Proceedings of the 4th International Conference on Mechatronics and Smart Systems
DOI: 10.54254/2755-2721/2026.34887

Numerical Modeling and Initiation Condition Analysis of Explosive Welding for Stainless Steel/Steel Composite Plates Based on LS-DYNA

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Abstract. Aiming at the keyword model of stainless steel/steel composite plate explosive welding given in simulation data, this paper systematically sorts out the three-dimensional modeling ideas, material parameter system and initiation conditions based on LS-DYNA. Combined with the explosive welding window theory, the rules of interfacial formation are analyzed. According to the analysis of the keyword file, the model consists of an explosive layer, a SUS304 stainless steel flyer plate and a Q345R steel base plate. MAT_HIGH_EXPLOSIVE_BURN and JWL equation of state are adopted to describe detonation loading, while the Johnson-Cook constitutive model and Gruneisen equation of state are used to characterize the high-velocity impact response of metals. The typical structural dimensions of the model are as follows: the flyer plate is 400 mm×300 mm×6 mm, the base plate is 360 mm×260 mm×26 mm, the explosive layer is 20 mm thick, and the initial stand-off distance is 14 mm. Two groups of initiation point settings are further compared: one is set near the left edge of the explosive layer, and the other is arranged at the partial central area of the explosive surface. The analysis results show that edge initiation is more conducive to forming a collision front that advances steadily along the welding direction, and it can generate a continuous plastic deformation zone on the flyer plate as well as a more uniform interfacial evolution path. By contrast, off-center initiation tends to introduce local curvature effect and inhomogeneous loading on the plate surface. The results obtained in this paper provide reusable model basis for subsequent supplementary calculation, extraction of post-processing results such as interfacial pressure, collision velocity and equivalent plastic strain, and improvement of result discussion in student conference papers.

Keywords: Explosive Welding, Stainless Steel/Steel Composite Plate, LS-DYNA, Johnson-Cook, Initiation Condition, Interfacial Evolution

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1. Introduction

1.1. Research background and research object

Explosive welding is a composite manufacturing technology that realizes solid-state joining of dissimilar metals by virtue of transient high pressure and high-velocity impact generated by explosive detonation. It possesses advantages including low heat input, wide range of weldable material combinations and high interfacial bonding strength, and thus has important application values in the manufacture of pressure vessels, chemical equipment, nuclear power heat exchange components and offshore engineering composite plates [1]. For the stainless steel/steel composite plate system, the flyer plate undertakes the corrosion resistance function while the base plate bears the main load-bearing function. The interfacial bonding quality directly determines the strength reserve, service life and stability of subsequent machining of components.

Different from conventional welding, the whole process of explosive welding lasts for an extremely short time. Parameters such as collision point velocity, collision angle, explosive coverage mode and inter-plate gap all significantly affect the interfacial jet, waveform formation and residual stress distribution [2]. Since the high-velocity impact interface cannot be fully captured by experiments, numerical simulation has become an important means to reveal the evolution mechanism of interface, optimize process parameters and shorten the test cycle [3-6].

1.2. Current status of numerical simulation research

From the perspective of current research progress, the finite element method, ALE/Euler method and meshless methods such as SPH have been applied to describe the large deformation and contact instability behavior in explosive welding [7-9]. Among them, LS-DYNA is mature in explicit dynamics, multi-material contact and detonation load processing, so it is suitable for studying the acceleration of flyer plate, propagation of collision front and stress-strain response near the interface during explosive welding.

1.3. Research objectives and main contents

Instead of redefining materials and dimensions, this paper takes the LS-DYNA keyword model provided by users as the research object, analyzes its geometric structure, material cards and contact settings as well as initiation modes, and compiles a first draft of conference paper on this basis. The key research contents are as follows: (1) sort out the actual parameters and dimensional system of the model; (2) compare two working conditions with different initiation positions; (3) summarize the macroscopic interfacial evolution and key mechanical results that need to be focused on in the follow-up paper.

