PAPER DETAILS

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Research Article

EFFECT OF FORMING HISTORY ON CRASHWORTHINESS OF A SPOT-WELDED AND DOUBLE-HAT ELLIPTICAL THIN-WALLED TUBE

Hüseyin BEYTÜT[1], Selçuk KARAGÖZ[2*], Serkan ÖZEL[3]

Thin-walled structures (TWTs) are widely used in automotive and aerospace industries due to their easy formability, high energy absorption capacity, low cost, and lightweight advantages. In this study, considering the forming history, the crashworthiness of spot-welded and double-hat shaped elliptical TWT was numerically investigated under dynamic axial load, by the finite element method (FEM). In addition, a bead-shaped trigger mechanism was added to the TWT to reduce the peak crushing force. Non-uniform thickness distribution (thickening or thinning of some elements), plastic strain and work hardening may occur during forming. To investigate the effect of the forming history on crashworthiness, the sheet metal was formed by single-acting deep-drawing process and forming data were mapped to the TWT. The results showed that forming history has an effect on the crashworthiness of the tube. With deep-drawing results mapped to the tube, energy absorption decreased by 5.218% and peak crushing force decreased by 3.614%. Numerical simulations were conducted by using the nonlinear finite element codes RADIOSS/explicit.

Keywords: *Crashworthiness; Thin-Walled Tubes; Forming History; Finite Element Method; Deep-Drawing.*

1. Introduction

Due to high competition, strict safety norms and increase in accident rates, the crashworthiness of TWTs are becoming more important these days. Since TWTs undergo large plastic deformation in a very short period during the accidents, their behavior is more complicated. Therefore, understanding how TWTs behave in the event of a possible accident is extremely critical in terms of passenger and goods safety.

In the years when FEM and computer technology have not been developed so far, researches have focused mainly on theoretical and experimental studies [1-4]. With the development of FEM and computer technology, dynamic analyzes can be made by using FE codes and thanks to these, time and money can be saved.

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In recent years, many studies have been conducted by researchers to improve the energy absorption capability of the TWTs. The studies are mainly focused on the effect of geometric configurations (different cross-section, conical, tampered) and materials [5-11].

TWTs under the dynamic axial load can undergo global (Euler type) or progressive (accordion, diamond) buckling. Since global buckling usually occurs from the center with single folding, energy absorption is limited [12]. Length, diameter, and thickness are the most important geometric parameters that determine the deformation mode [13, 14]. Thus, these parameters should be considered during the design of TWTs.

The absorbed energy (AE) in the course of plastic deformation, is found by the area under the force versus displacement curve which obtain by crash test. Generally, the peak crushing force (PCF) occurs at the first reaction force and it is one of the disadvantages of TWTs used for energy absorption. PCF should be low in terms of passenger and goods safety. In addition, since PCF occurs in a very short time, the effect on AE is limited. The studies have shown that by adding the trigger mechanism (hole, groove, hollow), the initial folding was start easier and the PCF decreased [15, 16].

TWTs can be produced by sheet metal forming methods such as deep-drawing, hydroforming and extrusion. Plastic deformation occurs during forming of thin-walled tube and plastic deformations produce work hardening. During the forming process, thickness variations, residual stresses, work hardening, plastic strain occur. Studies have shown that the forming history has a serious effect on crash performance [17-19]. Therefore, the forming history should be taken into account when evaluating the crash performance of the TWT.

Dutton et al. [20] examined the effect of forming parameters. They formed a s-rail structure by hydroforming and mapped the forming results (thickness, residual stress and plastic strain) to the impact analysis. They found forming history effect the crashworthiness and it was important to consider the forming history to obtaining a real crash condition. Gümrük and Karadeniz [21] numerically investigated the effects of deep-drawing process on the crashworthiness of top-hat thin-walled structure. They also found that the thickness variations and plastic strains significant effect the crashworthiness. Lee et al. [22] numerically investigated the influence of back stresses during forming processes of s-rail structure on crashworthiness. S-type structure produced by deep-drawing and tube formed by hydroforming processes. They found that to obtain a more reliable impact test, the back stresses during forming process should be taking into account. Krusper [23] examined the influences of the forming history on the crash performance for a simple hat profile structure. He found that plastic strain and thickness distribution had an important role in the crash response. Williams et al. [24] experimentally and numerically investigated the influence of the hydroforming process on the crashworthiness of EN-AW5018 aluminum alloy. They concluded that the energy absorption capability of the hydroformed aluminum tubes decreased by mapped the forming history to the structure. Kim et al. [25] Numerically examined the effect of plastic strain and thickness distribution on crashworthiness on a full vehicle. They found that forming effects have effect the deceleration pulse and deformation mode.

