Materials and Design 53 (2014) 719–726

Contents lists available at SciVerse ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Technical Report

The effect of impact velocity and target thickness on ballistic performance of layered plates using Taguchi method

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ARTICLE INFO

Article history:
Received 16 March 2013
Accepted 5 June 2013
Available online 26 June 2013

ABSTRACT

This paper presents the effect of test parameters such as Impact velocity, configuration and target thickness on ballistic performance of weldox steel plates against 7.62 mm APM2 projectile using Taguchi method. Trials were planned using an L 18 orthogonal array with 18 combinations of test variables to assess the influence of various factors. Numerical simulations have been carried out using Ansys Autodyn code with the above three process variables. Failure mechanisms of target plates of various single and multi-layered configurations were also discussed. Most portion of the kinetic energy of the projectile was expended in plastic deformation of the target material before perforation due to better bending stiffness of the target plate. Results showed that target thickness and impact velocity were the significant variables on residual velocity. Layer configuration was found to be insignificant relating to ballistic performance. Significant interaction is observed between impact velocity and target thickness from interaction plots. Simulated and experimental results showed good agreement with each other.

1. Introduction

The impact of projectiles on monolithic and multi-layer targets has attracted the attention of many researchers [1,2], while developing protective systems against various threat levels. The improvement of multi layer target design is essential for enhancing the resistance of the target and reducing the weight of the target. High strength steels have been used widely as armor materials for different armor configurations (single or multi-layer) due to good strength and superior ballistic properties. Several investigations have been made on steel alloys against various small and medium caliber projectiles. Even though experimental approach gives most exact results, an iterative procedure involving dynamic material testing and computer modeling may reduce the time and expense required for the development of advanced armor configurations. The simulated data obtained will be helpful for the purpose of design of products as well as for assessing the mechanism of penetration.

Many researchers studied the response of steel alloys against various threat levels and loading conditions. Palleti et al. [3] carried out ballistic impact experiments on metallic targets to study different mechanisms of energy absorption. The analysis comprises plug formation and plastic penetration for evaluating velocity and energy of the projectile during impact. Flores-Johnson et al. [4] performed numerical investigation of layered metallic plates impacted by 7.62AP projectile. FEM code LS-DYNA was used to develop numerical model. It was observed that single layer plates had superior ballistic resistance than multi layered plates. Gupta et al. [5] conducted ballistic experiments on aluminum targets by various shapes of steel projectiles. Different failure mechanisms like plugging, tearing and thinning of target plates were discussed. ABAQUS FEM code was employed to perform numerical modeling. Ubeyli et al. [6] compared the ballistic performance of steel and composite armors against 7.62AP projectile. Composites have shown 26% weight improvement to steel armor. Failure mechanisms like radial crack propagation and petalling were also investigated in this study. Jena et al. [7] investigated the penetration mechanism of metal–metal and metal–fabric layered structures against 7.62 armor piercing projectiles. Failure and fracture mechanisms of the samples were analyzed by using electron microscope, X-ray radiography and hardness measurement equipments. Borvik et al. [8] performed gas gun experiments on weldox 460E steel plates against different nose shape projectiles to determine residual velocity and energy absorption of target plate. It was observed that the nose shape of the projectile had influence on the energy absorption mechanism of the target plate. Gupta and Madhu [9] studied the effect of normal an oblique impact of hard core projectile on single and multi-layered targets.

Relations were established between residual velocity of the projectile and hardness of the target materials.

The available literature has so far dealt with the influence of bullet nose shape, velocity, configuration and geometry on ballistic performance of the target plates. No attempt has been made to study the effect of these test parameters on ballistic performance of steel target plates with minimum possible number of experiments by

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0261-3069/$ - see front matter © 2013 Published by Elsevier Ltd.
http://dx.doi.org/.2013.06.005

undertaking systematic study. The main objective of the present paper is to investigate effects of ballistic test variables on residual velocity of weldox 700E target plates. Impact velocity, configuration and target thickness are selected as main process variables of ballistic test. The suitable design of experiment (DOE) [10] is selected to carry out fruitful and precise experimental runs. In the current investigation, Taguchi orthogonal array (L18) was chosen for designing the experiments. Confirmation experiments were then conducted based on the statistical analysis.

