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Laws of deformation processes and fracture of plastic steel from the point of view of dynamic overloading

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1. Introduction

Earlier it was shown by the authors [1,2], that due to dynamic redistribution of loading in statically indefinable systems in a plastic material such deformation processes could proceed which could be referred as not enough investigated. The obtained data about decreasing of materials resistance to plastic deformation as a result of the influence of dynamic overloading contradict the well-known data about increasing the resistance of metals to the deformation with deformation speed increasing at tensile - compression tests [3,4].

It should be noted, that in some cases of the dynamic loading, for example, in the dynamic hardness testing and in the experiments on the distribution of additional loading in the material loaded by a shock wave, the decrease of the material resistance to plastic deformation with increasing of deformation speed [5,6] also is deserved. All this testifies that the known phenomenological equations take into account not all the processes which arise in a metal at high speeds of deformations and, what is especially important, they do not take into account the influence of the history of preliminary loading.

In the known models describing high-speed deformation of a material, the stresses are schematically expressed as $\sigma = f(\varepsilon,\dot{\varepsilon},T)$, kinetic processes of damages accumulation, as a rule, being neglected. However, the performed experiments have shown, that under the influence of dynamic overloading the materials damage essentially changes that can lead to the change of deformation behavior.

In this paper an attempt is made to compare the levels of deformations jumps and the load under the influence of powerful dynamic pulses of different intensity at various stages of deformation of plastic steel, with the levels of damage jumps of the material.

2. Test technique and researched material

As an object of researches St20 low-carbon steel was chosen. All experiments were carried out at the Department of Strength of Materials of National Agrarian University of Ukraine on the installation for materials testing with complete stress-strain softening diagrams plotting [1]. The installation contains variable rigidity loading system, which is adapted for different loading modes (static tension - dynamic overloading - static tension) and computer-aided measuring system for data processing.

Smooth cylindrical specimens of 8 mm diameter and working part length of 25 mm were used. The tests were carried out at two stages. At the first stage a number of specimens were tested under conditions "static tension - dynamic overloading" with dynamic overloading on the sites of elasticity, hardening and softening. Fracture forces of fragile tests which provided dynamic overloading in the system were accordingly, 19.1 kN, 32.1 kN. The obtained results are shown in Fig. 1.

For micro structure condition analysis of the steel during dynamic overloading a phenomenological model of damage accumulation in metal is used [7]. As a parameter describing the speed of process at the set stage of deformation, the factor of cross-section deformation was accepted. The obtained data in Fig. 1 are grouped so that kinetics of changes of conditional and true stresses, and loosening deformations under the influence of dynamic overloads are evident.

The analysis of the data given in Fig. 1, a shows, that dynamic overloading changes the deformation processes of the steel greatly. And, under the influence of dynamic overloading an essential jump of loosening deformation is fixed. Thus the module of elasticity of a material can be decreased in hundreds times. For example, for the tested specimen No13 (Fig. 1) the module of elasticity under dynamic overloading was decreased approximately in 140 times. Dangerous jumps of deformations up to several percent are observed. Dynamic pulse intensity is influenced by occuring processes.

Similar effects are also revealed on the site hardening of material, and practically at all dynamic overloading the strength decrease of the material (Fig. 1, b) is observed. The increase of dynamic pulse intensity results in an intensification of softening process in the material, the depth of stress jump and the width of deformations jump increased.

The feature of a material behaviour under the influence of dynamic overloading on the falling stress-strain diagram line is that it is possible to choose such a value of dynamic pulse, under the influence of which the specimen can practically be divided into two parts. The technique of tests provides continuous fixing of loading not only in a tested specimen, but also in all parallel elements and in the system as a whole, therefore it is easy to calculate the redistribution of dynamic pulse between the specimen and parallel elements and, the limiting value of dynamic pulse for the tested specimen.

Similar effects were observed earlier at testing reactor steel [2].

