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DETERMINATION OF DYNAMIC CHARACTERISTICS OF AUSTENITIC STEEL TO BE UTILIZED IN FEM SIMULATION AND ITS VERIFICATION

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ABSTRACT

This paper presents the dynamic mechanical properties of austenitic steel with improved durability, which is used in the construction of hulls of minesweepers, mine destroyers, submarines and other naval vessels. Dynamic tensile tests performed on the steel samples using a rotary hammer with a strain rate of up to 1000 s-1 allowed determination of elastic-plastic characteristics of the material in the form of a polynomial of Johnson-Cook constitutive model, taking into account the influence of strain rate and temperature. A characteristic of this type is utilized in numerical calculations in the CAE software. The obtained characteristics were experimentally verified by bending tests of flat samples with a drop-weight type impact hammer. Simultaneously numerical calculations were performed in order to compare the deformation state.

Key words:

dynamic characteristics of material, drop-weight type impact hammer, rotary hammer, Johnson-Cook constitutive model.

Research article

INTRODUCTION

Continuous improvement in computing power has a direct influence on the development of computer techniques and the computer aided engineering (CAE) software employed for mechanical analysis of structures. Advanced algorithms of the finite element method (FEM) in a dynamic explicit approach makes it possible to analyse moving objects, taking into account the forces of inertia where a fundamental equation of motion is described by the formula [1, 2, 7, 10]:

$$\boldsymbol{M\ddot{U}} + \boldsymbol{C\dot{U}} + \boldsymbol{KU} = \boldsymbol{F} \tag{1}$$

where:

$\boldsymbol{M}$ — inertia matrix;
$\boldsymbol{C}$ — damping matrix;
$\boldsymbol{K}$ — structural rigidity matrix;
$\boldsymbol{F}$ — load vector;
$\boldsymbol{U}, \boldsymbol{\dot{U}}, \boldsymbol{\ddot{U}}$ — displacement, velocity and acceleration vectors.

FEM solves the equations of motion using direct integration methods, also called step by step methods, which engulf central difference, Houbolt, Newmark, Euler and Wilson methods [3–5, 7, 8].

Recent years have brought a progress in algorithms allowing analysis of highly dynamic processes. They are applied in automotive, aerospace and military industry and utilized for simulation of such hazards as the collision of objects, punch-through of armour with bullet, detonation wave impact on vehicles, ship hull impact of pressure wave originating from non-contact explosion of floating mine, etc. shown fig. 1.

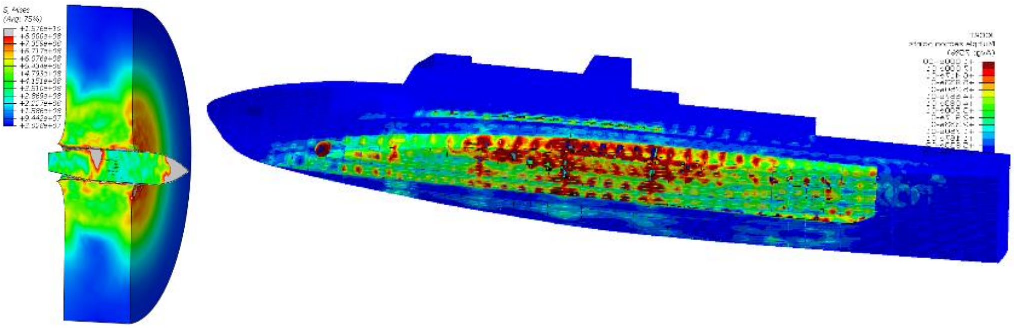

Fig. 1. Examples of highly dynamic processes: punch-through of steel armour with bullet, ship hull impact of pressure wave originating from mine explosion

DYNAMIC CHARACTERISTICS OF AUSTENITIC STEEL

The aforementioned problems are highly non-linear due to load character, construction material behaviour, significant deformation of structure and other factors taken into account during the analysis, for instance contact forces between the colliding elements of the structure. Then an exemplary equation of motion takes the form [11]:

$$\boldsymbol{M}(\boldsymbol{U})\ddot{\boldsymbol{U}} + \boldsymbol{C}\dot{\boldsymbol{U}} + \boldsymbol{K}(\boldsymbol{U}, \dot{\boldsymbol{\varepsilon}}, \boldsymbol{\varepsilon}_{\text{failure}})\boldsymbol{U} = \boldsymbol{F}(t, m, v_{\text{c}}, \alpha, \text{BC}, C_{\text{int}}, \text{A}, \text{B}, \dots) \tag{2}$$

$$\boldsymbol{U}(t_0) = \boldsymbol{U}_0 \qquad \dot{\boldsymbol{U}}(t_0) = \dot{\boldsymbol{U}}_0$$

where:

