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EFFECT OF MATERIAL MODEL TO THE RESULT OF HIGH VELOCITY IMPACT ANALYSIS

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Abstract

Light-weighted armor plates as being a discrete application of composite materials, are usually designed by finite elements programs such as ANSYS-AUTODYN, and proven by real fire tests before procurement. In this study, effect of material model choose to the numerical results is presented. Considering the material data as an important function of the analysis, a standard material model is selected and AISI 4340 steel is used for all analyses. Besides the material deformation and crater dimensions on the impact area, heat as appearing of thermal energy and yield stress dissipation on the completed analyses, is presented to the readers.

YÜKSEK HIZLI ÇARPIŞMA ANALIZINDE MALZEME MODELININ SONUCA ETKISI

Özetçe

Kompozit malzemelerin farklı bir uygulama alanı olan hafifletilmiş zırh levhaları, genel olarak ANSYS-AUTODYN gibi sonlu elemanlar programları ile tasarlanmakta, üretim öncesinde ise gerçek atışlı testler ile ispatlanmaktadır. Bu çalışmada, sayısal analiz programında kullanılan malzeme modeli seçiminin sonuçlara etkisi incelenmiştir. Malzeme verilerinin analizin önemli bir fonksiyonu olduğu göz önüne alınarak standart bir model seçilmiş ve tüm analizlerde AISI 4340 zırh çeliği kullanılmıştır. Tamamlanan analizlerde, malzeme deformasyonunun ve çarpışma bölgesinde oluşan kraterin boyutlarının yanı sıra, termal enerji olarak açığa çıkan sıcaklığın ve akma gerilmesinin dağılımı da okuyuculara sunulmuştur.

Keywords: *Johnson-Cook, Von-Misses, Impact, Autodyn, Composite Armor.*
Anahtar Sözcükler : *Johnson-Cook, Von-Misses, Çarpma, Autodyn, Kompozit Zırh.*

1. INTRODUCTION

There has been significant improvement in the study of composite materials which is a combination of two or more materials in the last half century since they have much better performance compared to steel in terms of strength/weight ratio and they can be designed for a specific need.

Materials science has been forced to develop new material types in parallel to technological advancement in many areas including space programs that requires more distances with less fuel, the everlasting competition in the area of military warfare and personal demands of people which includes more comfort and luxury. Engineering sciences have been doing research about these materials in order to understand their nature and try to use them in real-world applications. Especially aerospace industry has played a significant role in developing the use of these materials in commercial sector since it requires lightweight and durable materials at the same time. In some applications, incombustibility is also a key factor and these various needs make the composite materials one of the most advantageous areas to study.

Kabir et al. [1] stated that, the most and the only reason that composite materials have been chosen in commercial and military applications is the flexibility of design that needs to meet the requirements in terms of angle of recovery, binder type, manufacturing technique and the ability to determine the structural and material properties.

In order to protect the personnel against kinetic-energy (KE) ammunition, systems that is based on composite, ceramic or a hybrid of these materials have been developed in the last few years. However, armor steel still play a significant role and they have still been used as a reference in understanding the mechanism of the penetration of the ammunition against new threats.

Moreover, simulation studies enables people to understand the mechanical behavior of the material-bullet interaction, the change in the bullet geometry and how the kinetic energy has been used during the impact. They also helps researchers to visualize the possible damage that can occur before the test has been performed. These simulation programs also share similarities with the damage analyses that are done after the test while they make a big contribution to solving these problems. Thus, in most situations, the ballistic behavior of the material can be determined without the need of an actual firing [2-7].

In this paper, the behavior and deformation of AISI 4340 standard armor steel has been studied in two different material models, by using ANSYS-AUTODYN which has been widely used effectively in designing armor types. The reason that standard steel has been chosen as a material is that a new material model won't be developed after the study and the effects of material type to the design has been aimed to be shown to the reader.

In order to determine the ballistics of most materials, firing tests need to be used. However, these tests are usually expensive and need high quality protection requirements. For this reason, usually numerical methods are used in preliminary design of armors.