For the estimation of the influence of damage jump the materials resistance to deformation, special experiences have been carried out to influence a specimen by a powerful dynamic pulse of the intensity (Fig. 2)

$$q = \int_0^t P dt = 19.1 \text{ kN} \cdot \text{sec} \quad .$$

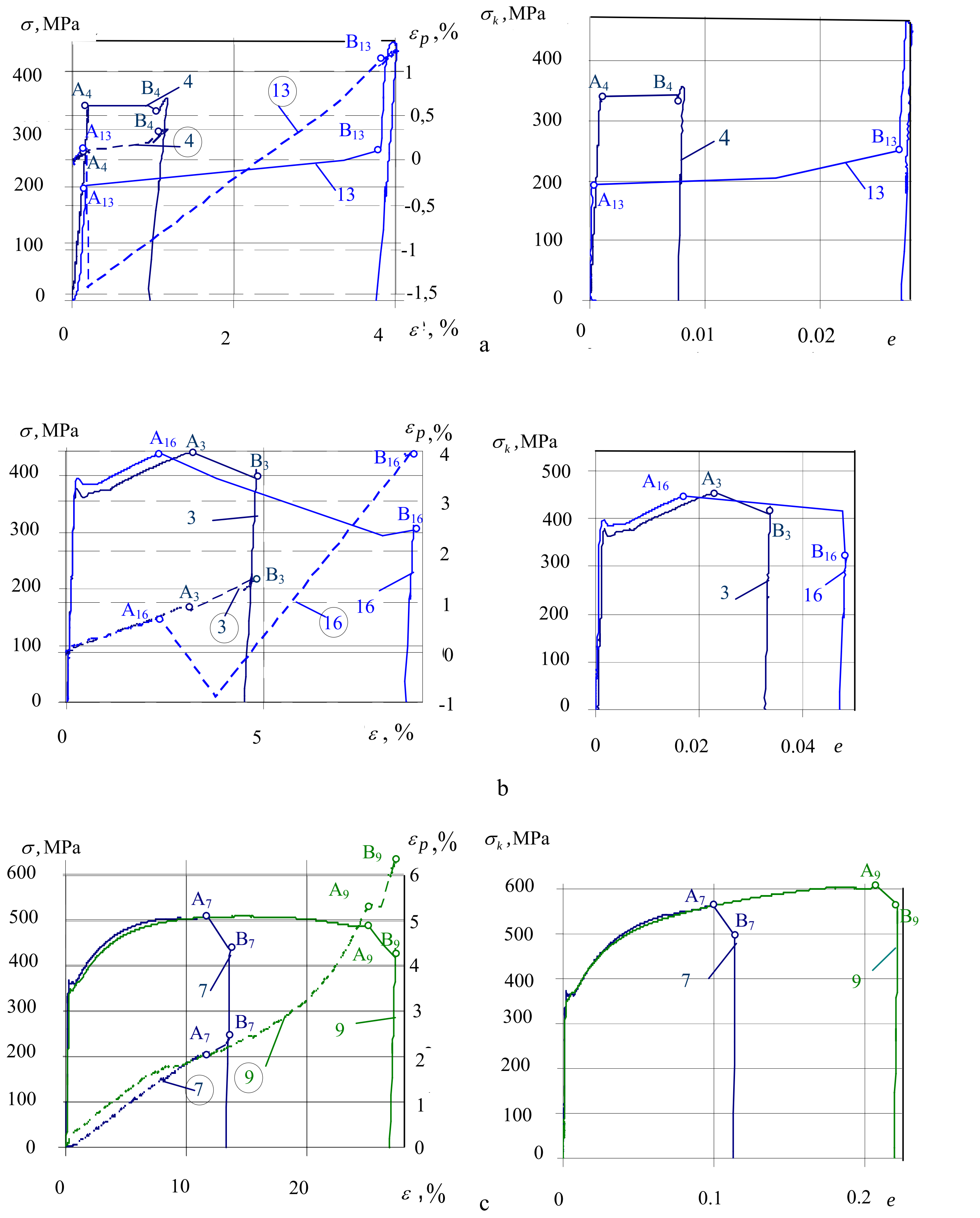

Fig. 1 Fragments of stress-strain diagrams of steel St20 with a dynamic overloading: a - on the site of elasticity; b - on the site of hardening; c - on the site of softening (*3, 4, 7, 9, 13 ,16* - numbers of the tested specimens)

