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Building and Validation of the Johnson–Cook Constitutive Model of Nano-Composite NANOS-BA® Steel for Armour Applications

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Abstract. Constitutive modeling of the NANOS-BA® steel is described in this article. Results of the experiments (quasi-static uniaxial tension and uniaxial compression, high strain rate compression with use of the Split Hopkinson Pressure Bar) are shown. On the basis of the experiments results, the values of constants of the Johnson–Cook (J–C) model for the NANOS-BA® steel were determined. Verification of the determined values of constants was described, in which the stresses and strains obtained in samples in experiments and simulations were compared. The additional verification of the determined parameter values was the comparison of the depth of penetration tests (*DP* tests) results of NANOS-BA® steel plates placed on the Armox 500T „witness" plate fired with a 12.7 mm B-32 projectile, obtained experimentally and in simulations. Small differences between simulation and the experiments results testify that the determined values of constants of J–C model for NANOS-BA® steel provide good agreement with experiments.
Keywords: numerical simulations of penetration, nanosteel, penetration of steel, API projectile

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1. INTRODUCTION

Numerical simulations are a popular and commonly applied engineer tool for the analysis of complex dynamic physical phenomena in high strain rate conditions. Widely available commercial computer hydro-codes (LS-Dyna, Autodyn) can simulate a body's behaviour in different load conditions, thanks to the use of different techniques of calculations. These programs allow the observation of dynamic phenomena (strain or stress changes in the material in every moment of simulation, etc.), the accurate analysis of which is difficult or impossible during tests.

The use of numerical methods in the initial stages of the armour designing process allows us to evaluate the effectiveness of developed constructions, without the necessity of constructing a prototype and conducting firing tests with it. It significantly reduces costs and time needed for the construction of new types of armour.

To obtain simulation results which are concurrent with tests results, reliable and accurate material models of armour and projectiles must be used during preparing the simulation. Building the correct numerical model for the given material requires determination of values of several parameters (material constants) in the material constitutive model. Many of these parameters show dynamic character, i.e. they change, depending on the strain rate. Therefore, in order to determine these values it is necessary to conduct expensive and accurate strength tests, both static and dynamic.

The building process of a numerical model of the nano-composite NANOS-BA® steel, used for armour applications, is described in this article. The developed in the Institute for Ferrous Metallurgy (Gliwice, Poland) high-carbon bainitic steels are characterised by yield strength of 1.3÷1.5 GPa, hardness of ca. 55 HRC and good ductility. Additionally, relatively low mass of alloying elements (5÷6%) makes cost of production of nano-structural bainitic steel lower than other steels, having similar strength properties (e.g. martensitic steels, maraging steels, etc.). Such qualities enable application of the bainitic steels in armours constructions, where high strength and impact resistance are required.

The NANOS-BA® steel numerical model, built on the basis of material constants obtained in tests, will be used for the preliminary numerical analysis of new armour designs, consisting, among others the NANOS-BA® steel plates within their construction.

2. EXPERIMENTAL TESTS

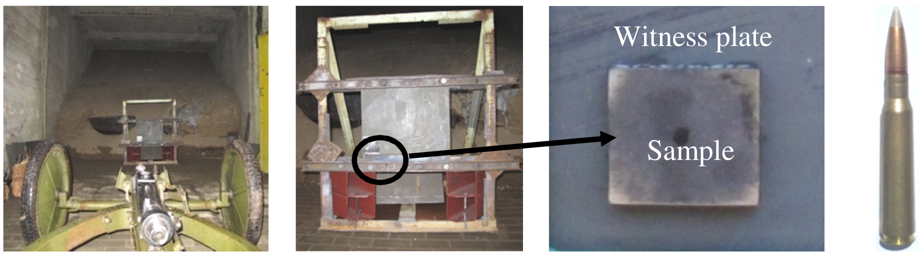
For the purpose of the construction and validation of the nano-composite NANOS-BA® steel numerical model, the following tests were performed:

1. static uniaxial tension,
2. static uniaxial compression,
3. compression under high strain rates, with the use of the modified Split Hopkinson Pressure Bar,
4. *DP* tests of the NANOS-BA® steel plates placed on Armox 500T „witness" plate, fired with the 12.7 mm B-32 type projectile.