2. Taguchi method: planning of experiments

To assess the influence of test parameters on residual velocity and to identify the optimal residual velocity, a specifically designed trial plan is required. Conventional experimental design procedures are too complicated and difficult to apply. A large number of numerical simulations have to be performed when number of test variables increases. In this method, test variables which affect the output parameters are split into two main groups: control factors and noise factors. Taguchi proposed to acquire the characteristic data by using orthogonal arrays, and to analyze the performance measure from the data to decide the optimal test parameters. In the present investigation, Taguchi technique [11] was adopted to optimize the test variables for residual velocity using Minitab software. The operational levels of input parameters are presented in Table 1. The essential steps for the design of experiments using Taguchi method are development of objective function, identification of the parameters and their levels, selection of a suitable orthogonal array (OA), conducting experiments as per plan, analysis of the data and the confirmation experimentation. Two major tools used in this method are (i) ANOVA (Analysis of variance) which is to determine the sum of squares and *F*-value to assess the level of significance and (ii) orthogonal arrays [12,13] to develop a matrix consisting of various combinations of parameters to model the response characteristics. In this study, three test variables were chosen as input factors. Trials were planned using an L 18 orthogonal array with 18 combinations of process parameters that was selected to assess the influence of different factors (Table 2). The results of response measures are converted into S/N ratio by using ANOVA. The smaller value of response denotes better, such as residual velocity, is called 'lower is better'.

Table 1
Input process parameters and their levels.

Parameters	Level 1	Level 2	Level 3	Units
Impact velocity	800	950	–	m/s
Configuration	Monolithic	Doublelayer	Triplelayer	–
Thickness	12	16	20	mm

Table 2
Experimental design using L 18 orthogonal array.

Expt. No	Impact velocity (m/s)	Configuration	Thickness (mm)	Residual velocity (m/s)
1	800	Monolithic	12	403
2	800	Monolithic	16	54
3	800	Monolithic	20	8
4	800	Doublelay	12	452
5	800	Doublelay	16	96
6	800	Doublelay	20	4
7	800	Triplelay	12	503
8	800	Triplelay	16	184
9	800	Triplelay	20	2
10	950	Monolithic	12	694
11	950	Monolithic	16	517
12	950	Monolithic	20	142
13	950	Doublelay	12	691
14	950	Doublelay	16	512
15	950	Doublelay	20	127
16	950	Triplelay	12	709
17	950	Triplelay	16	532
18	950	Triplelay	20	174

In order to achieve the desired aim, the numerical simulations were planned in the following sequence:

(1) Selection of appropriate constitutive models for both projectile and target.
(2) Choosing optimum meshing elements to obtain better results.
(3) Application of initial conditions to projectile and boundary conditions for target.
(4) Construction of design of experiments (DOE).
(5) Carrying out numerical simulations as per plan.
(6) Studying the analysis of results obtained from numerical simulations.
(7) Achieving significant test parameters from the results.
(8) Validation of numerical results.

3. Problem description and model validation

Weldox 700E of various configurations of thicknesses (12, 16 and 20 mm) has been impacted by 7.62 mm APM2 projectiles using numerical simulations. The 7.62 mm APM2 projectile was modeled as three independent parts: brass jacket, steel core and lead filler as shown in Fig. 1. The numerical simulations have been performed using Ansys Autodyn code. The total number of elements of projectile was 12,428. The magnitudes of the velocities have been kept as 800 and 950 m/s. All tests were conducted in the normal impact configuration as shown in Fig. 1. The 7.62 mm APM2 A linear equation of state and Johnson-cook strength models were used to simulate the material response of weldox 700E [4]. The Lagrange processor was used to represent both projectile and target. The Lagrangian scheme in numerical simulation requires an artificial technique to treat large deformation called erosion technique. Degenerated cells were eroded at an instantaneous geometric strain rate equal to 1.5. Figs. 2–4 depict the perforation of target plate against 7.62 mm APM2 projectile for various layers of target plates. Lagrange–Lagrange contact impact algorithm was employed between the target and projectile. Residual velocity [20] of the projectile of the plate was evaluated by the simulated data from Fig. 5. The target was modeled using Johnson-Cook constitutive relation [4]. The equivalent stress in the constitutive relation is expressed as:

$$\sigma = [A + B\varepsilon^n][1 + C\ln\dot{\varepsilon}^*][1 - T^{*m}] \quad (1)$$

A is the yield stress at 0.2% strain, B and n is the strain hardening constants, C is the strain rate sensitivity constant and m is the temperature softening constant.