The data given in Fig. 2, convincingly testifies that for all tested specimens the influence of metal warming up in adiabatic process of its plastic deformation lowering strength, prevails over the influence of hardening due to the increase of viscosity. For the further analysis of experimental results the following working hypothesis has been accepted. If during a dynamic overloading process the essential jump of loosening deformation is in addition fixed the material softening will be intensified due to mutual influence of thermal warming up and loosening the material. In fact the laws of change of true stress during dynamic overloading will considerably differ for the cases of insignificant and essential jump of loosening deformation. The comparison of curves *17* and *16*, *18* in Fig. 2 confirms the proposed working hypothesis.

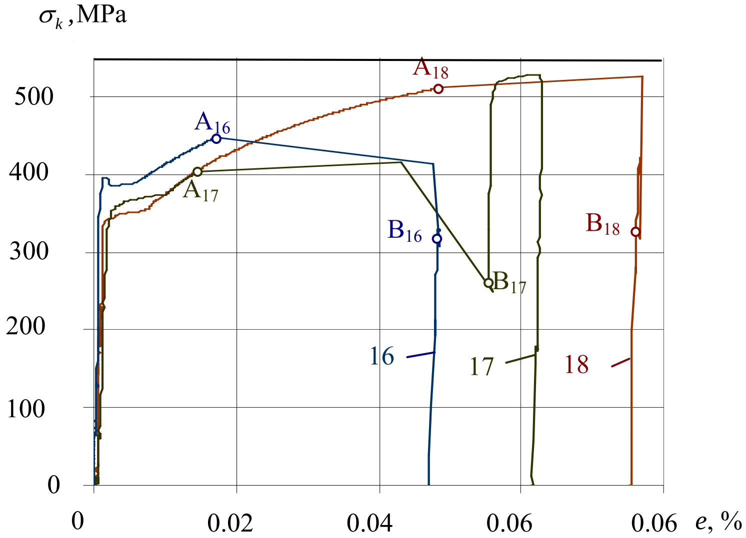

Fig. 2 Fragments of stress-strain diagrams of steel 20 with dynamic overloading at a stage of hardening (*16, 17, 18* - numbers of the tested specimens)

After the first stage of tests the specimens were maintained for some hours, and then they were repeatedly statically loaded up to their partial or full division into parts with plotting the complete stress-strain softening diagrams. Thus, the increase of strength of metal to the deformation for all tested specimens was observed at a second tension in comparison with "merely" static tension (Fig. 3). Thus, Cottrell's theory proves that for endurance of specimen there is an opportunity again to be condensed by impurity dislocation atmospheres and the most part of dislocations which under the influence of dynamic overloading take off the dislocation and began to move, is repeatedly blocked by dislocation.