Stress-strain curves, obtained as a result of carried out tests, allow the determination of the NANOS-BA® steel mechanical parameter values (elastic constants) and the J–C model material constants. These values were used to make simulations of tests. Based on the comparison of character and values of samples stress and strain obtained in simulations to the experiments results, the values of the failure model constants were determined. The verification of the numerical models were made by the comparison of the *DP* of the NANOS-BA® steel plates placed on the Armox 500T „witness" plate, fired with a 12.7 mm B-32 type projectile, obtained experimentally and in simulations.

Static uniaxial tension and compression tests were carried out on the universal material testing machine Instron 8802 with FastTrack control software. During tests, to measure the longitudinal and transverse strain, the strain rosettes and bridge were used. The strain measurements with the rosettes were carried out to obtain the value of the longitudinal strain 0.05 and transverse strain 0.025. During static compressive tests, to strain measurement, the longitudinal extensometer with a 12.5 mm measuring base and the ±5 mm range was used. Measuring signals were converted by the computer with special extensometer software.

Compression tests under high strain rates were carried out with the use of the modified Split Hopkinson Pressure Bar stand. The Tasler LTT500 preamplifier and the NOR USB-6366 measuring card was used to amplify signals from measuring bars.



a b c d

Fig. 1. The 12.7 mm ballistic barrel (a), the frame to fix the Armox 500T plate (b), the way of placing the sample on the witness plate (c), 12.7 mm cartridge with the B-32 type API projectile (d)

Armox 500T plates *DP* tests were carried out on the range of the Military Institute of Armament Technology in Zielonka (Poland).

The NANOS-BA® steel plates of a size of 50 × 50 × 5 mm were placed on the Armox 500T „witness" plate of 500 × 500 × 10 mm size. Elements of the *DP* testing stand and the projectile used in the firing tests are shown in Figure 1.

Samples for tests were prepared from cubicoid bainitic NANOS-BA® steel plates. The semi-finished elements for samples to tension and compression tests were cut out with the use of a water-cutting machine. The method of preparing the semi-finished elements from the plate is shown in Figure 2.

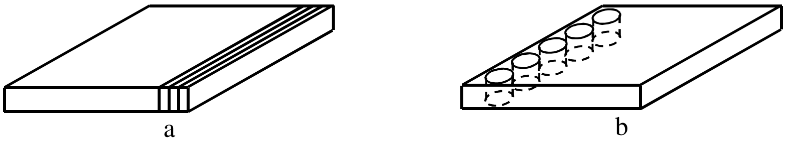


Fig. 2. The method of preparing of samples: a – to tension tests, b – to compression tests

After cutting out from the semi-finished elements, the samples for the tension tests were grinded to 3 mm thickness then shaped on a CNC milling machine, until they obtained a dumbbell shape of a measuring part width $b = 8$ mm (Fig. 3). The strain rosettes were stuck onto the ready samples and the cables were soldered. The set of samples prepared for the tests are shown in Figure 3.

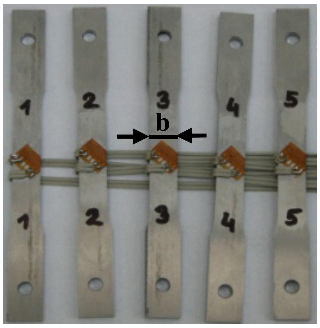


Fig. 3. Samples to quasi-static tension tests: thickness 3 mm, width of the measuring part (b) 8 mm

The samples for the compression tests after being cut out from the semi-finished elements were grinded to obtain a parallel surfaces. Next they were turned in order to obtain a cylindrical shape of $D = 7$ mm in diameter and of $L = 12$ mm in length for static tests, and of $L = 8$ mm in length for tests at high strain rates. The strain rosettes were placed on the ready samples and then the cables were soldered. The set of samples prepared for the quasi-static compression tests are shown in Figure 4.