The initial element size of each target plate was selected as $0.5 \times 0.5 \times 0.5$ mm^3, of 20 elements along the thickness of target. Meshing of the weldox 700E target plate was carried out to obtain exact results within minimum computational time. The aspect ratio of elements was fixed to be unity near the impact zone. Convergence study was undertaken to determine the optimum size of the element for obtaining a proper solution. The number of elements in the target plate was varied from 20 to 70, keeping the aspect ratio unity in the impact region. The number of elements in the weldox plate varied as 18,152, 62,453, 125,687, 212,158, 294,168 and 390,265. The weldox plate was meshed with the above seven mesh patterns and impacted by 7.62APM2 projectile at a velocities of

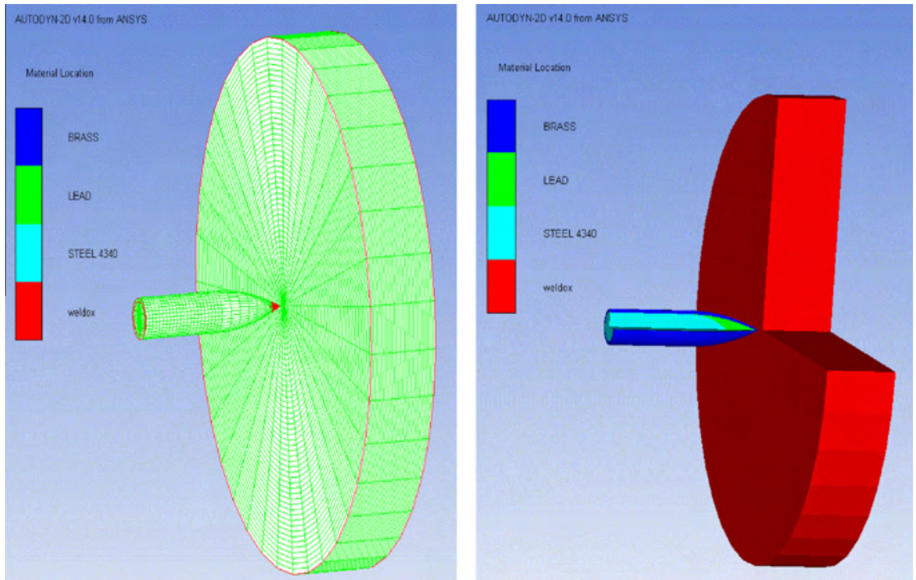
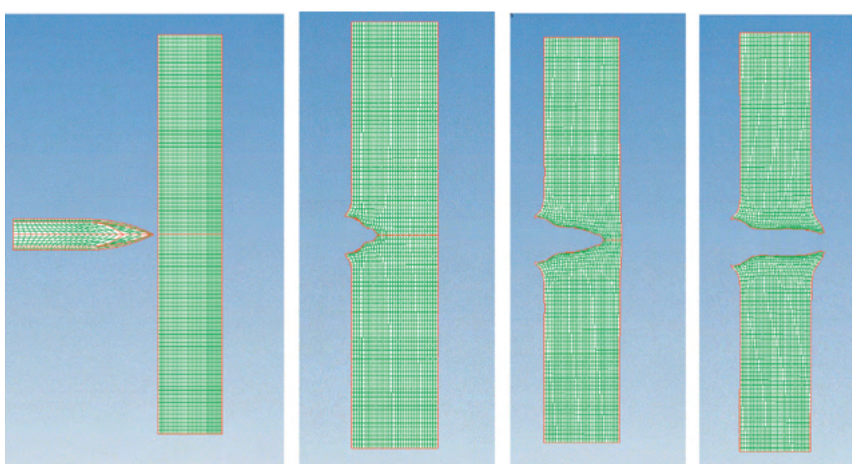
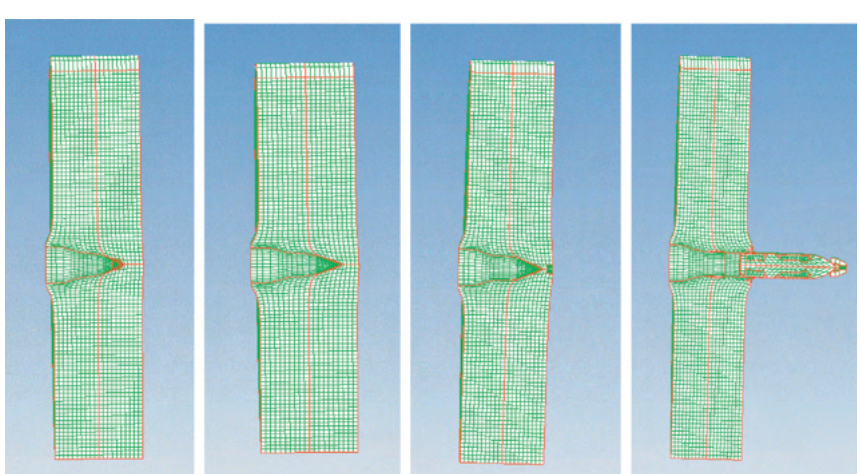