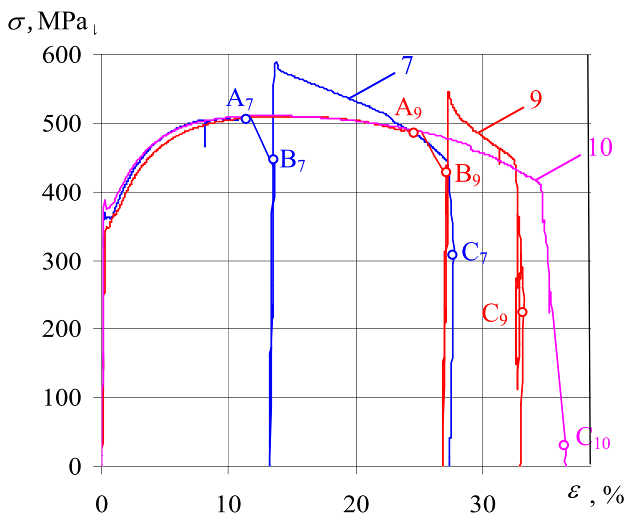

Fig. 3 Complete stress-strain softening diagrams of steel St20 (*7, 9, 10* - numbers of tested specimens); *7, 9* - under dynamic overloading; *10* - static tension

Like in papers [2,7] in the present research the specific work of fracture A_f as the parameter estimating limiting damages of steel was accepted.

The comparison of specific work of fracture A_f of the investigated steel at static tension and the influence of dynamic overloading of one intensity taken in to account at different stages of deformation, has allowed to establish the most dangerous rates of deformations under the influence of dynamic overloading (Fig. 4). It turned out, that the minimal values of specific work of fracture A_f are observed under the influence of dynamic overloading on yield drop and ultimate strength limit of the steel. It is interesting to note, that dynamic overloading on initial

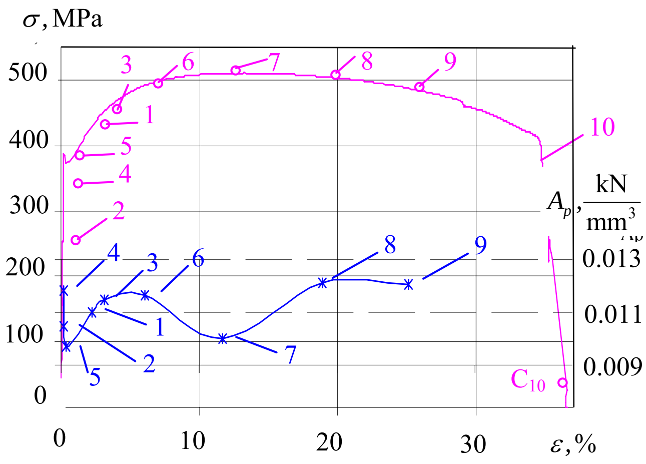

Fig. 4 Rates of deformation of steel St20 at dynamic overloading and corresponding to it values of specific work of fracture A_p (*1, 2, 3, 4, 5, 6, 7, 8, 9, 10* - numbers of the tested specimens)

zones of stress-strain diagrams can even increase specific work of fracture of the steel. However, the dynamic overloading carried out at advanced "gudgeon" of specimens resulted in essential reduction of parameter A_f and in the present research these data are not given. In the view of the influence of dynamic overloading one can try to explain the revealed features of the deformation process from the point of view of an estimation of current damages of a material. Taking into account, that characteristic points on the stress-strain diagram (on the yield drop and ultimate strength of a material) characterize transitive sites of S-shaped curve of the accumulation of damages in the material at static tension (the beginning of voids growth and their merge) [7], therefore just in these points it should be expected the greatest effects under the influence of dynamic overloading.

3. Modelling of processes of deformation and fracture

On the basis of the obtained experimental data file at modelling processes of deformation and fracture of plastic steel taking in to account the influence of dynamic overloading two approaches are offered and approved.

The first approach is based on known Johnson-Cook's [8] equation which assumes the independence of the influence of deformation hardening, speeds of plastic deformation and the rise of temperature at the change of loading speed. Taking into account the essential growth of damages under the influence of dynamic overloading, in Johnson-Cook's equation the fourth independent function is used. Hence, the resistance of a material to deformation under the influence of dynamic overloading can be described by the expression as products of four functions

$$\sigma = f_1(\varepsilon) f_2(\dot{\varepsilon}) f_3(T) f_4(\varepsilon_p) \quad (1)$$