$\boldsymbol{K}$	— structural rigidity matrix;
$\boldsymbol{M}$	— inertia matrix;
$\boldsymbol{C} = \alpha\boldsymbol{M} + \beta\boldsymbol{K}$	— damping matrix, where α and β are constant coefficients [5];
$\boldsymbol{U}, \dot{\boldsymbol{U}}, \ddot{\boldsymbol{U}}$	— displacement, velocity and acceleration vectors;
$\boldsymbol{U}_0, \dot{\boldsymbol{U}}_0$	— initial conditions of displacement and velocity;
$\boldsymbol{F}$	— load vector;
$\dot{\boldsymbol{\varepsilon}}$	— strain rate vector;
$\boldsymbol{\varepsilon}_{\text{failure}}$	— failure strain vector;
t	— time;
m	— mass of explosive (shrapnel);
v_{c}	— speed of sound in water (air);
α	— incidence (reflection) angles of pressure wave with respect to element (shrapnel);
BC	— influence of boundary conditions;
C_{int}	— interactions and contact forces between colliding elements of structure;
A, B, ...	— other parameters influencing on load of the construction.

The above parameters of this model are defined based on static tensile test and Hopkinson's or Taylor's tests. For the strain rate up to 1000 s-1 these parameters can be determined with dynamic tensile test using a rotary hammer.

This paper presents dynamic characteristics obtained with the use of the rotary hammer for austenitic steel 1.3964 subjected to heat treatment W72387 (hot rolled, solution annealed, pickled) according to the standard EN 10029-11. Austenitic steels are applied in shipbuilding industry. Due to their enhanced durability and non--magnetic properties austenitic steels are used for construction of hulls of minesweepers, mine destroyers, submarines and other naval vessels. The rotary hammer (fig. 2) is a tensile testing machine, in which one end of a sample (fig. 3) is fixed. The sample is subjected to dynamic tension via gearing of its other end with a tooth moving with a velocity ν due to rotational speed of the hammer's flywheel.

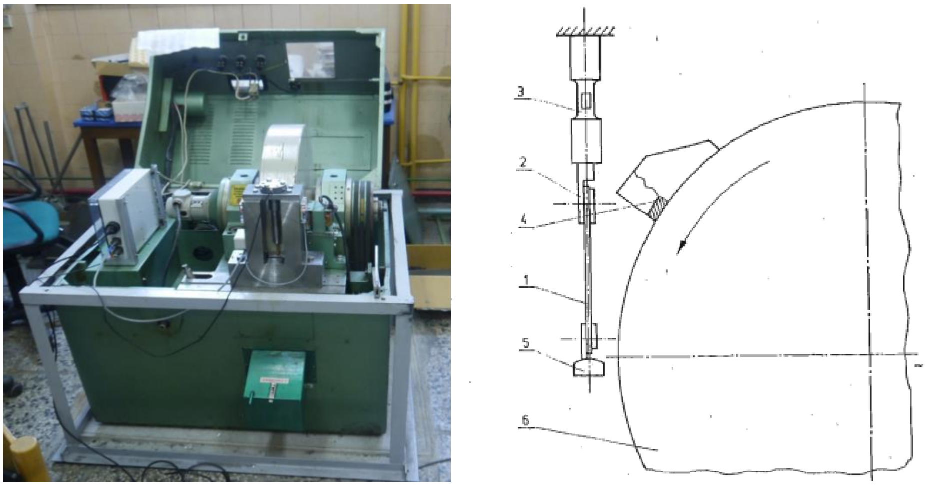

Fig. 2. Scheme of tensile test using rotary hammer: 1 — sample, 2 — upper holder, 3 — dynamometer, 4 — tooth, 5 — lower holder, 6 — flywheel

Fig. 3. A photo of selected samples prior to investigation using rotary hammer

Having obtained the results of static tensile test performed on a MTS tensile testing machine and the results of dynamic tensile test carried out with the rotary hammer for the strain rate up to 1000 s-1, a characteristics of steel 1.3964 was determined (fig. 4). Detailed methodology of determination of dynamic characteristics and Johnson-Cook equation's coefficients is provided in the paper [6].

A rotary hammer with a strain rate of up to 1000 s-1 was used and a characteristic of steel 1.3964 was determined (fig. 4). Detailed methodology of determination of dynamic characteristics and Johnson-Cook equation's coefficients [6] is provided in the paper [11].

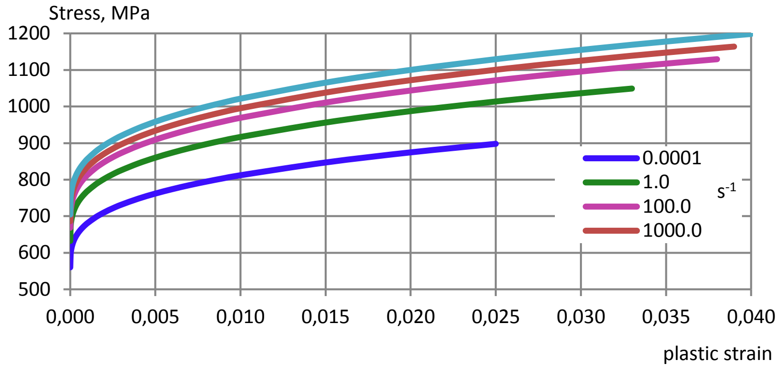

Fig. 4. Characteristics of steel 1.3964 for different strain rates:
A = 550 MPa, B = 1100 MPa, n = 0.32, m = 1.13, θ_{top} = 1793 K, θ_0 = 293.15 K, C = 0.006, $\dot{\varepsilon}_0$ = 0.0001 s^{-1};
the remaining parameters are as follows:
young's modulus — $E = 2.1 \cdot 10^5$ MPa, poisson ratio — ν = 0.3, static yield stress — $R_{e\,Stat}$ = 560 MPa,
static ultimate strength — $R_{m\,Stat}$ = 880 MPa