Crash analysis of TWTs can be performed either quasi-static or dynamic depending on applied load [26]. Thought most of the studies about the crashworthiness of TWT have been conducted using quasi-static tests, it is important to also take into consideration the dynamic high-speed impact response of TWTs.

In this paper, the impact response of spot-welded elliptical thin-walled tube under dynamic axial load was investigated. Besides, the bead-shaped trigger mechanism was added to the tube to reduce the peak crushing force and to obtain a more stable deformation mode. To investigate the effect of forming history on crashworthiness, the TWT was produced by single-acting deep-drawing method. After deep-drawing process, thickness variations, plastic strain, and stresses were mapped to the tube and dynamic analysis was repeated. RADIOSS used as solver and explicit and nonlinear FE codes used.

2. Material and Methods

Double-hat shaped elliptical TWT was design with bead-shaped trigger mechanism (fig. 1). All dimension is in millimeter.

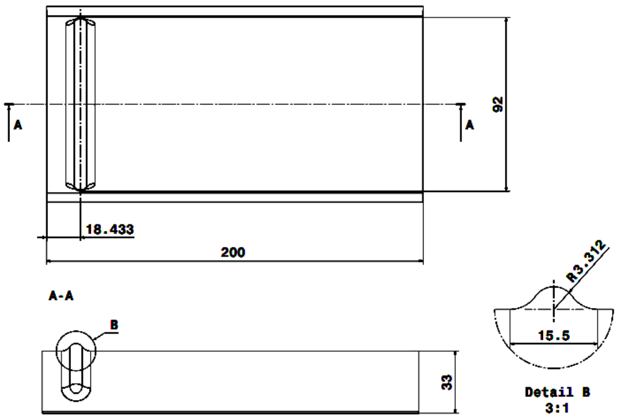

Figure 1. Details of bead-shaped trigger mechanism and TWT.

The parts of TWT were joined by using twenty-four spot welds. The tube has 1.5 mm wall thickness (t), 200 mm length (L), 33 mm semi-minor axis (a) and 46 mm semi-major axis (b). The radial ratio is (a/b) 0.717. While the sides of added trigger mechanism is concave, the middle is convex. By adding the trigger mechanism, it is aimed to reduce peak crushing force and obtain more stable deformation mode.

2.1 Material Characterization

Since reducing vehicle weight affects fuel consumption and emission rates, the use of aluminum and magnesium alloys, which may be alternative to steel in recent years, has increased. In this paper, Al6061 was used as TWT material with Young's module E= 69 GPa, density $\rho = 2.7$ gr/cm^3 and Poisson ratio ν=0.33. Since under axial dynamic impact, strain-rate effects and inertia force have significant effect on crashworthiness [27-29], Johnson-Cook material model [30] was utilized to obtain more realistic impact results. The Johnson-Cook material model expressed as follow.

$$\boldsymbol{\sigma = \left(A + B\varepsilon_p{}^n\right)\left(1 + Cln\frac{\dot{\varepsilon}_{pl}}{\dot{\varepsilon}_o}\right)\left(1 - \left(\frac{T-T_a}{T_m-T_a}\right)^m\right)} \tag{1}$$

Where σ is flow stress, A is yield stress, B is hardening parameter, ε_p is plastic strain, n is hardening exponent, $\dot{\varepsilon}_o$ is references strain rate, $\dot{\varepsilon}_{pl}$ is plastic strain-rate, C is strain rate coefficient and can be found with split Hopkinson (Kolsky) pressure bar test [31]. In this study the thermal effect is neglected. Johnson-Cook parameters of Al6061 are given in Table 1.

Table 1. Johnson-Cook parameters [32].

A (MPa)	B (MPa)	n	C	$\dot{\varepsilon}_o$ (s^{-1})
314	114	.42	.002	1

2.2 Finite Element Model and Deep-Drawing Process

Double-hat elliptical TWT consists of two parts. The parts were joined by using twenty-four spot welds. 4-node shell elements of type quad were utilized with 3 mm mesh size (in the region of the trigger mechanism, smaller size elements were used) for TWTs and 1D spring elements for spot welds. Five integration points across the thickness were chosen to avoid the hourglass mode and obtain good accuracy in the crash simulation. “Nodes to Surface Contact” between the tube and rigid-wall is defined with 0.2 friction coefficient and self-contact algorithm is used (to avoid penetration between the surfaces during folding), provided by RADIOSS. 250 kg mass was added to the end of the tube and moved a speed of 10 m/s to a rigid wall. The tube is restricted to all degrees of freedom except for the axis of speed y (fig. 2).

