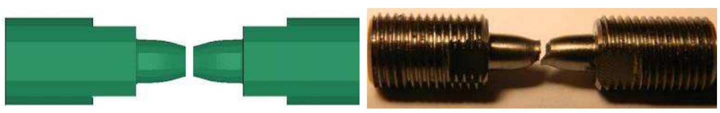
Table 1. *MAT_120_JC parameters.

f_C	ε_N	s_N	f_N	f_F	q_1	q_2	l_1	l_2	d_1	d_2	d_3	d_4
0,03	0,45	0,14	0,05	0,05	1,5	1	0,32	-0,34	-0,095	0,25	-0,5	0,014

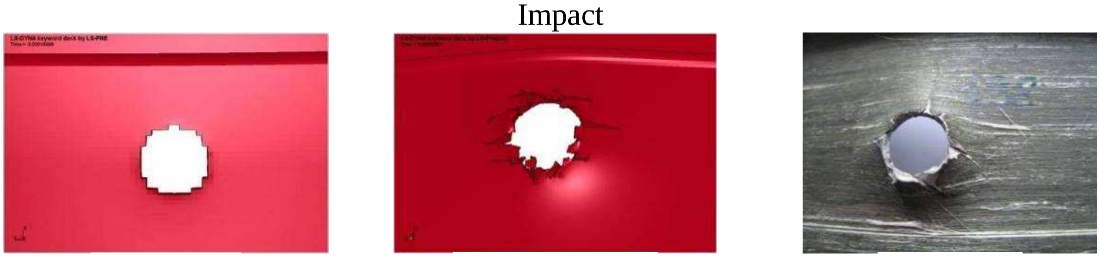
Figure 9 and table 2 compares the results of full-scale and virtual experiments, implementing different types of stress state. A comparison of various models for the impact penetration problem is also provided.

Compression **(*MAT_224)** Tension (***MAT_224**)





Impact



***MAT_024** ***MAT_120_JC** Experiment

Figure 9. Comparison of full-scale and virtual test result with different fracture criteria.

Table 2. Impact test results comparison for different fracture criteria.

№		Plate thickness, mm	Impactor velocity, m/s	Residual velocity, m/s	Plug velocity, m/s	Plug mass, g
1	Experiment	2.5	290	0	—	0,35
	*MAT_24				No plug	
	*MAT_224				219	0,3
	*MAT_120_JC				86	0,3
2	Experiment	2.5	333	149	240	0,33
	*MAT_24			143	No plug	
	*MAT_224			135	277	0,33
	*MAT_120_JC			146	276	0,35
3	Experiment	2.7	333	66		0.4
	*MAT_24			72	No plug	
	*MAT_224			52	261	0.315
	*MAT_120_JC			77	256	0.39

Conclusion

Adequate construction of the failure criterion involves an experimental study of fracture in different types of stress state, while experiments in tension and compression traditionally used for this purpose are not enough by force of a significant nonmonotonicity of fracture surface. On the basis of experimental studies the hypothesis about the complexity and the nonmonotonic dependence of the ultimate fracture strain on the type of stress state was confirmed and an attempt to describe this effect using various models of fracture was undertaken. Moreover, for the construction of fracture criteria in addition to traditional experiments in tension and compression of circular and notched cylindrical specimens ballistic impact tests were used. With the use of virtual verification experiments carried out using the nonlinear LS-DYNA code, the parameters for two models of fracture were defined.

References

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