Dynamic characteristics of steels or other materials determined for the CAE simulation must be verified experimentally. A series of bending tests of flat samples made of previously investigated austenitic steel was carried out using a drop-weight type impact hammer. In this test a flat steel sample was struck with a rigid ram having a different mass — from 10 to 30 kg and different velocity — from 1 to 7 m/s (fig. 5).

Fig. 5. Bending test of flat sample using drop-weight type impact hammer

Simultaneously, a dynamic explicit type numerical simulation of analogous task was performed using the CAE software solving the following equilibrium equation [11]:

$$\boldsymbol{M}(\boldsymbol{U})\ddot{\boldsymbol{U}} + \boldsymbol{C}\dot{\boldsymbol{U}} + \boldsymbol{K}(\boldsymbol{U}, \dot{\boldsymbol{\varepsilon}})\boldsymbol{U} = \boldsymbol{F}(m, v_C, \mathrm{BC}, C_{\mathrm{int}}) \tag{3}$$

where

v_c — speed of sound in water (air).

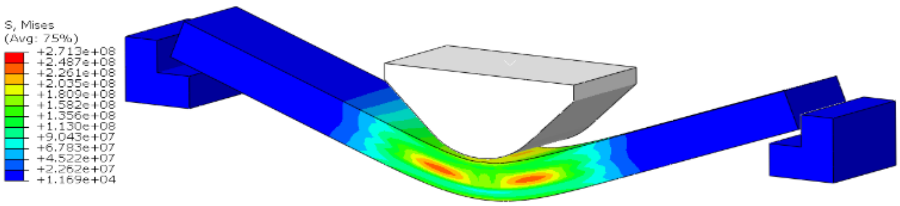

Fig. 6. CAE simulation of bending test on a flat sample using drop-weight type impact hammer

Material characteristics were subjected to numerous corrections and a number of simulations were performed for different ram mass and ram impact velocity searching for the best convergence with the experiment. A comparison of the results is presented in tab. 1.

Tab. 1. Comparison of results from experimental bending test and CAE simulation

No.	Ram height m	Initial length H, mm	Permanent bending upon drop-weight type impact hammer	Permanent bending upon numerical simulation mm
1	0,5	97	3,8	4,0
2	1,5	97	21,6	23,4
3	2,0	97	31,4	34,6

CONCLUSIONS

The determined material characteristics in the form of JC material model for austenitic steel, for a strain rate of up to 1000 s-1 can be utilized to simulate highly dynamic processes such as the collision of objects, analysis of armour resistance to machine gun fire or analysis of a structure subjected with a pressure wave originating from an explosion. The characteristics were acquired based on relatively inexpensive laboratory investigations including quasi-static tensile test on the MTS tensile testing machine and dynamic test with the rotary hammer for the strain rate up to 1000 s-1. The FEM simulation of dynamic bending of the flat sample using the drop-weight type impact hammer, in which the aforementioned characteristics were implemented in the form of a JC material model, provided satisfactory results compared to the experiment. As far as evaluation of structure resistance to impact is concerned, a model of material is only one of many important elements, which have an influence on the results obtained.

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WYZNACZANIE CHARAKTERYSTYKI DYNAMICZNEJ STALI AUSTENITYCZNEJ NA POTRZEBY SYMULACJI MES I JEJ WERYFIKACJA

STRESZCZENIE

W artykule przedstawiono dynamiczne właściwości mechaniczne stali austenitycznej o podwyższonej wytrzymałości, która jest wykorzystywana do budowy kadłubów trałowców, niszczycieli min, okrętów podwodnych oraz innych jednostek wojennych. Na podstawie dynamicznego rozciągania próbek na młocie rotacyjnym w zakresie prędkości odkształcenia do 1000 s-1 opracowano sprężysto-plastyczną charakterystykę materiału w formie wielomianu w postaci modelu konstytutywnego Johnsona-Cooka uwzgledniającego prędkość odkształcenia i wpływ temperatury. Charakterystyka tego typu wykorzystywana jest w obliczeniach numerycznych w programach CAE. Otrzymaną charakterystykę zweryfikowano, wykonując eksperyment udarowego zgięcia płaskownika na młocie opadowym, dla którego równolegle wykonano obliczenia numeryczne, porównując stan deformacji.

Słowa kluczowe:

dynamiczna charakterystyka materiału, młot rotacyjny, młot opadowy, model konstytutywny Johnsona-Cooka.

Article history

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