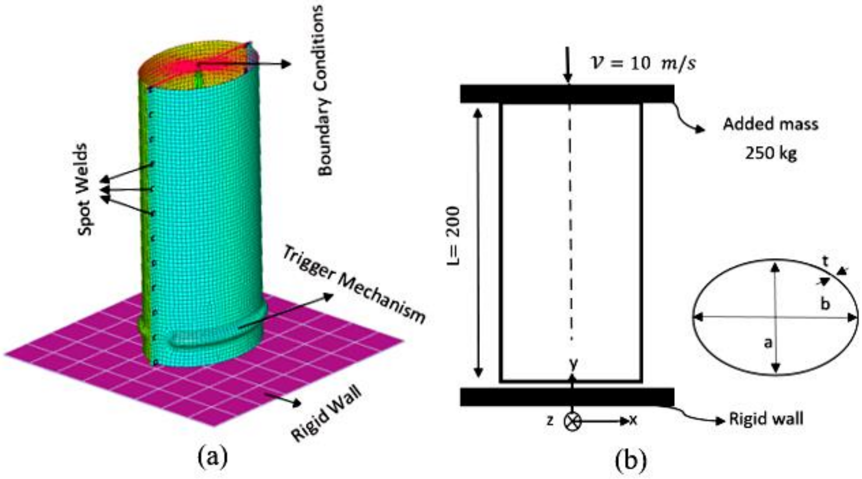

Figure 2. a) Finite element model b) schematic diagram of TWT.

The model was meshed by using HyperMesh software. Time step is 1.77E-4 and 1.98E-7 for unmapped and with mapped TWTs respectively. Therefore, the analysis of the mapped tube lasted longer. The dynamic simulation was conducted using RADIOSS/Explicit software.

In order to examine the effect of forming history on impact performance, the tube was formed by the single-acting deep-drawing method. Die and punch are defined as rigid. 3x3 mm quad mesh type was utilized with Adaptive mesh. Therefore, mesh size decreased in the regions where the stresses were higher. The die and the punch, form the blank together. Blank was placed between die and punch and the blank is forced into the die for creating the desired shape. FE model of deep-drawing process and after deep-drawing analysis, the appearance of the sheet metal is shown in figure 3. HyperForm software was used for deep-drawing analysis.

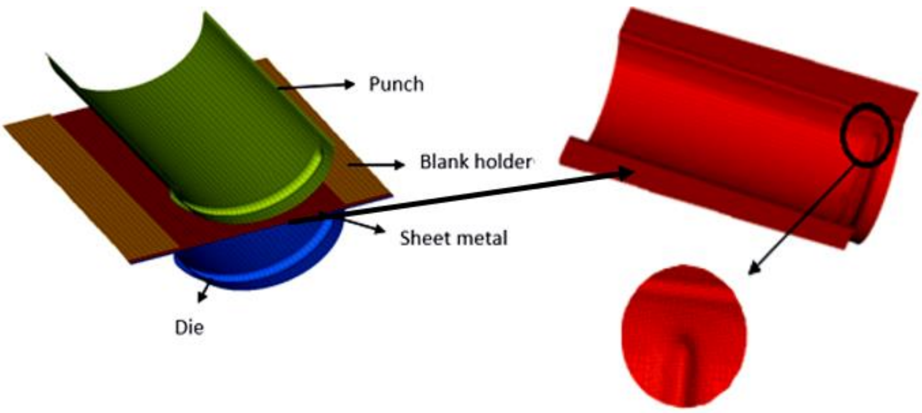

Figure 3. Finite element model of deep-drawing process.

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2.3. Model Validation

Zarei and Kröger [33] experimentally performed the impact test of a cylindrical TWT. With the purpose of validating the FEM, a cylindrical TWT of the same dimensions was designed, the finite element model was generated and impact analysis was performed. A good agreement was obtained on deformation shapes of the TWTs at a 75.5 mm crush distance (fig. 4). In the experimental study, the mean crushing force value was 13.03 kN while 11.04 kN by FEM (the difference is 15.27 percent). This difference was acceptable, as the forming history had a significant impact on the crashworthiness of TWTs [34-36].