Fig. 1. (a) Finite element model of projectile and target (b) material modeling.



Cycle 0 Cycle 3000 Cycle 7000 Cycle 9000

Fig. 2. Perforation stages of single layered weldox 700E plates impacted by 7.62APM2 projectile at 800 m/s.



Cycle 4000 Cycle 6000 Cycle 7000 Cycle 9000

Fig. 3. Perforation stages of doubled layered weldox 700E plates impacted by 7.62APM2 projectile at 950 m/s.

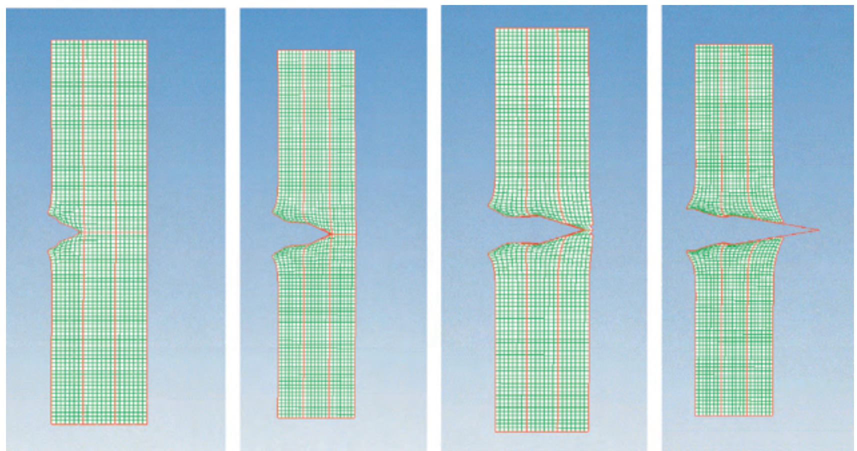


Fig. 4. Perforation stages of triple layered weldox 700E plates impacted by 7.62APM2 projectile at 950 m/s.

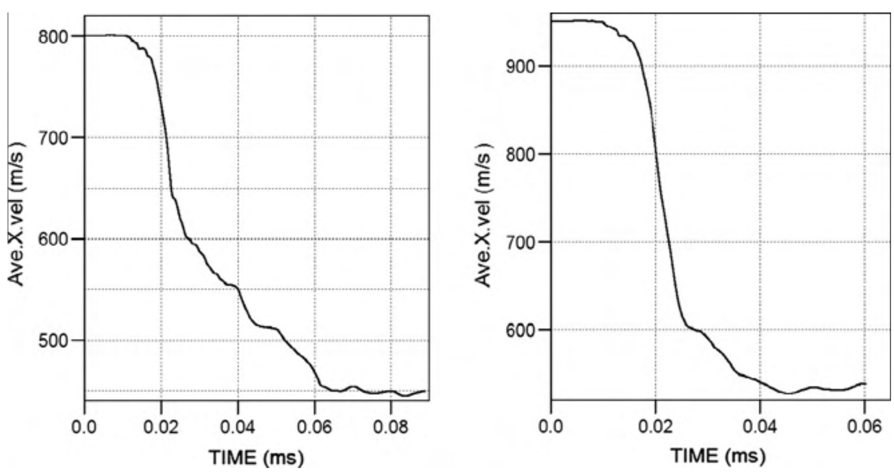


Fig. 5. Velocity profiles of projectiles at 800 m/s and 950 m/s.