In overwhelming majority of cases the influence of deformation hardening and thermal softening of materials is described by power dependences, and the influence of the speed of deformation can be taken into account as logarithmic dependence. In the present research the influence of damages growth of the decrease of material resistance to deformation also is described by power dependence. Thus, the constitutive equation can be written as follows

$$\sigma = \sigma_{0.2}\left(1 + A\varepsilon^n\right)\left(1 + B\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\left(1 - CT_*^m\right)\left[1 - \left(\frac{\varepsilon_p}{\varepsilon}\right)^{\alpha+1}\right]^{\frac{1}{r+1}} \quad (2)$$

where $\sigma_{0.2}$ is yielding strength of the material; *A*, *B*, *C* are constants of the material; n is a factor of deformation hardening; $\dot{\varepsilon}_0 = 1 \cdot \mathrm{sec}^{-1}$; $T_* = \frac{\Delta T}{T_{melt}}$; T_{melt} is the temperature of material melting; m is the factor which is taking into account the influence of temperature; ε_p is loosening deformation; α, r are the factors which are taking into account the influence of temperature and speed of deformation. In the first approximation it is possible to accept α, $r = 0$.

Using the equation (2) it is possible to show, that under the influence of dynamic overloading on decreasing of resistance of the metal both thermal softening and damage growth of the material influence to the same extent.

In the other approach for the description of the process of deformation and fracture of plastic materials taking in to account the dynamic overloading the interconnected multiparameter nonlinear function is accepted.

In the paper [9] the model which qualitatively predicts transformation of the complete stress-strain softening diagram at a crack-tip taking in to account the real properties of a material and a kind of an intense state is offered. In the given model for the description of stress distribution in the zone of pre-fracture the two-parametrical nonlinear function which consists of two parts is accepted: power dependence, that describes hardening of the material matrix and exponential, that describes the features of damage accumulation in the material in the view of a kind of an intense state and an operating time

$$\sigma = \sigma_{0.2}\left(x/R\right)^n \left(1/B\right)^{(3K_\sigma - 1)(1 - x/R)} \quad (3)$$

where $\sigma_{0.2}$ is yielding strength of the material; x is the current distance from a crack-tip; R is the extent of plastic zone; n is a factor of deformation hardening; B is the characteristic of sensitivity of the material to a kind of an intense state concerning accumulation of damages; K_σ is Bridgman's parameter.

For the description of the process of deformation and fracture of plastic materials at all stages we shall accept opposite to the formula (3) the function to increase the sensitivity of the function to real processes of deformation and fracture in exponential parts of the function we shall enter additional factor $\alpha = n/B$. Then physical correlation can be written as

$$\sigma(\varepsilon) = \begin{cases} \sigma_{0,2}\left(\varepsilon_{el}/\varepsilon_{0,2}\right), & 0 \le \varepsilon_{el} \le \varepsilon_{0,2}; \\ \sigma_{0,2}\left(1 - \dfrac{\varepsilon_{pl}}{\varepsilon_{eq}}\right)^n \left(\dfrac{1}{B}\right)^{\left[(3K_\sigma - 1)\left(\varepsilon_{pl}/\varepsilon_{eq}\right)\right]^\alpha}, & 0 \le \varepsilon_{pl} \le \varepsilon_{eq}; \\ 0, & \varepsilon_{pl} > \varepsilon_{eq}; \end{cases} \quad (4)$$

where ε_{el} is elastic deformation; ε_{pl} is plastic deformation; $\varepsilon_{0.2}$ is the deformation which corresponds to yielding strength of the material; ε_{eq} is limiting deformation for completely equilibrium state. The results of the carried out experiments have shown, that the equations (4) well describe the complete stress-strain softening diagrams of a wide class of plastic materials due to the change of two factors n and B. And as it was noted above [9], $0 \le n, B \le 1$.

It proved, that due to the introduction in the equations (4) of additional functions $F(Pdt)$, which take into account the influence of dynamic overloading, it is possible to describe such complex modes of deformation as “static tension - dynamic overloading - static tension”.