2. SOLUTION METHOD

In numerical studies, usually "explicit" methods are used which enables researchers to do dynamical calculations for high-speed impacts. The program that is used in this study is widely used in nonlinear problems (explosion, penetration, particle impacts etc.) The software divides the dynamical problem into finite elements and solves it in time domain. Conservation of mass, momentum and energy are used in every time step.

Table 1. Governing Equations: Laws of Conservation [12].

Laws of Conservation	*Lagrangian Description*	*Eulerian Description*
Mass	$\frac{d\rho}{dt}+\rho\frac{\partial v_i}{\partial x_i}=0$	$\frac{\partial\rho}{\partial t}+\frac{\partial(\rho v_i)}{\partial x_i}=0$
Momentum	$\frac{dv_i}{dt}=f_i+\frac{1}{\rho}\frac{\partial\sigma_{ij}}{\partial x_j}$	$\frac{\partial v_i}{\partial t}+v_j\frac{\partial v_i}{x_j}=f_i+\frac{1}{\rho}\frac{\partial\sigma_{ij}}{\partial x_j}$
Energy	$\frac{dE}{dt}=-\frac{p}{\rho}\frac{\partial v_i}{\partial x_i}+\frac{1}{\rho}s_{ij}\dot{\varepsilon}_{ij}$	$\frac{\partial E}{\partial t}+v_i\frac{\partial E}{\partial x_i}=\frac{p}{\rho^2}(\frac{\partial\rho}{\partial t}+v_i\frac{\partial\rho}{\partial x_j})+\frac{1}{\rho}s_{ij}\dot{\varepsilon}_{ij}$

The software divides the dynamical problem into small 6 sided cubes and defines each node with IJK coordinate axis.(Figure 1) [9]. Dimensions of these divided elements play an important role in solving the problem. If element dimensions are smaller, it takes longer to solve. By combining these elements, the solution web can be obtained.

Table 2. Definitions and Units of the Variables given in Table 1.

Symbol	Unit	Definition
t	s	Time
v	$m.s^{-1}$	Velocity
x	m	Displacement
E	j	Internal energy
p	Pa	Hydrostatic pressure
s	Pa	Deviatoric Stress
T	K	Temperature
ρ	$Kg.m^{-3}$	Density
σ	Pa	Stress
ε	-	Strain

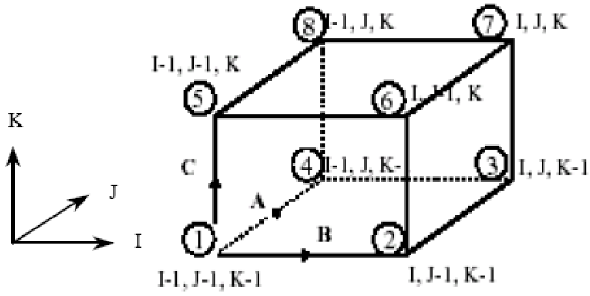

Figure 1. Element IJK coordinate system (ANSYS AUTODYN Theory Manual).

Explicit finite element software includes various solvers and in order to find the optimum solution, one needs to use the appropriate solver. In this study, Lagrance solver is used.

2.1. Lagrange Solver

Lagrance solver is one of the widely used solvers by explicity finite element software. In this solver, the solution web moves along with the material properties. This means that, material properties are not transferred among elements by element surfaces. Nodes are defined as x,y,z coordinate, $\dot{x}, \dot{y}, \dot{z}$ velocity, $\ddot{x}, \ddot{y}, \ddot{z}$ acceleration and at the center; m mass, σ stress, p pressure, e internal energy, ρ density, T temperature. Solution web deforms according to material properties and if these deformations are too large, problems may emerge. They may increase calculation time or make the process stop. This software uses a feature called erosion in order to overcome this problem.

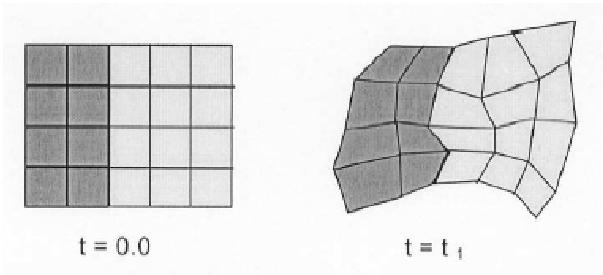

Figure 2. Web deformation [10].

