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Response of CMT Welded Aluminum AA5086-H111 to AA6061-T6 Plate with AA4043 Filler for Ballistic

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Abstract

Cold Metal Transfer (CMT) is a proven type of welding method using Metal Inert Gas (MIG). It is a welding technique which can be employed for marine fabrications too. Plates of AA5086-H111 and AA6061-T6 with AA4043 filler is welded by CMT. Parameters like current, voltage, arc length, shield gas pressure etc. are varied to obtain a continuous weld without any crack. Welded thin plates are subjected to a tensile test as per American Welding Society (AWS B4.0:2007) and thereafter impact loads are applied. The plates subjected to impact loads in the range of sub-ordinance level velocities, the feasibility of ordinance and ultra-ordinance can be scaled and compared. Responses and terminal ballistics limit are determined for plate thickness of 1.2 mm and 3 mm. Present work consists of simulation using Abaqus Software and experiments using Laboratory prepared gun. It was observed that, there was petaling in very thin plates and in some plates it was perforated by plugging for lower ballistic loads and thinner plates. The work gives new insights into the application of CMT in joining plates of different materials with varied thickness values. The material property of plates joined by this welding method was found to be new resource information to the permanent literature of material technology.

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Keywords: CMT; Ballistics; Petaling; Perforation; Spalling.

1. Introduction

This study concentrates on ballistic resistance performance of thin welded Aluminum plates. In the past the ability to withstand and resist high impact loads has been investigated by many researchers. Numerous studies have been carried out in relation to the mechanics of penetration. Among these studies, the work done by Awerbuch and Bodner [1], mentioned in a later study by Ben and Dubinsky [16], was found relevant for the present work. Aluminum alloys are light weight materials which are used in the shipbuilding, automotive, electronics and aerospace industries. It is stressed that the welding technology for Al alloys and other light weight metals has been an important research topic in the metal fabrication process. For example, the fusion weld problem of Al alloys both similar and dissimilar welding co-exists in ship building. Aluminum is classified into seven major classes of wrought alloys according to their major alloying elements.

Wingrove [2] concentrated on targets like Aluminum alloy grade 2014 plate and suggested that the projectiles with a blunt nose could be penetrated better than ogive or hemispherical nose shapes when the target thickness to projectile

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length-diameter ratio was less than one . Recht and Ipson [3] worked on blunt projectiles which penetrated the moderate thickness targets more efficiently than conical projectiles . Corran et al. [4] investigated on aluminum and steel plates and found out the effect of projectile nose shapes of blunt and cylindric-conical projectiles of dimension 12.5 mm diameter, mass about 15-100g, with impact velocity ranging from 50-150 m/s and reported that critical impact energy was dependent on projectile nose radius. The authors also found that failure mode changed to tensile stretching with shear plugging . Camacho and Ortiz [5] relied upon Finite Element Method (FEM) for simulation of projectile impact. The authors tried to eliminate the meshing distortion with adaptive meshing and also paid attention to contact evolving problems. There was good agreement with the experimental and simulation results on the impact of aluminum plates by conical nosed projectiles .Gupta et al.[6,7] had studied Aluminum alloy of thin plates with different noses and thicknesses . Jones and Paik [8] had relied upon experimental and empirical response of impact studies using thin Aluminum alloy plates . Brvik et al. [9–12] performed numerous studies on different projectile noses and concluded that implementation of adaptive meshing, would improve the numerical results significantly . Experimental and simulation studies of the deformation behavior of such plates of various ballistic velocities and thicknesses, when impacted by the hemispherical nosed projectile, are presented in this paper. FEM simulation for the present problem was carried out using ABAQUS. The ballistic limit velocities, as well as residual velocities of the projectiles, were obtained using the post-processing module. The values of residual velocities from prediction were compared with the experiments and found to be a good correlation between them. The predicted failure mechanism of the targets was also found in agreement with that in experiments. The class of AA5xxx is Aluminum-Magnesium alloys, the class of AA6xxx is Aluminum-Silicon-Magnesium and AA4xxx is Aluminum -Silicon. AA5xxx and AA6xxx were plates and the AA4xxx is mostly used filler for metallurgical and chemical composition needs in the weld. The commercial use of AA5xxx & AA6xxx plates is superstructures in ships and hulls, superstructures and offshore structures are subjected serious welding issues like cracking, porosity, inclusions etc. Welding of AA5086-H111 to AA6061-T6 can reduce the burden in the manufacture of intricate shape of casting component of the hull structural parts and also improve the strength and the flexibility in design. This saves time in production and also the cost of the manufactured component.