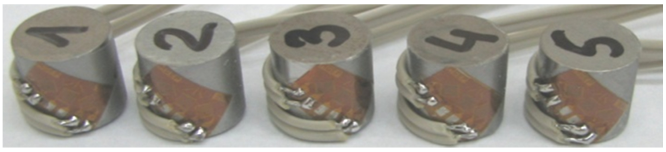
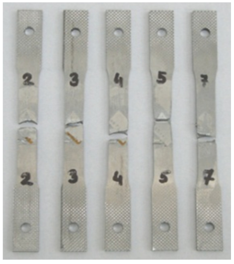
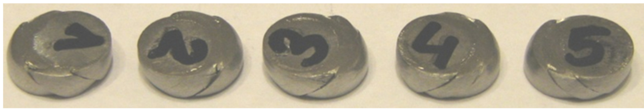


Fig. 4. Samples to quasi-static compression tests

The static tension and compression tests were carried out on a Instron 8802 material testing machine with a controlled displacement increment ratio of 5 mm per minute. During tests the following parameters were registered: the displacement of the testing machine jaws, force, and sample strain with the use of extensometer, longitudinal and transverse strains with the use of strain rosette. The tension and compression tests were carried out upon the destruction of samples shown in Figure 5, the samples after the tests are also shown.



a



b

Fig. 5. Samples after the quasi-static tests: a – tension, b – compression

After the tests the registered data was subject to further processing in order to achieve stress-strain functions, yield stress and failure strain values.

Additional discs with diameters equal to test bars and of 10 mm in thickness were used in the tests at high strain rates due to the hardness of steel.

On the basis of the signals received from the test bars the strain, stress and strain rates in the samples were calculated, following dependence for elastic bars system:

$$\varepsilon(t) = -2\frac{C_o}{L}\int_0^t \varepsilon_R(t)d\tau \tag{1}$$

$$\sigma(t) = 2\frac{ES_{po}}{S_{pr}}\varepsilon_T(t) \tag{2}$$

$$\dot{\varepsilon}(t) = -2\frac{C_o}{L}\varepsilon_R(t) \tag{3}$$

where: C_o – velocity of elastic wave propagation in the initiating bar, L – sample length, E – Young modulus, S_{po} – cross-section area of the receiving bar, S_{pr} – cross-section area of the sample, $\varepsilon_R(t)$ – signal in time for reflected wave, $\varepsilon_T(t)$ – signal in time for wave in the transmitter bar.

Values of true stresses and strains were calculated from the above equations only to the point when necking of specimens occurs (ultimate strength of specimens). With the formation of necking the uniaxial state of stress in sample turns into tri-axial state of stress. Equations 1 and 3 are no valid then. In order to obtain the true stress-strain data after necking the stress values should be corrected with a Bridgmann correction factor.

Calculated values $\varepsilon(t)$ and $\sigma(t)$ allowed us to draw the stress-strain dependence curve for the determined strain rate. The results of the quasi-static (strain rate = 8×10^{-3} s^{-1}) tension and compression tests, and compression at high strain rates (strain rate = 0.9×10^{3} s^{-1}) for the NANOS-BA® steel samples are shown in Table 1.

Table 1. Results of tension and compression tests of the NANOS-BA® steel samples

Sample no.	Static tension				Static compression		Dynamic compression	
	E, GPa	ν	R_m, GPa	ε_n	R_m, GPa	ε_n	σ_{maks}, GPa	ε_{pl}
1	193	0.30	1.88	0.12	3.87	0.38	3.96	0.033
2	197	0.29	1.87	0.14	4.01	0.37	4.07	0.036
3	191	0.27	1.86	0.11	4.11	0.40	3.84	0.038
4	191	0.28	1.86	0.18	3.80	0.38	4.02	0.036
5	215	0.32	1.86	0.12	3.71	0.38	3.99	0.033
Average (Engineering)	197	0.29	1.87	0.13	3.90	0.38	3.97	0.035
Average (True)	197	0.29	2.23	0.13	2.72	0.45		
Deviation	10	0.02	0.01	0.03	0.2	0.01	0.09	0.002

Example diagrams of quasi-static tension and compression tests are shown in Figure 6.

After the tests, deformations of the Armox 500T „witness" plate were measured in the areas where the projectile impacted the plate (Fig. 7).

The deformations of the Armox 500T plate measured after the projectile's impact, are shown in Table 2.