2.2. Material Models

In this study, material model is divided into two categories. These are state equations and strength models. In order to define the problem correctly, one needs to understand both categories.

In state equations, p is pressure, ρ density similar to Hooke's law.

$p = K\mu$ where, $\mu = (\frac{\rho}{\rho_o}) - 1$ and K is bulk modulus of the material.

2.2.1. Strength Models

In general, it is the strength of the material against yielding and shear. The transition regime between elastic and plastic region ıs determined by yielding criteria. Yielding criteria is stated below.

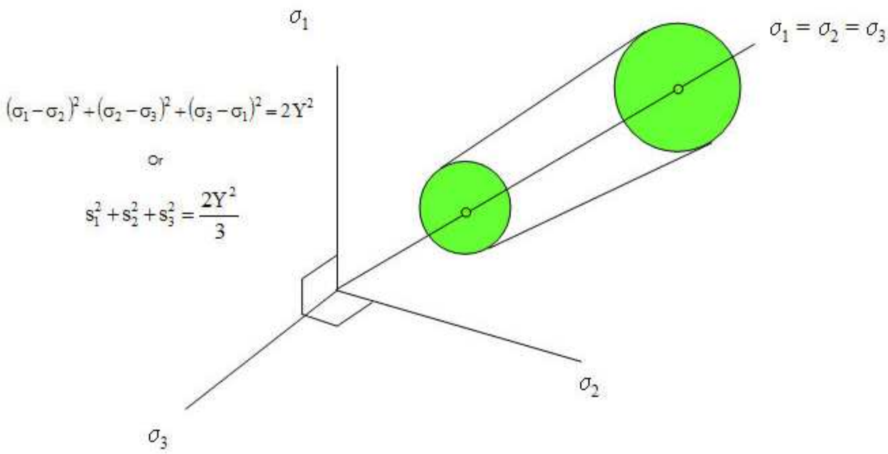

Figure 3. Von Mises Strength Model.

2.2.1.1. Johnson-Cook Stregth Model

Deformation-stiffening relation of metals is given in the equation below. Here, .σ_0 is yielding stress, n is deformation stiffening exponential and k is strength coefficient.

$$\sigma = \sigma_0 + k\varepsilon^n$$

This equation does not include the thermo effect in high-speed deformations, so it may result differences in the results. Thermo effect can be stated as below and needs to be added to the equation. Here Tm is fusion temperature, T_r is the reference temperature that the process is being done,

σ_r is the reference stress in reference temperature and lastly T is the temperature which the stress is being calculated.

$$\sigma = \sigma_r \left[1 - (\frac{T - T_r}{T_m - T_r})^m \right]$$

Johnson and Cook formed the following equation using this method [11]. The coefficients used in the equation are found by experimental studies. Here σ_o is the yielding stress, B is the strength coefficient, C is the expansion coefficient and m is the deformation velocity sensitivity exponent. These coefficients are especially important for ballistic materials and they are available in material libraries.

$$\sigma = (\sigma_o + B\varepsilon^n)\left(1 + C\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_o}\right)\left[1 - (\frac{T - T_r}{T_m - T_r})^m\right]$$

2.2.1.2. Von Mises Strength Model

In this model, it is assumed that the yielding strength is constant and thus Von Mises cylinder has constant diameter (Figure 3). This model does not account fort he strain stiffening, strain ratio precision and the thermal softening due to impact. However, these effects can be compensated by using moderate numbers defined by the dynamic value of yielding stress. Usually 2 is used as a dynamic gain coefficient.

3. Modeling

Generally, modeling includes the defining of material properties, determining the boundary conditions, defining the relations among parts and solving the problem. In this study, different materials are used for both the armor and the bullet. In order to enable the problem to be shorter, problem is defined in two dimensions and symmetric in y axis. Calculations are made using the Von Mises Strength model and they are repeated by using Johnson-Cook Strentgh Model. State equations are selected linear.