Nomenclature

A	Yield Stress
B	Strain Hardening Factor
C	Dimensionless strain rate hardening coefficient
E	Young's Modulus
m & n	Power Exponents in 1
P	Mean Stress
T	Test Temperature
α	Thermal diffusivity
ρ	Density
ν	Poison's Ratio
T_r	Room Temperature
T_m	Melting Temperature
$\dot{\epsilon}$	Strain Rate
ϵ^*	Plastic Strain
ϵ_{eq}	Equivalent Strain
$\dot{\epsilon}_{eq}$	Equivalent Strain rate
σ_{eq}	Equivalent Stress
D_1 to D_5	Material Parameters

1.1. Laboratory setup

Experiments were done initially by preparing the samples through the CMT welding as shown in appendix Fig 1 AA5086-H111 grade Aluminium is welded to the AA6061-T6 grade plate with the AA4043 filler, a right match for metallurgical compatibility. Here, the weld is prevented from the cold crack, pores, distortions, inclusions and other welding defects. Therefore, the samples were machined and cleaned by buffing operation with eight hole fixture diameter of 10 mm. Extra samples were made for inventory purposes and the test is carried out with the laboratory prepared gun. The target specimens were prepared with dimensions of 150X150 (all dimensions are in mm) and the

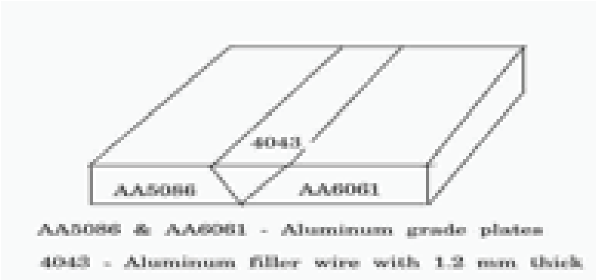


Fig. 1: Layout of weld for joining two dissimilar aluminium grade materials

projectiles were of 9 mm diameter and length of 14mm respectively. The experiments were performed with a gas gun test setup which is shown in appendix Fig 3. Air pressure in the chamber was varied to get different velocities. Plates of required size were clamped at the edges and were subjected to impact by a hemispherical projectile.

Events of each experiment were recorded with high-speed camera Phantom V 1.2 version camera, data acquisition of initial and final velocities were obtained from the recorded video files once the experiments were completed

1.2. Experimental procedures

AA5086-H111, AA6061 & AA4043 grades were used after studying the composition of the weld. It was observed that the amount of magnesium and silicon in weld was higher than 2-3.8% weight, the limit that could be retained in solid solution for corrosive resistance, which resulted in the development of the special temper H111. The experimental program involved about 4 laps joint tensile test specimens taken based on a monthly basis which was dipped in the laboratory prepared a marine solution. The results were then used to calibrate modified version of the constitutive equation of Johnson and Cook model. During the test, there was compression of the material normal in the direction of the projectile path. The tests were carried out with a thickness of a 1.2 mm and 3 mm thick plate with hemispherical projectiles. Hemispherical-nose steel projectiles with nominal length, mass, diameter and hardness of 14 mm, 7.1-7.3g, 9.0 mm and HRC 58-60 respectively were used. The experiments were done with compressed gas gun described in Fig 2. The target plates, of dimensions 150X150 mm and thickness of 1.2 mm and 3 mm, were then clamped in a rigid square frame by 8 numbers of pre-stressed M10 bolts. Except for the initial velocity of the projectile and the target thickness, the boundary conditions were same in all experiments. Mechanism of penetration and perforation was identified with high-speed camera. It is observed that some targets were failed due to ductile hole growth, without any plug separation, and some targets were failed by plugging at high ballistic velocities. Based on the experimental results, velocity curves for impact and residual velocities were plotted and the limit for the ballistic velocity of each target was arrived at. Results are plotted and shown in Fig. 5. The target thickness limitation study proved that, If the target thickness is more than double, say from 1.2 mm and 3 mm, the resistance in perforation was increased drastically. Perforated target plates subjected to impact velocities were found to be within ballistic limits. It is shown in Fig. 4(a), 4(c) and 4(e) are based on the simulation and analysis. The deformation decreases globally and as the target thickness increases and penetration channel in the bulge direction are also on the rise.