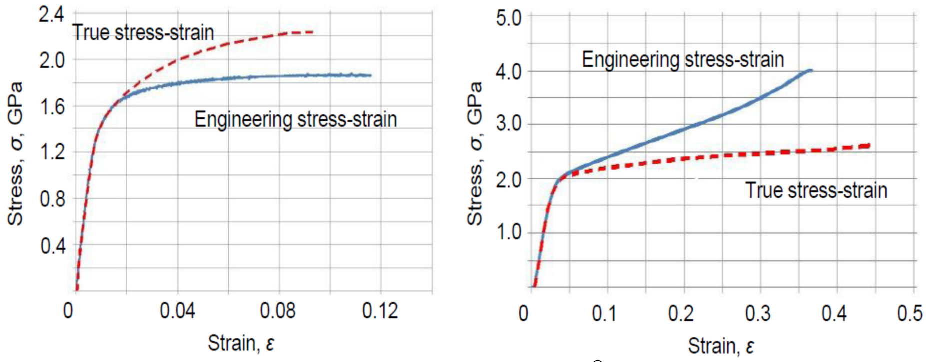


Fig. 6. Stress in function of strain for the NANOS-BA® tension and compression test (strain rate = 8×10^{-3} s^{-1}): left – tension test, right – compression test

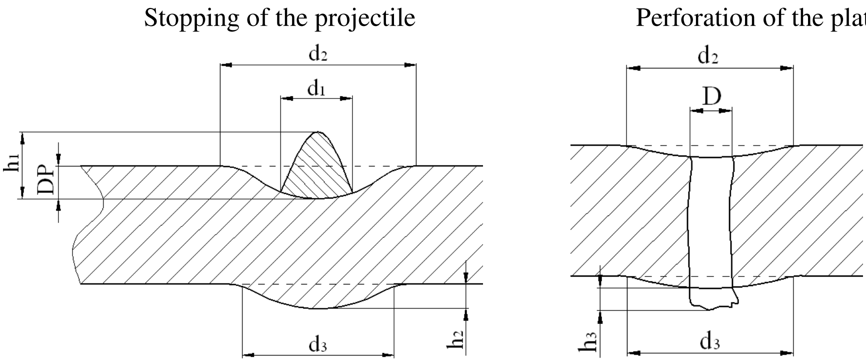


Fig. 7. The Armox 500T plate after the projectile impact:
DP – depth of penetration/dinge, h_1 – height of hill, d_1 – diameter of hill,
d_2 – diameter of dinge, d_3 – diameter of bulge of the back side of the plate,
h_2 – height of bulge of the back side of the plate, h_3 – height of the back side of the plate torn off, *D* – diameter of inlet crater of the perforated plate

Table 2. Results of measured deformations of the Armox 500T plate after *DP* test of the NANOS-BA® plate with the 12.7 mm B-32 type projectile

Plate no.	Deformations of the Armox 500T plate							
	Depth of penetration, *DP*, mm	Diameter of dinge, d_2, mm	Height of hill, h_1, mm	Height of bulge, h_2, mm	Diameter of bulge, d_3, mm	Height of the plate back side torn off, h_3, mm	Diameter of inlet crater, *D*, mm	Diameter of outlet crater, *d*, mm
1	5.7	27.1	–	3.2	45.0	–	–	–

3. BUILDING OF THE CONSTITUTIVE MODEL OF NANOS-BA® STEEL

The described tests were carried out in order to determine the values of the material parameters, introduced into the J–C constitutive model, as [3, 4]:

$$\bar{\sigma} = [A + B(\bar{\varepsilon})^n]\left[1 + Cln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right]\left[1 - \left(\frac{T - T_0}{T_m - T_0}\right)^m\right] \tag{4}$$

where: A – yield stress at ambient temperature, B – hardening constant, n – hardening exponent, C – strain rate constant, $\dot{\varepsilon}$ – strain rate, $\dot{\varepsilon}_0$ – reference strain rate, T – temperature of the tested material, T_0 – ambient temperature, T_m – melting temperature, m – thermal softening parameter.

The constants A, B and n were determined from the true stress-true strain curves obtained from quasi-static compression tests. First the A constant value was read from the diagram as a yield stress $R_e = 1303$ MPa. Then the part of the curve describing plastic range was drawn in log-log graph and the constant B was determined as a value of stress corresponding to $\varepsilon = 1$ (2723 MPa) decreased by the yield stress, of 1420 MPa. Then the value of n constant was determined by the fitting the J–C curve (with constants $C = 0$ and $m = 0$) to the true stress-true strain curve obtained from quasi-static compression tests (for the data describing plastic range of the curve) (Fig. 6).