3.1. Armor Steel Model

AISI 4340 is selected as Armor steel. Values of the armor steel are formed by using the values in the software library (Table3 and 4). Dimension of the model is 100x100 mm and solution web has 2500 lagrange element.

Table 3. Von Mises Strength Model for Armor Steel.

Equation of State	**Linear**
Reference density	7.83000E+00 (g/cm3)
Bulk Modulus	1.59000E+08 (kPa)
Reference Temperature	3.00000E+02 (K)
Specific Heat	4.77000E+02 (J/kgK)
Strength	**von Mises**
Shear Modulus	8.18000E+07 (kPa)
Yield Stress	7.92000E+05 (kPa)
Erosion	**Geometric Strain**
Erosion Strain	2.00000E+00 (none)
Type of Geometric Strain	Incremental

Tablo 4. Johnson-Cook Strength Model for Armor Steel.

Equation of State	**Linear**
Reference density	7.83000E+00 (g/cm3)
Bulk Modulus	1.59000E+08 (kPa)
Reference Temperature	3.00000E+02 (K)
Specific Heat	4.77000E+02 (J/kgK)
Strength	**Johnson Cook**
Shear Modulus	8.18000E+07 (kPa)
Yield Stress	7.92000E+05 (kPa)
Hardening Constant	5.10000E+05 (kPa)
Hardening Exponent	2.60000E-01 (none)
Strain Rate Constant	1.40000E-02 (none)

Thermal Softening Exponent	1.03000E+00 (none)
Melting Temperature	1.79300E+03 (K)
Ref. Strain Rate (/s)	1.00000E+00 (none)
Strain Rate Correction	1st Order
Erosion	**Geometric Strain**
Erosion Strain	2.00000E+00 (none)
Type of Geometric Strain	Incremental

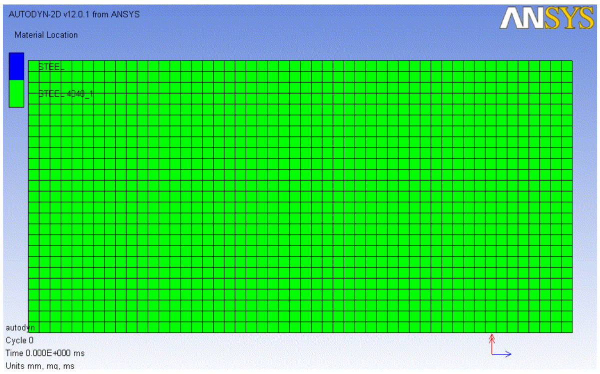

Figure 4. Half model of armor steel (symmetric at y axis)

3.1. Bullet Model

Structure steel has been used as bullet which has the yielding stress of 200 MPa. State equation is linear and the strentgh model is Von Mises Strentgh Model.(Table 3). Bullet diameter is 5 mm and bullet speed is 10 km/s(Figure 5).

Table 5. Bullet Material Model.

Equation of State	**Linear**
Reference density	7.89600E+00 (g/cm3)
Bulk Modulus	1.97500E+08 (kPa)
Reference Temperature	3.73000E+02 (K)
Specific Heat	0.00000E+00 (J/kgK)
Strength	**von Mises**
Shear Modulus	9.00000E+07 (kPa)
Yield Stress	2.00000E+05 (kPa)
Erosion	**Geometric Strain**
Erosion Strain	2.00000E+00 (none)
Type of Geometric Strain	Incremental

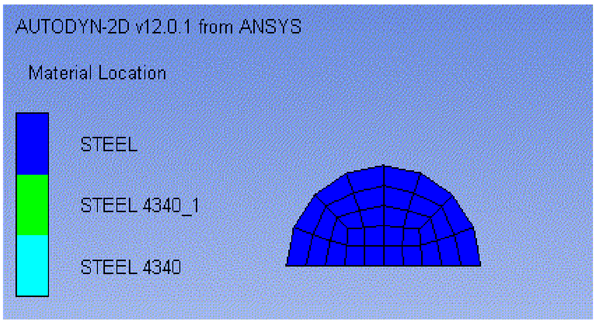

Figure 5. Half bullet model (symmetric to y axis).