However, the deformation in global of these targets was seen in moderate level. The cavity is almost cylindrical, smooth in all tests. Material anisotropy effect on the failure mode was observed due to change in metallurgical compositions in the weld. Petals in very small size on the back side of the plate is found in certain tests but are not found to be responsible for energy dissipation during the tests. Thus, mechanism of ductile hole growth was almost predominant in the modes of failure. During perforation, the material is pushed towards lateral side in the bulges.

Fig. 2: Layout of welding setup comprises of 1.Digitally controlled MIG/MAG, 2.Power Source, 3.Cooling Unit 4.Robot Control 5.Wire feeder 6.CMT welding torch 7.Wire Buffer

Fig. 3: Layout of laboratory ballistic gun setup comprises of 1.Laser diode, 2.Barrel, 3.Projectile loading point 4.Chamber, 5.Actutor to open the barrel 6.NI data acquisition system

2. Computer Simulations

The simulation is carried using non-linear problem in Abaqus software. The target was designed using slightly modified versions of Johnson-cook model [15] (Johnson and Cook and Von Mises stress are also expressed in BØrvik et al., [14]

$$\sigma_{eq} = (A + B\epsilon_{eq}^{n})(1 + Cln(\frac{\epsilon}{\epsilon^{\cdot}})((1 - \frac{T - T_r}{T_m - T_m})^m) \quad (1)$$

where material constants like A, B, C, n and m determined from tests. The strain rate is considered as per stated in BØrvik [11]. The increase in temperature under the adiabatic condition and the JC model is implemented in Abaqus as per Johnson and Cook by considering strain rate, temperature, and plastic strain.

$$\epsilon_f = (D_1 + D_2 e^{D_3(\frac{P}{\sigma_{eq}}}))(1 + D_4 ln(\frac{\epsilon}{\epsilon_{eq}}))((1 - D_5\frac{T - T_r}{T_m - T_m})^m) \quad (2)$$

The criterion is based on many variables and critical parameters. Element erosion is set to zero when a stress component in the element reaches the damage criteria.

3. Material constants

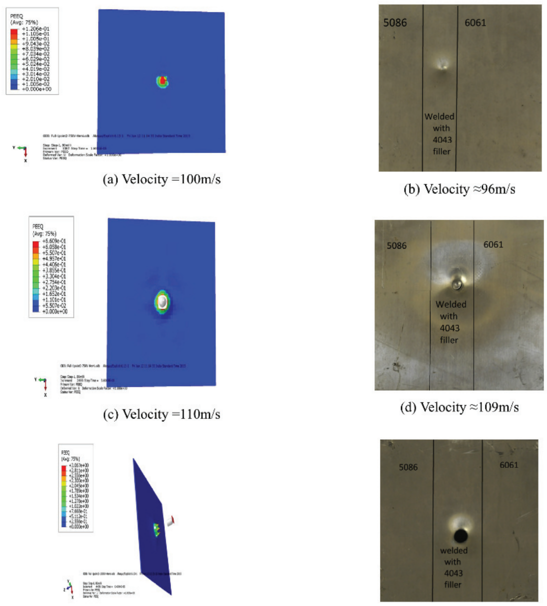
The terms for hardening JC model as per Eq.(1) to the fracture model as per Eq.(2) are taken into considerations to have possible fit, the material constants for JC model are given in Table 1, The comparison of power law to stress-strain found to be in good agreement for welded aluminum plates with 1.2 mm and 3 mm plates. The weld exhibits Dynamic Strain Aging (DSA) (causing negative strain rate sensitivity) room temperature and lower strain rates, which cannot be taken for the JC model. Strain rate sensitivity in negative is neglected, a mean value of C was chosen for fit to all the data. Here, only data giving strain rate sensitivity for positive values was used in the model.