For the SPHB tests at high strain rates the average strain rate $\dot{\varepsilon}$ was specified and then the C constant of the J–C equation was tuned to the value of $C = 0.075$ to fit the J–C curve (with $A = 1303$ MPa, $B = 1420$ MPa, $n = 0.195$ and $m = 0$) to the stress-strain curve obtained from SPHB compression tests (for the data describing the plastic range of the curve). The m constant was not determined but adopted from literature (the value of RHA steel) [9]. The values of constants of the J–C equation are shown in Table 3.

Table 3. Values of the J–C constitutive model parameters for the NANOS-BA® steel and the projectile materials

Element	Material	A, MPa	B, MPa	n	C	m	Reference
NANOS-BA® steel		1303	1420	0.195	0.075	1.17	Own research
Projectile core	N12e steel	1580	2905	0.117	0.075	1.17	Own research
Projectile jacket	4340 steel	792	510	0.26	0.014	1.03	[4]
Projectile can	Lead	24	300	1	0.1	1.0	[5]
Plate	Armox 500T	1470	702	0.199	0.00549	0.81	[6]

For the determined parameters values, simulations of mechanical tests were performed to the determine values of the NANOS-BA® steel failure model's parameters. As in the material failure model the J–C equation was adopted:

$$\varepsilon_f = \left[D_1 + D_2 e^{D_3\sigma^*}\right][1 + D_4 ln\dot{\varepsilon}^*][1 + D_5 T^*] \tag{5}$$

where: $D_1 \div D_5$ – failure parameters, $\dot{\varepsilon}^*$ – dimensionless effective strain rate, σ^* – dimensionless coefficient of pressure to stress relation.

The dumbbell shape sample in static tension simulations was made of 19644 eight-nodal hexagonal solid elements of 0.5 mm in size. The cylindrical sample in static compression simulations was made of 43408, and in the compression at high strain rate simulations – of 287578 four-nodal tetragonal solid elements of 0.5 mm in size. In simulations of NANOS-BA® steel plate penetration, the 12.7 mm B-32 type projectile was made of 52261 four-nodal tetragonal solid elements of 1 mm in size, while the armour – of 52436 eight-nodal hexagonal solid elements of 0.75 mm in size. In order to reduce the time of calculation only the $50 \times 50 \times 10$ mm size fragment of the NANOS-BA® steel plate was modelled. Adopted coefficients of friction between the elements of simulations are shown in Table 4.

Table 4. Values of coefficient of friction between the elements of simulations

Type of contact	Static friction coefficient	Dynamic friction coefficient
Steel-steel	0.8	0.8
Steel-lead	0.95	0.95

Correctness of the adopted J–C model parameters values was evaluated by the comparison of the strain character, and also the stress and strain values obtained in samples during tests and simulations (Fig. 8). Only the parameters $D_1 \div D_3$ of the J–C failure model having the biggest influence on the failure strain values was determined [7]. The J–C failure model has a status of the instantaneous failure model, what that means is that after the element damage (a part of it) its stiffness and strength is removed automatically. The failure occurs when the parameter D achieves a value of 1:

$$\mathrm{D} = \sum \frac{\Delta\bar{\varepsilon}^{\mathrm{p}}}{\varepsilon_{\mathrm{f}}} = 1 \tag{6}$$

where: $\Delta\bar{\varepsilon}^p$ – increment of the effective plastic strain, ε_f – failure strain.

Similar to experiments of static tension, in simulation sample accumulated stresses of approx. 2.2 GPa and was damaged after achieving approx. 13% strain.

Similar to experiments of static compression, in simulation sample accumulated stresses of approx. 2.8 GPa and was damaged after achieving approx. 45% strain. Both during the simulation and experiments before the failure sample had specific „barrel" shape and then it was broken at approx. 45º. In case of the simulation of the SPHB tests the sample did not fail, and its plastic stain was approx. 8%. Maximum stresses, which were registered in sample, amounted approx. 4 GPa, like in experimental tests.