Function $F(P \cdot dt)$ looks like

$$F(Pdt) = d\left|(\varepsilon - \varepsilon') - 1\right| exp^{-s(|(\varepsilon-\varepsilon')|+a(\varepsilon-\varepsilon'))} \qquad (5)$$

where d, s and a are the interconnected parameters which determine the stress jump depth and deformations jump width at the dynamic overloading, ε' is the deformation at which the dynamic overloading is carried out.

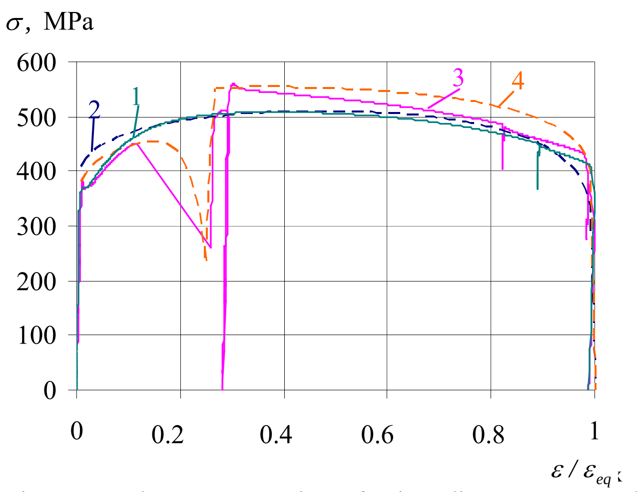

Fig. 5 Complete stress-strain softening diagrams of steel St20: *1, 3* - experimental data; *2, 4* - results of machine experiment

Thus it is should be taken into account, that during the dynamic overloading the deformation hardening (softening) and damage of the material, that is new values of parameters n and B in the equations (4) and at the subsequent static tension in the equations (4) are substituted.

It is noted, that as the equations (4) are giving the relative value, the limiting deformation for completely equilibrium state is accepted at modelling as known.

The complete characteristic stress-strain softening diagrams of the investigated steel given at static tension and in the view of dynamic overloading and the results of experiment with the use of equations (4), (5) are shown in Fig. 5.

From Fig. 5 it is seen, that the results of the carried out experiment are well coordinated with experimental data that proves the theoretical preconditions made in equations (4, 5).

3. Conclusions

1. It is established, that dynamic overloading carried out on any section of deformations, starting with elastic, greatly change the processes of steel deformation. An essential part in decreasing the strength of plastic deformation influence the damage growth in material during a dynamic overloading.

2. It is shown, that for the tested steel the most dangerous is the dynamic overloading carried out on yield drop and ultimate strength. The range of disorder of specific work of steel fracture, in the view of the influence of dynamic overloading of one intensity at different stages of deformation, achieves 30 %.

3. On the basis of new experimental data two approaches for modeling of the processes of deformation and fracture of plastic steel in the view of the influence of dynamic overloading are offered and approved.