Table 1: Johnson Cook strength model parameters for Weld AA 5086-H111 to 6061-T6 with AA 4043 required for computer simulations

A (N/mm^2)	B(N/mm^2)	C	m	n
324.1	113.8	0.008	0.859	0.42

Table 2: Damage Johnson Cook law parameters for the equation

D_1	D_2	D_3	D_4	D_5
0.071	1.248	-1.142	0.147	0



(a) Velocity =100m/s
(b) Velocity ≈96m/s
(c) Velocity =110m/s
(d) Velocity ≈109m/s
(e) Velocity = 120 m/s
(f) Velocity ≈ 124m/s

Fig. 4: Complete perforation of Hemispherical bullet on Al plate of 1.2 mm thick Model (a) Velocity =100m/s; (b) Velocity ≈ 96m/s; (c) Velocity =110m/s; (d) Velocity ≈109m/s; (e) Velocity = 120 m/s; (f) Velocity ≈ 124m/s

4. Results & Discussions

Results were presented for perforation on rigid hemispherical nose projectiles that penetrate into 5086-H111 welded to 6061-T6 with 4043 filler aluminum plates. The target thickness is assumed as elastic as well as plastic, where the plastic region is considered as incompressible.

This perforation predicts clearly the dominant problem in experimental and simulation studies on velocity, thickness, and other parameters. Model predictions as per Fig. 7 and also shows for correction factor for target inertia with an increase of plate thickness.

As stated in the experimental section, the intention of major approximations was to develop these perforation equations. The solutions in the equation of perforation are in reasonable agreement with six data sets for 3 mm plate and 9 data sets for 1.2 mm plate, but the prediction accuracy beyond the range of these data sets was not experimentally tested due to resource limitations in the lab. JC model taken into consideration in the present study for the thin plates the petaling and plugging effect is observed in the weld.

Plugging is due to dynamic strain aging resulted in some cases, whereas in some cases it failed by the petaling effect almost all the specimens. It is understood from the Fig. 4(d) that the projectile got repelled for lower velocities approximately 90 m/s for 1.2 mm plates and 109 m/s for 3 mm plates. The second order curve fit is predicted using the python code, and leads to an analytical value of ballistic limits for the 1.2 mm thick plate is 87 m/s and 105 m/s for 3 mm thick plate respectively. One data set event of test is captured and presented in the Fig. 2 using Interpolation method.

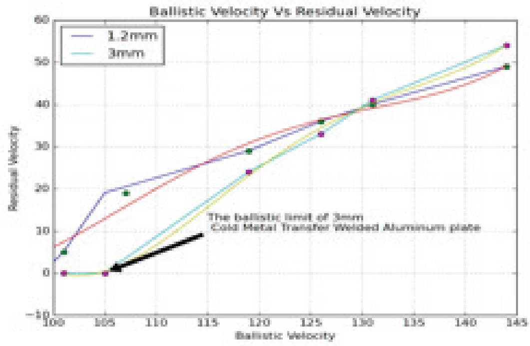


Fig. 5: Ballistic test results conducted on 1.2 mm and 3 mm CMT welded aluminum plates with python coding