The additional verification of constructed numerical models was the simulation of the NANOS-BA® steel plate, placed on the Armox 500T plate, penetration with the 12.7 mm B-32 type projectile (Fig. 9).

Table 5. Values of the J–C failure model parameters for the simulation elements

Element	Material	D_1	D_2	D_3	D_4	D_5	Reference
NANOS-BA® plate	Steel NANOS-BA®	0.047	0.165	–2.7	0	0	Own research
Projectile core	Steel N12e	0.036	0.083	–3.0	0	0	Own research
Projectile jacket	Steel 4340	0.05	3.44	–2.12	0.002	0.61	[4]
Armox 500T plate	Armox 500T steel	0.068	5.328	–2.554	0	0	[8]

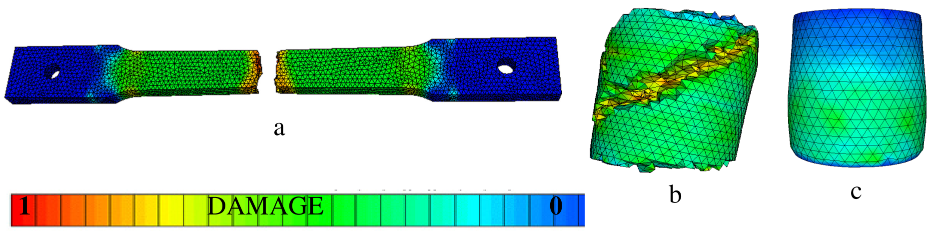


Fig. 8. Damage map of the N12e steel sample after simulation: a – static tension, b – static compression, c – compression at high strain rates

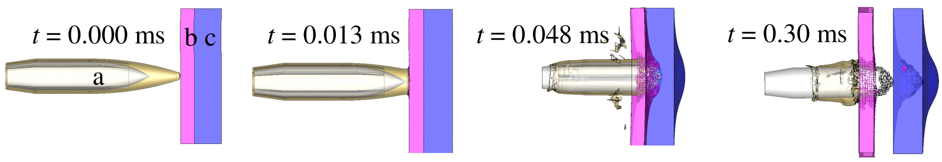


Fig. 9. Simulation of the NANOS-BA® steel plate placed on the Armox 500T „witness" plate penetration with the 12.7 mm B-32 projectile: a – projectile, b – NANOS-BA® plate, c – Armox 500T plate

The depth of penetration obtained in the simulation ($DP_s = 6$ mm) was compared to the depth of penetration obtained in the test ($DP_e = 5.7$ mm).

The high conformity of results obtained (a difference of 5%) confirms that the J–C parameter values were determined correctly.

4. CONCLUSIONS

On the basis of the test results and the computer simulations carried out, the following conclusions have been drawn:

1. The constitutive model providing reasonable agreement with experiments was built for the new material – NANOS-BA® steel.
2. The course of stress-strain curves for NANOS-BA® steel samples greatly depend on the strain rate. In compression tests at high strain rates the samples had much higher yield stress (approx. 2.0 GPa), in relation to static compression tests (approx. 1.5 GPa).
3. The characteristics and values of the parameters obtained from the tests conform to the numerical simulations, which confirms the true adopted values of the Johnson–Cook constitutive model parameters.
4. During the simulations NANOS-BA® steel samples fail in similar way like in static tension tests. In both cases samples accumulated stresses of approx. 2.2 GPa and were damaged after achieving approx. 13% strain.
5. During the simulations NANOS-BA® steel samples fail in similar way like in static compression tests. In both cases samples accumulated stresses of approx. 2.8 GPa and were damaged after achieving approx. 45% strain.
6. Both during the simulation and experiments before the failure sample had specific „barrel" shape and then it was broken at approx. 45º.
7. Both in simulations and in experiments at high strain rates the sample did not fail, and its plastic stain was approx. 7%. Maximum stresses, which were registered in samples in simulations, amounted approx. 4 GPa, like in experimental tests (at strain rate = 0.9×10^3 s^{-1}).
8. The depth of penetration of the Armox 500T steel plate, obtained during simulations ($DP_s = 6$ mm) is very similar to the test results ($DP_e = 5.7$ mm), and the small difference of 5% testifies, that the Johnson–Cook parameters values provide reasonable agreement with experiments.

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