Table 3
Variation of residual velocity with element size.

Number of elements along target thickness	Size of element (mm^3)	Residual velocity of projectile (m/s)
20	0.5 × 0.5 × 0.5	320
30	0.45 × 0.45 × 0.45	338
40	0.4 × 0.4 × 0.4	361
50	0.35 × 0.35 × 0.35	389
60	0.3 × 0.3 × 0.3	392
70	0.25 × 0.25 × 0.25	393

800 and 950 m/s. It was observed that the residual velocity of projectile increased up to 50 elements and then it became almost constant (Table 3). The total number of elements was taken as 50 in the target plate and corresponding element size 0.35 × 0.35 × 0.35 mm^3 for all numerical simulations in this investigation. The influence of significant variables such as element size as well as its aspect ratio on the simulation results was also discussed. The influence of friction between the projectile and target was found to be negligible. This was confirmed by taking two values of friction as 0.0 and 0.05 but no considerable difference was noticed in the simulation results. The target was meshed with seven various patterns, taking element size as 0.5 × 0.5 × 0.5, 0.45 × 0.45 × 0.45, 0.4 × 0.4 × 0.4, 0.35 × 0.35 × 0.35, 0.3 × 0.3 × 0.3 and 0.25 × 0.25 × 0.25 mm^3 corresponding to 20, 30, 40, 50, 60 and 70 elements, and impacted by 7.62APM2 projectile at a velocities of 800 and 950 m/s.

4. Results and discussion

Fig. 2 exhibits the influence of various process variables on residual velocity. It has been noticed that residual velocity decreases when target thickness is increased, and increases when impact velocity is enhanced. The configuration of the target plates is found to be insignificant with residual velocity. As residual velocity is the "smaller the better" type quality characteristic, Fig. 8 shows that the third level target thickness and first level impact velocity provide minimum residual velocity. ANOVA [14,15] is employed to check the null hypothesis relating to the data obtained through tests and it is assumed that there is no difference in treatment means. For the *S*/*N* ratio [16,17] of residual velocity, the results explained that target thickness and impact velocity had an influence on response measure. The results of ANOVA for the process parameters are furnished in Table 4. Larger *F*-value represents that the variation of the process variable has large influence on the response measures i.e. residual velocity etc. *F*-values of the process variables are compared with the confidence table. *F*-values of the process variables on the residual velocity are shown in Table 4. According to Table 4, impact velocity was found to be the major

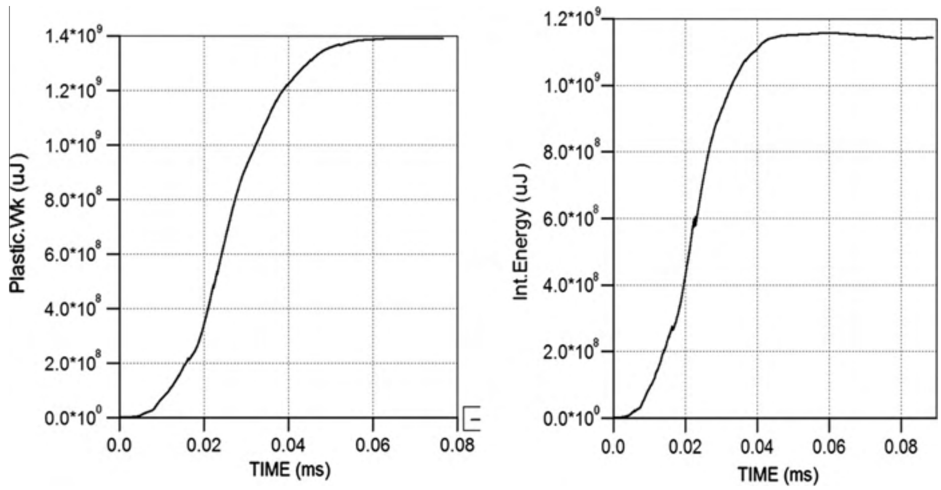


Fig. 6. Plastic work and internal energy profiles of double layered target plate.