4. ANALYSES

4.1. Analyses Using Von Mises Strength Model

Initial bullet velocity has been selected as 10 km/s. The temperature change in armor-bullet contact zone is seen in Figure 6.

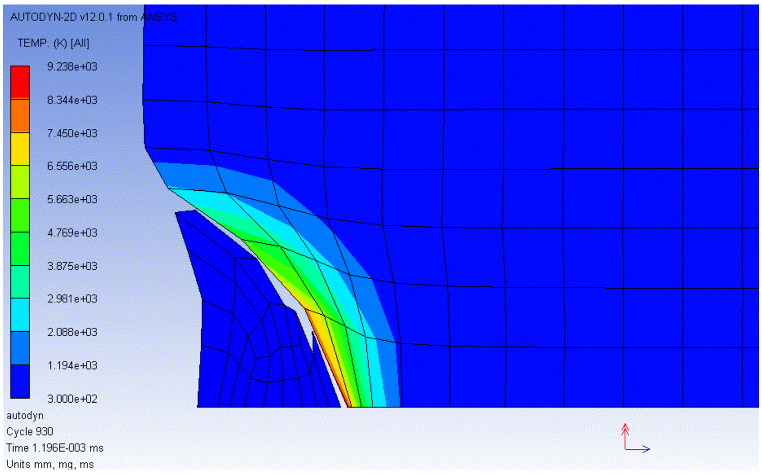

Figure 6. Bullet-armor contact point temperature.

Even if the temperature is far above the fusion point, as expected by Von Mises Strength Model , there is no change in yielding stress. The diameter of the crater after impact is 29 mm.

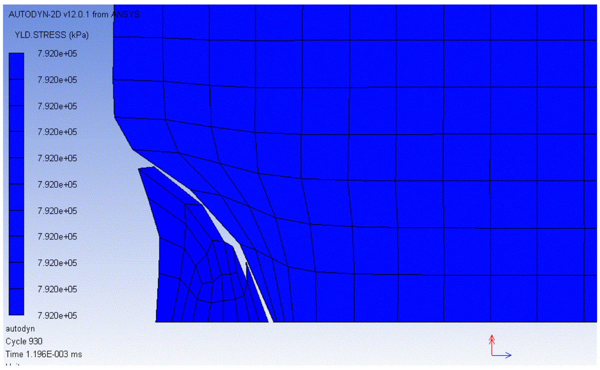

Figure 7. Yielding point change in armor during impact.

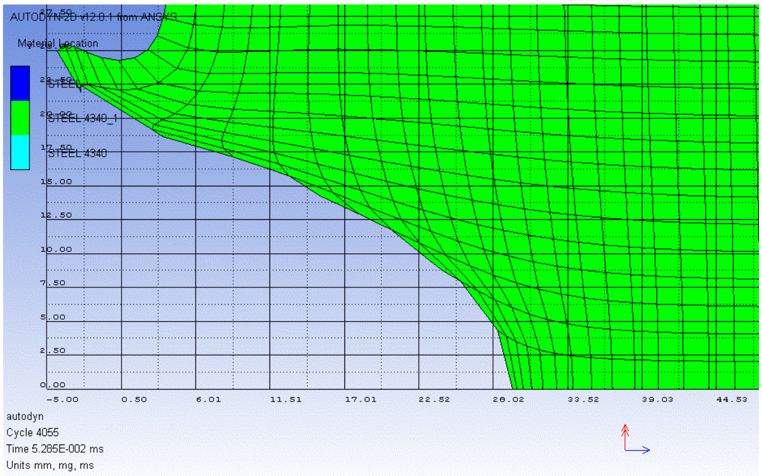

Figure 8. Crater depth after impact

4.1. Analyses Using Johnson-Cook Strength Model.

Highest velocity is shown in Figure 9 after the impact. Since Johnson-Cook considers the thermal softening caused by heat increase, yielding stress seems zero above the fusion point. The diameter of the crater after impact is 23 mm.