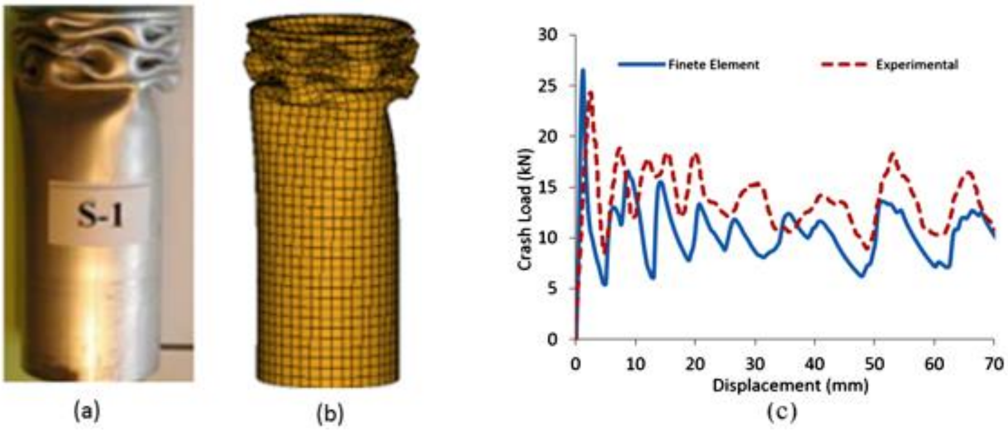

Figure 4. Comparison deformation shape at 75.5 mm crush distance a) Experimental b) Finite Element c) Comparison crash load versus displacement

3. Results and Discussion

After deep-drawing analysis, thickness variations, stresses, and plastic strain were occurred in the sheet metal (fig. 5). In particular, thinning is concentrated in the region where the trigger mechanism is located. The wall thickness value, which was initially 1.5 mm, ranged from 1.569 mm to 1.106 mm. After the results were mapped to the tube, the thickness varied between 1.554 and 1.107. This difference, which did not affect the results, was due to the decrease in the size of sheet metal elements after deep-drawing analysis.

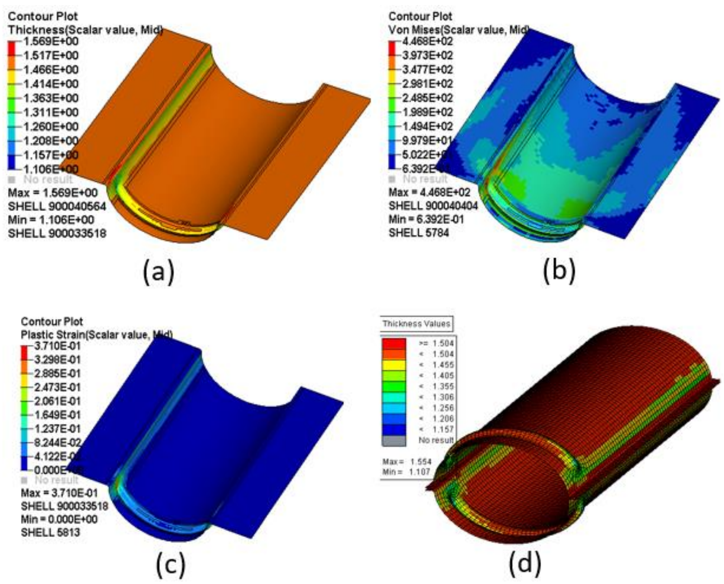

Figure 5. Deep-drawing results a) thickness variations b) Von Mises stress c) plastic strain d) elliptical TWT which deep-drawing results were mapped.

In the tubes, the first folding occurred in the region where the trigger mechanism was added. Progressive deformation mode occurred for both and deformation modes of the tubes differed in the course of impact (fig. 6).