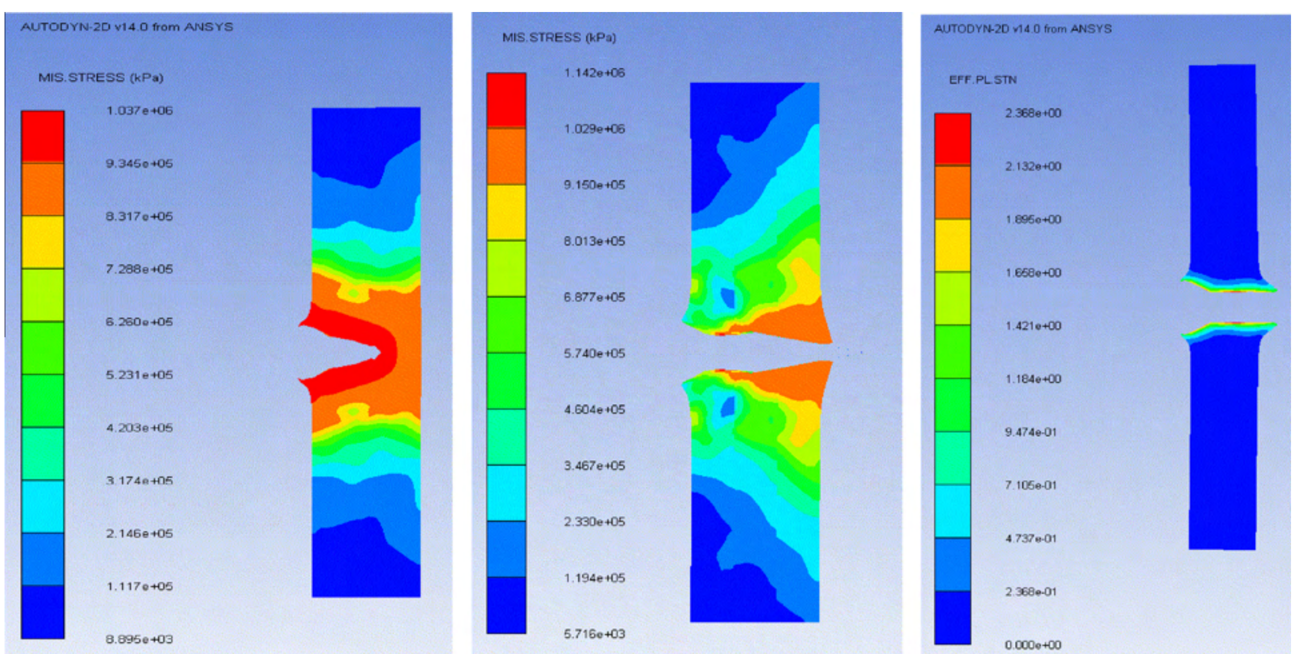


Fig. 7. von-Mises stress and plastic strain contours of double layered weldox plate.

influencing factor (20.75) followed by target thickness (20.04). The effect of type of configuration on residual velocity is not very significant. Residual plots are used to evaluate the data for the problems like non-normality, non-random variation, non-constant variance and higher-order relationships. Fig. 9 illustrates that the residuals follow an approximately straight line in normal probability plot [18]. Residuals possess constant variance as they are scattered randomly around zero in residuals versus the fitted values. Since residuals exhibit no clear pattern, there is no error due to time or data collection order. The confirmation test [19] is an essential step for validating conclusions drawn from DOE with experimental results [4]. The response characteristics of significant variables have been shown in Table 5. From Fig. 10, it has been noticed that there is no interaction between type of configuration and other parameters (impact velocity and target thickness). Significant interaction is observed between impact velocity and target thickness.

Von-Mises stress, plastic strain, and energy absorption profiles were obtained from Autodyn simulations (Figs. 6 and 7). From numerical simulations of projectile impact on target plates, it is observed that most part of input energy is dissipated through localized plastic deformation (Fig. 6). Deformed material was taken out as a block (Fig. 3), no stretching or thinning was noticed. The deformation mechanism is attributed to shear formation due to large momentum. The amount of plastic deformation of target gets reduced with the impact velocity. Equivalent plastic strain and von-Mises stress in the plate enhanced as the projectile penetrated the plate, and attained maximum values at failure. Peak values of stress and plastic strain were achieved when deformed materials separated from the target plate. Once failure commenced, the value of the von-Mises stress declined. It was also understood that locations of max shear stress and von-Mises stress are identical. The ability of energy absorption of weldox 700E plate enhances with an increase in the projectile impact velocity and target thickness. The amount of the plastic strain increased with the initiation of penetration. Most portion of the kinetic energy of the projectile was expended in plastic deformation of the target material before perforation. Following the impact of the projectile the internal en-