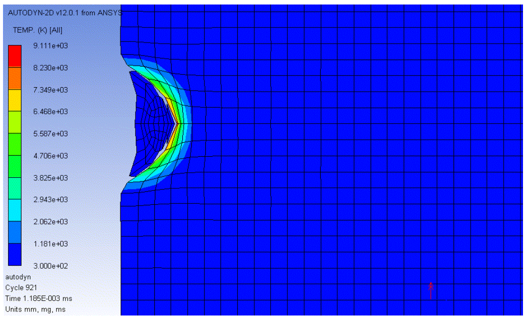

Figure 9. Bullet-Armor contact point temperature.

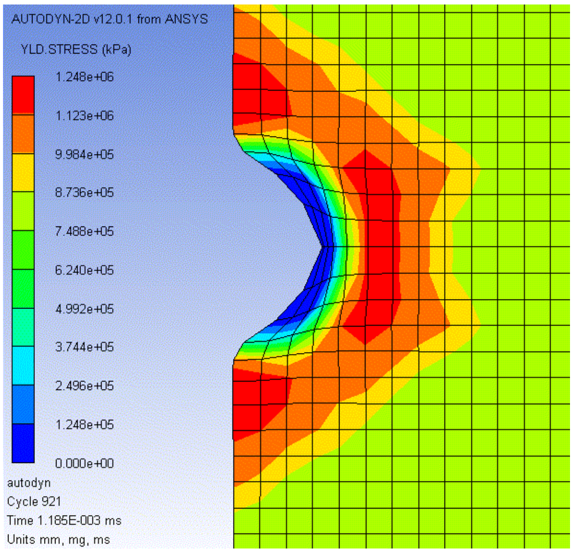

Figure 10. Yielding point change during impact.

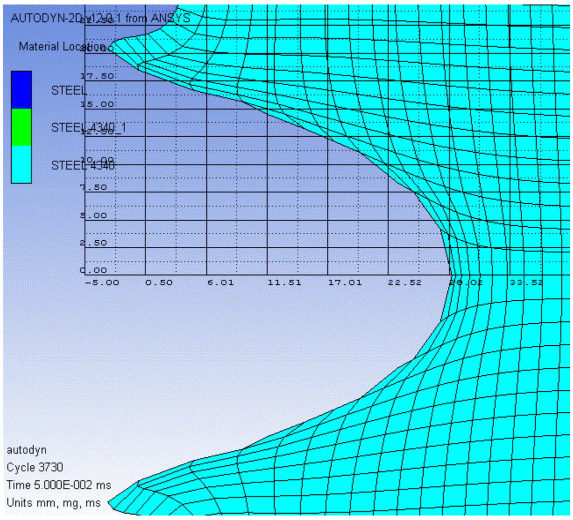

Figure 11. Crater depth after impact.

5. DISCUSSION AND RESULTS

Contact point temperature, change in yield stress and crater dimensions have been analyzed using Von Mises and Johnson-Cook Strength Model for AISI 4340 armor material.

It has been shown that contact point temperatures are the same for both models and this temperature mainly caused by the kinetic energy of the bullet which converts into heat energy after impact. A relatively small portion is caused by the friction between bullet and armor during the impact.

Since Von Mises model does not include thermal softening during impact, even if the temperature is far above the fusion point, yielding stress remained the same with initial conditions (see Figure 7). It can be seen in Figure 10 that yield stress is zero where the thermal softening occurs and it increases while the shock wave progresses through the material because of the strain stiffening.

Crater depth is almost the same for both models which is 24 mm for Von Mises and 23 mm for Johnson-Cook. Even if Von Mises model does not consider some effects as Johnson-Cook model, Dynamic Gain Coefficient enables this model to have the required precision in terms of crater depth. The 1 mm difference between the model enables the Johnson-Cook model to have 8 kg lighter material in a 1 m2 armor.

Finally, it can be said that Johnson-Cook strength model describes the parameters during ballistic impact successfully and it is a better model compared to Von Mises. Thus, it is not only used for metals but also seramics successfully.

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