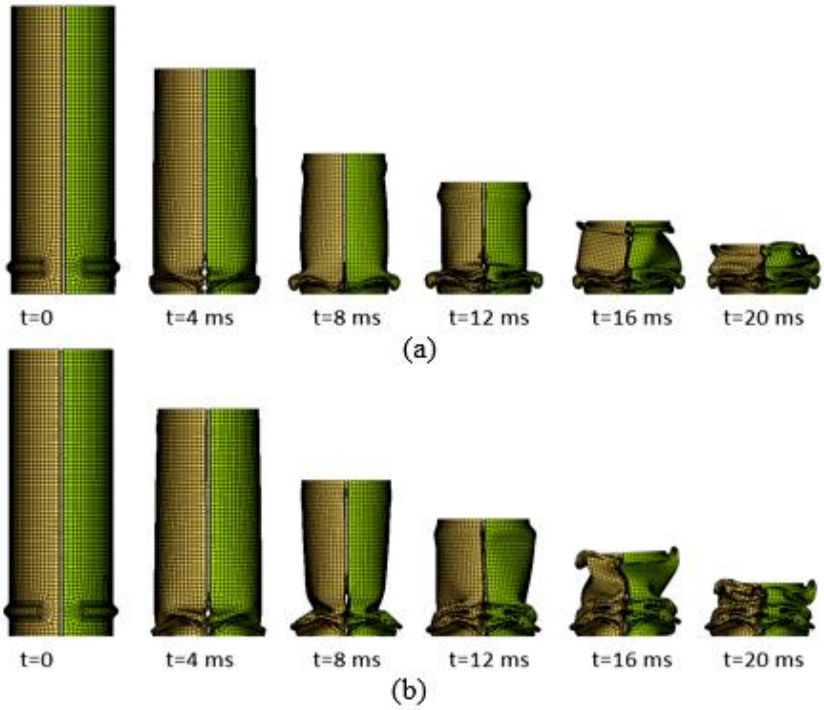

Figure 6. Comparison of deformation mode during impact a) unmapped b) mapped.

With the mapped forming history, the PCF was 62.346 kN with a decrease of 3.614% from 64.6878 kN (fig. 7). Due to the thinning in the location of the trigger mechanism during the deep-drawing process, the first folding was occurred easier and the first reaction force was lower. The AE was 7063.86 J with a decrease of 5.218% from 7452.68 J (fig. 8). The crush distance was 156 mm for both tubes.

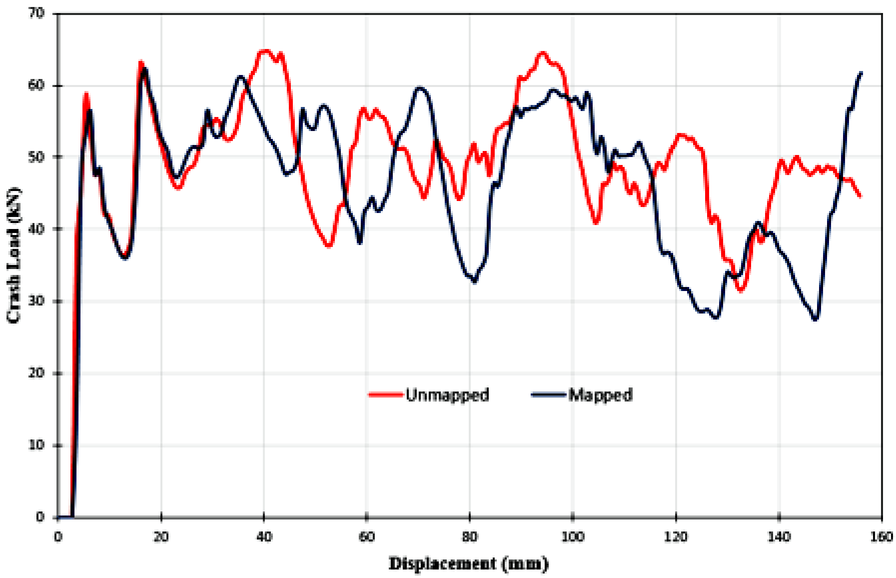

Figure 7. Crash load versus displacement.