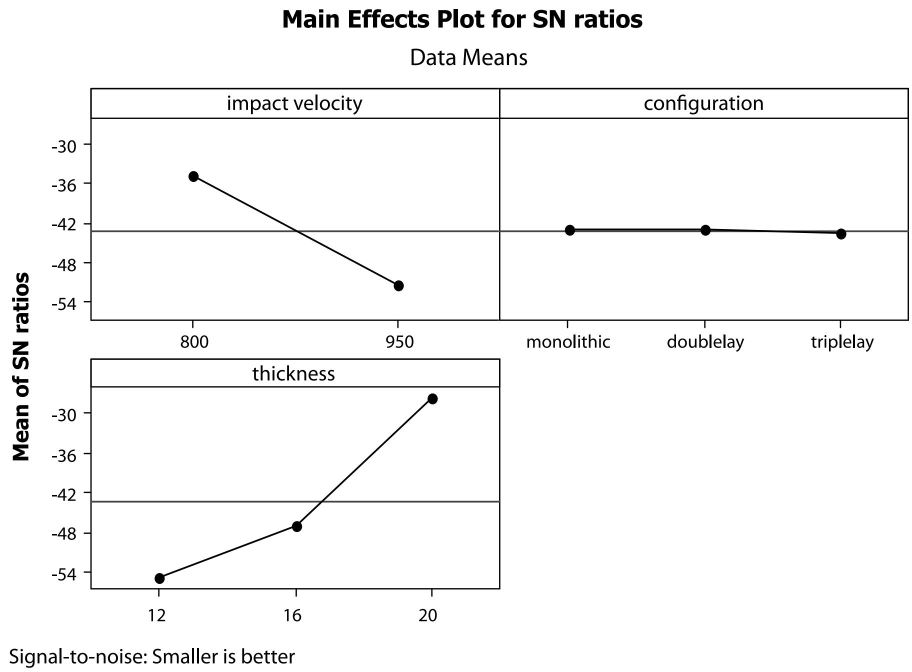


Fig. 8. Effect of parameters on residual velocity.

Table 4
Analysis of variance for residual velocity.

Source	DF	Seq SS	Adj MS	*F*	*P*
Impact velocity	1	1226.5	1226.49	20.75	0.001
Configuration	2	1.31	0.65	0.01	0.989
Thickness	2	2369.26	1184.63	20.04	0.000
Residual Error	12	709.26	59.11		
Total	17	4306.31			

ergy increases at the expense of kinetic energy of the projectile. The kinetic energy of the projectile is determined by summation of the product of mass and square of nodal velocity. The energy loss is caused due to the deceleration of projectile. Once the front layer is perforated, the next layer has to absorb the residual energy of the projectile by deforming and local bending and converting deformed energy to heat energy. This is due to bending effect which induces an increase of plastic work. For high impact velocity the failure appears quickly without bending effect and in this case the plastic work is lower. It was also observed that monolithic