References

1. **Chausov, N.G., Pilipenko, A.P.** Influence of dynamic overloading on fracture kinetics of metals at the final stages of deformation.-Mechanika.-Kaunas: Technologija, 2004, Nr.3(48), p.3-18.
2. **Чаусов Н.Г., Недосека С.А., Пилипенко А.П.** Комплексная оценка поврежденности пластичных материалов при различных режимах нагружения. -Техническая диагностика и неразрушающий контроль, 2004, No3, с.16-21.
3. **Трощенко В.Т., Красовский А.Я., Покров-ский В.В., Сосновский Л.А., Стрижало В.А.** Сопротивление материалов деформированию и разрушению. Справочное пособие.-Киев: Наук. Думка, 1994, ч.2. -702с.
4. **Степанов Г.В.** Анализ кривых деформирования металлов при растяжении с учетом влияния скорости нагружения и температуры.-Пробл. прочности, 1995, No7, с.68-75.
5. **Степанов Г.В.** Сопротивление материалов деформированию при ударном нагружениии.-Пробл. прочности, 2002, No3, с.7-14.
6. **Канель Г.И., Разоренов С.В., Уткин А.В., Фортов В.Е.** Исследования механических свойств материалов при ударно-волновом нагружении.-Изв. РАН, МТТ, 1999, No5, с.173-188.
7. **Лебедев А.А., Чаусов Н.Г.** Новые методы оценки деградации механических свойств металла конструкций в процессе наработки.-Киев, 2004.-133с.
8. **Johnson, G.R., Cook, W.H.** A constitutive model and data for metals subjected to large strains, high strain rates and high temperatures.-Proc. of the 7th International Symposium on Ballistics.-Den Haag, Netherlands, 1983, p.541-547.
9. **Чаусов Н.Г., Богданович А.З.** Моделирование кинетики деформирования металла в зоне предразрушения.-Пробл. Прочности, 2003, No2, с.54-65.

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PLASTIŠKOJO PLIENO DEFORMAVIMO IR SUIRIMO PROCESŲ DĖSNINGUMUI ĮVERTINUS DINAMINIŲ PERKROVŲ ĮTAKĄ

R e z i u m ė

Darbe bandyta atitinkamo intensyvumo dinaminių jėgos impulsų paveikto mažaanglio plieno deformacijų ir apkrovų šuolių lygius palyginti su medžiagos pažeidžiamumo lygiais.

Detaliai išanalizuota dinaminių perkrovų, pasireiškiančių įvairiose deformavimo stadijose įtaka plieno suirimo kinetikai. Nustatyta, kad bandytam plienui pavojingiausios dinaminės perkrovos pasireiškia aukščiausiame takumo taške ir stiprumo riboje.

Remiantis naujais eksperimentų duomenimis pasiūlyti ir aprobuoti du nauji būdai plastiškųjų plienų deformavimui ir suirimui modeliuoti atsižvelgiant į dinaminių perkrovų poveikį.

M.G. Chausov, A.P. Pylypenko

LAWS OF DEFORMATION PROCESSES AND FRACTURE OF PLASTIC STEEL FROM THE POINT OF VIEW OF DYNAMIC OVERLOADING

S u m m a r y

In this paper an attempt to compare the levels of the jumps of deformations and loadings is undertaken under the influence of a powerful dynamic pulse of the set intensity in testing low-carbon steel, with a level of current damages of the material.

The influence of the dynamic overloading which are carried out at different stages of deformations, on kinetics of steel fracture is analysed in details.

It is shown, that for the tested steel the most dangerous is the dynamic overloading which is carried out on yield drop and ultimate strength.

On the basis of new experimental data two approaches for modelling of the processes of deformation and fracture of plastic steel are offered and approved in the view of the influence of dynamic overloading.

Н.Г. Чаусов, А.П. Пилипенко

ЗАКОНОМЕРНОСТИ ПРОЦЕССОВ ДЕФОРМИРОВАНИЯ И РАЗРУШЕНИЯ ПЛАСТИЧНОЙ СТАЛИ С УЧЕТОМ ВЛИЯНИЯ ДИНАМИЧЕСКИХ ПЕРЕГРУЗОК

Р е з ю м е

В данной работе предпринята попытка сопоставить уровни скачков деформаций и нагрузки в процессе воздействия силового динамического импульса заданной интенсивности при испытании малоуглеродистой стали, с уровнем текущей поврежденности материала.

Детально проанализировано влияние динамических перегрузок, осуществляемых на разных стадиях деформаций, на кинетику разрушения стали.

Показано, что для испытанной стали наиболее опасными являются динамические перегрузки, осуществляемые на зубе текучести и пределе прочности.

На базе новых экспериментальных данных предложены и апробированы два подхода для моделирования процессов деформирования и разрушения пластичной стали с учетом воздействия динамических перегрузок.

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