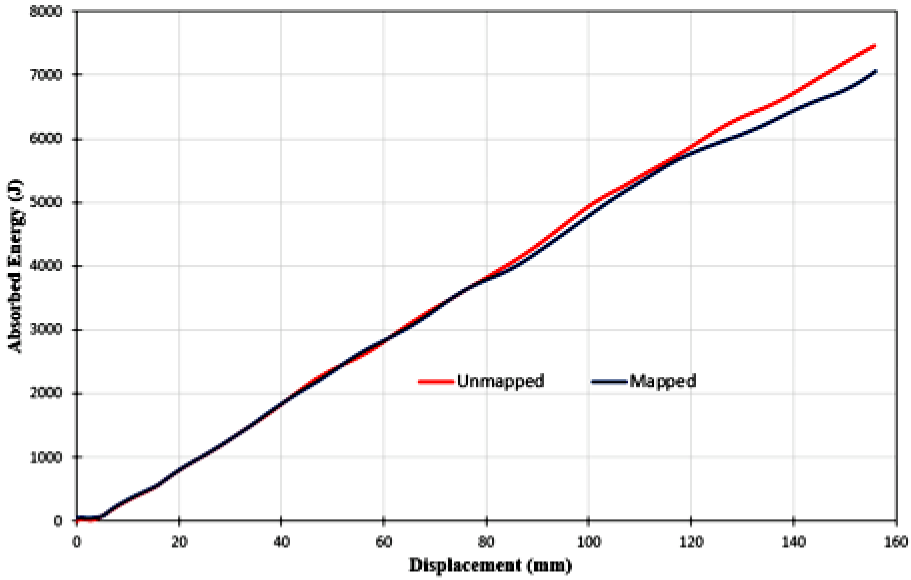

Figure 8. Absorbed energy versus displacement.

It is important to check whether the energy balance is ensured after the analysis in terms of the accuracy of the FE model. For obtain a good energy balance, the total energy must be constant throughout the analysis and must be equal to the sum of the absorbed energy, kinetic energy, contact energy and the hourglass energy. In addition, zero or negligible amount of hourglass energy is important in terms of the accuracy of the analysis.

The thin-walled tube with a velocity of 10 m/s and a 250 kg added mass has 12500 J kinetic energy at the beginning of crash. The kinetic energy of the tube started to fall with the crash. The amount of energy absorbed must be equal or too close to the loss in kinetic energy. At the end of the analysis, the absorbed energy was 7063 J, the kinetic energy was 5369 J, the total energy was 12433 J, the hourglass energy was zero and contact energy was 63 J. The results showed that a good energy balance was obtained (fig. 9)

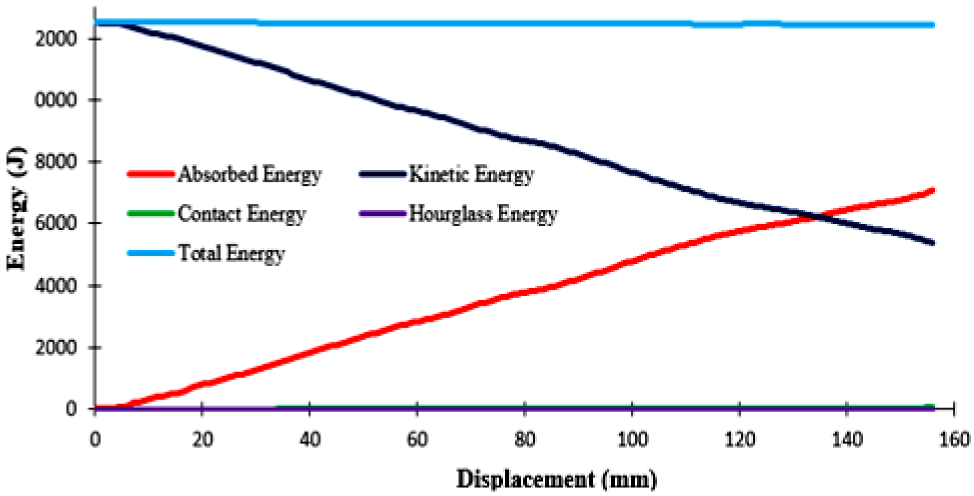

Figure 9. Energy balance of unmapped TWT.

4. Conclusion

With the addition of the trigger mechanism, the PCF, which usually occurs at the first reaction force, has occurred in subsequent force fluctuations. Especially in the region where the trigger mechanism is located and in the corners of sheet metal, thickness variations, residual stresses and plastic strain were occurred during forming process. With the results were mapped the tube, the deformation mode was changed in the course of impact and AE decreased by 5.218%, PCF decreased by 3.614%. The results showed that the forming history has effect on crash performance of the TWTs. Therefore, in terms of providing a realistic crash atmosphere and obtaining accurate results, forming history should be taking into account.

5. Future works

In this study, only one trigger mechanism was added to the tube. A new study can be done by changing the number or position of the trigger mechanism. In addition, the tube was shaped by deep-drawing method, the effects of other sheet metal forming methods on crash performance can be investigated. To investigate which forming result (wall thickness, plastic strain, residual stress) is most effective on crashworthiness, the results can be mapped one by one to the TWT.

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