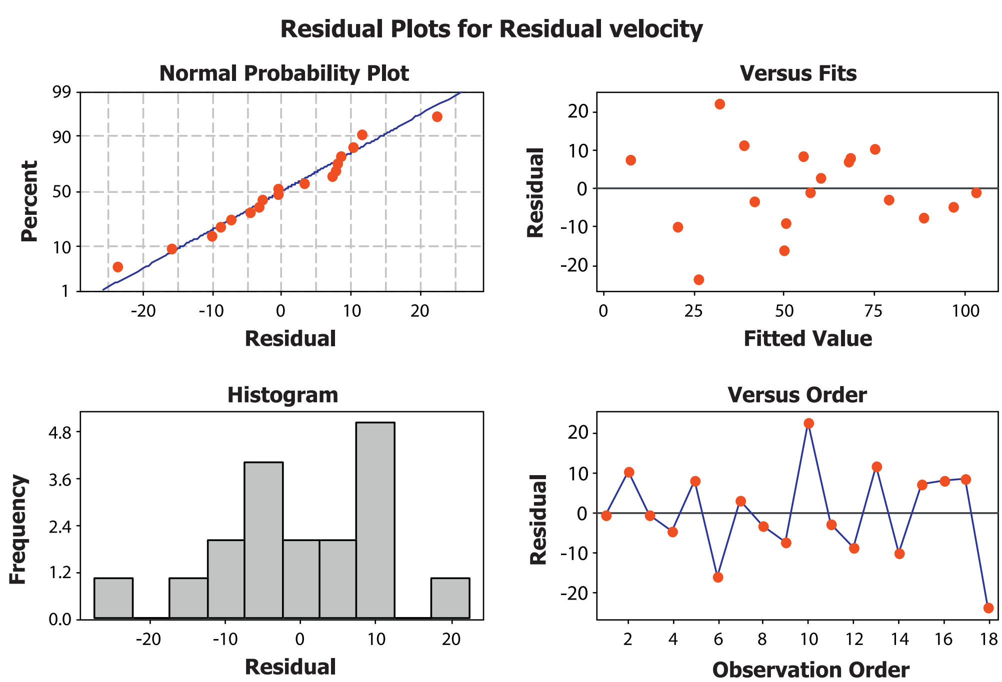


Fig. 9. Residual plots for residual velocity.

Table 5
Results of the confirmation experiments.

Performance responses	Testing set of parameters	Simulated result	Experimental result [18]
Residual velocity	Impact velocity (650 m/s), configuration (double layer) and target thickness (12 mm)	2.45	1.78

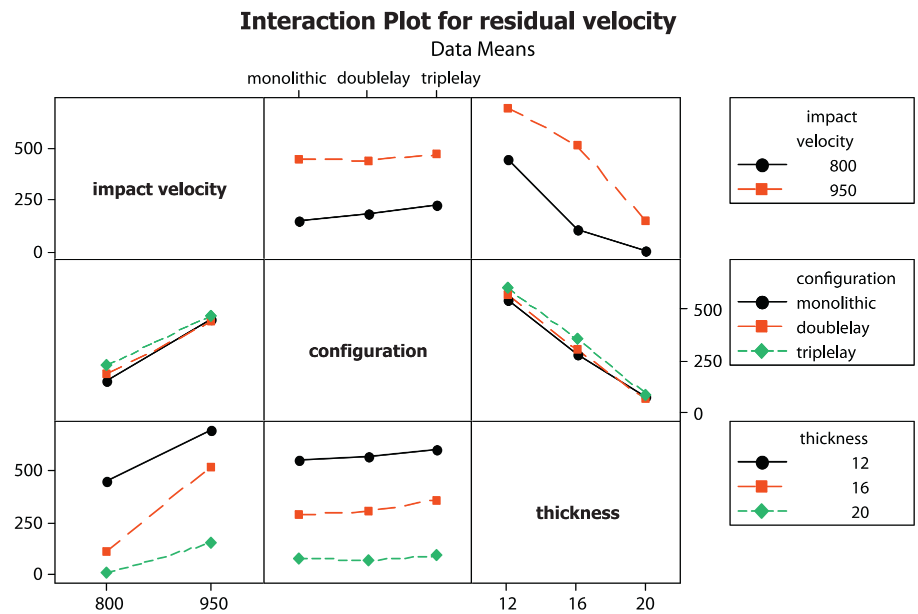


Fig. 10. Interaction plots for residual velocity.

plates showed superior bending resistance compared to other configurations.

5. Conclusions

The significance of input variables of ballistic performance of weldox 700E has been studied. Design of experiments has been adopted to assess the effect of input variables on the response characteristics. The conclusions are as follows:

- Results exhibit that target thickness and impact velocity are significant variables to the residual velocity of the projectile. Impact velocity was found to be the major influencing factor (20.75) followed by target thickness (20.04). Layer configuration was found to be insignificant relating to ballistic performance of the target plate.
- It has been noticed that there is no interaction between type of configuration and other parameters (impact velocity and target thickness). Significant interaction is observed between impact velocity and target thickness.
- Most portion of the kinetic energy of the projectile was expended in plastic deformation of the target material before perforation. It could be attributed to better bending stiffness of the target plate.
- The confirmation experiments have also been conducted to validate the results obtained by Taguchi technique. Simulated and experimental results were compared with each other and found well.

Acknowledgements

The authors would like to thank DRDO, India for financial help in carrying out the experiments. The authors express their gratitude to Director, DMRL for giving permission to publish this work.

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