5. Conclusions

The materials tests show that the welded AA5086-H111 to AA6061-T6 plates with AA4043 filler are anisotropic in flow stress, plastic flow, and ductility (or strain to fracture). Weld AA5086-H111 to AA6061-T6 plates with AA4043 filler alloy in the current study from a metallurgical perspective, shows that the strain aging and dynamic strain aging has made the material lead to plugging effect in some plates. The remaining plates are responded to petaling effect. The experimental results reveal that thin plate 1.2 mm with projectile traveling at low or moderate impact velocities require the smallest impact energy, but with hemi, spherically-tipped projectiles require the greatest energy to perforate aluminum alloy plating. This observation is reflected in the significant attention which has been given by the research community in developing empirical equations for the perforation of plating by increasing the thickness. The welded plates discussed in this paper is applicable to marine conditions for ballistic-limit as specified in the ranges for 1.2 mm and 3 mm thin walled structures. It is possible to perform the ballistic test experiments for plates with higher thickness using CMT, which will give further insights into the relevance of such technology in fabrication techniques.

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References

[1] Awerbuch J, Bodner SR. Analysis of the mechanics of perforation of projectiles in metallic plates. International Journal of Solids and Structures. 1974;10:671-84.
[2] Wingrove AL. The influence of projectile geometry on adiabatic shear and target failure. Metallurgical Transactions. 1973;4:1829-33.
[3] Recht RF, Ipson TW. Ballistic Perforation Dynamics. Journal of Applied Mechanics. 1963;30:384-90.
[4] Corran RSJ, Shadbolt PJ, Ruiz C. Impact loading of plates ? An experimental investigation. International Journal of Impact Engineering. 1983;1:3-22.
[5] Camacho GT, Ortiz M. Adaptive Lagrangian modelling of ballistic penetration of metallic targets. Computer Methods in Applied Mechanics and Engineering. 1997;142:269-301.

[6] Gupta NK, Iqbal MA, Sekhon GS. Experimental and numerical studies on the behavior of thin aluminum plates subjected to impact by blunt- and hemispherical-nosed projectiles. International Journal of Impact Engineering. 2006;32:1921-44.
[7] Gupta NK, Iqbal MA, Sekhon GS. Effect of projectile nose shape, impact velocity and target thickness on deformation behavior of aluminum plates. International Journal of Solids and Structures. 2007;44:3411-39.
[8] Jones N, Paik JK. Impact perforation of aluminium alloy plates. International Journal of Impact Engineering. 2012;48:46-53.
[9] BØrvik T, Langseth M, Hopperstad OS, Malo KA. Perforation of 12 mm thick steel plates by 20 mm diameter projectiles with flat, hemispherical and conical noses: Part I: Experimental study. International Journal of Impact Engineering. 2002;27:19-35.
[10] Clausen AH, BØrvik T, Hopperstad OS, Benallal A. Flow and fracture characteristics of aluminium alloy AA5083?H116 as function of strain rate, temperature and triaxiality. Materials Science and Engineering: A. 2004;364:260-72.
[11] BØrvik T, Forrestal MJ, Hopperstad OS, Warren TL, Langseth M. Perforation of AA5083-H116 aluminium plates with conical-nose steel projectiles ? Calculations. International Journal of Impact Engineering. 2009;36:426-37.
[12] BØrvik T, Dey S, Clausen AH. Perforation resistance of five different high-strength steel plates subjected to small-arms projectiles. International Journal of Impact Engineering. 2009;36:948-64.
[13] Gungor B, Kaluc E, Taban E, Sik ?? A. Mechanical and microstructural properties of robotic Cold Metal Transfer (CMT) welded 5083-H111 and 6082-T651 aluminum alloys. Materials & Design. 2014;54:207-11.
[14] Balaganesan G, Velmurugan R, Srinivasan M, Gupta NK, Kanny K. Energy absorption and ballistic limit of nanocomposite laminates subjected to impact loading. International Journal of Impact Engineering. 2014;74:57- 66.
[15] Johnson GR, Cook WH. A constitutive model and data for metals subjected to large strains, high strain rates and high temperatures. Proceedings of the 7th International Symposium on Ballistics: The Hague, The Netherlands; 1983. p. 541-7.
[16] Ben-Dor G, Dubinsky A, Elperin T. Applied high-speed plate penetration dynamics: Springer; 2006.