2. Establishment and methodology of simulation model

2.1. Geometric model and mesh generation

By analyzing the node coordinates and solid element connection relations in *templsppfile.k*, it is confirmed that the model adopts three-dimensional solid modeling, which contains three parts: explosive layer, flyer plate and base plate. The coordinate system of the model matches the supporting test data, and the consistent unit system of cm-g-μs is applied. Therefore, the thickness values in the z-direction of 0.6, 1.4 and 2.6 correspond to the 6 mm-thick flyer plate, 14 mm inter-

DOI: 10.54254/2755-2721/2026.34887

plate gap and 26 mm-thick base plate respectively. It can be seen that this model is well consistent with the SUS304/Q345R explosive welding specimens [2].

In terms of plane size, both the explosive layer and the flyer plate measure 40 cm×30 cm, namely 400 mm×300 mm, and the base plate is 36 cm×26 cm, namely 360 mm×260 mm. The explosive layer is 2.0 cm (20 mm) thick and fully covers the upper surface of the flyer plate. The model contains approximately 680,000 solid elements in total, among which the explosive layer, flyer plate and base plate have about 93,100, 213,600 and 373,700 elements respectively. The mesh can accurately describe the stress wave propagation and local plastic deformation near the collision zone.

Fig. 1 Plan View and Initiation Points of the Keyword Model

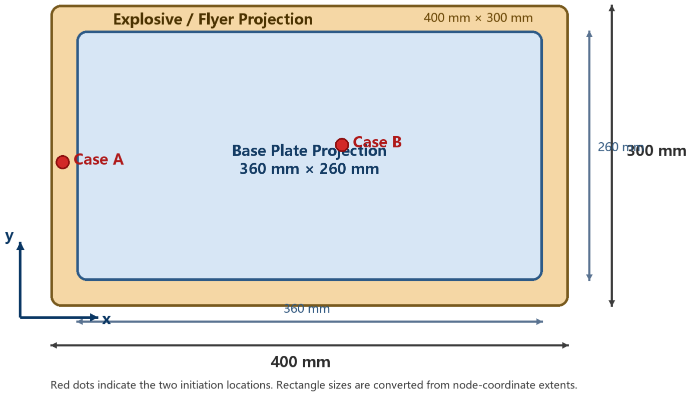

Figure1. Plan view and initiation points of the keyword model

Fig. 2 Through-Thickness Layer Stack and Initial Stand-off

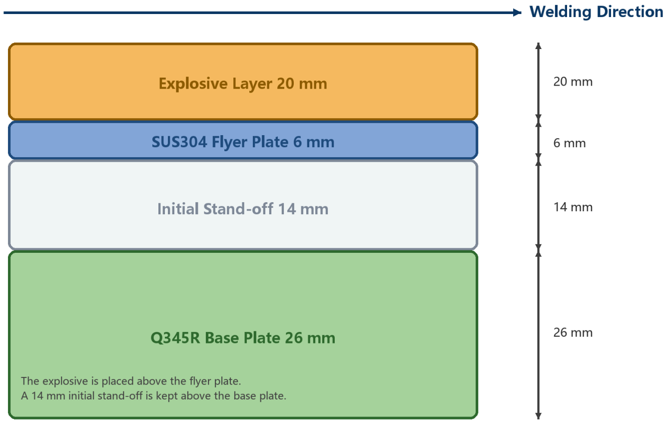

Figure2. Through-thickness layer stack and initial stand-off

The geometric dimensions and mesh information of each part are listed as follows:

Explosive layer: x = -20.0~20.0 cm, y = -15.0~15.0 cm, z = 0.0~2.0 cm, corresponding to 400 mm×300 mm×20 mm, with 93100 elements.

SUS304 flyer plate: x = -20.0~20.0 cm, y = -15.0~15.0 cm, z = 2.0~2.6 cm, corresponding to 400 mm×300 mm×6 mm, with 213600 elements.

Q345R base plate: x = -18.0~18.0 cm, y = -13.0~13.0 cm, z = 4.0~6.6 cm, corresponding to 360 mm×260 mm×26 mm, with 373680 elements.

Inter-plate gap: z = 2.6~4.0 cm, corresponding to 14 mm.

2.2. Material model and equation of state

For material models, MAT_HIGH_EXPLOSIVE_BURN combined with JWL equation of state is adopted for explosives. Metal components use MAT_JOHNSON_COOK with the Gruneisen equation of state attached. This combination is suitable for describing the high-velocity collision process of stainless steel/steel driven by low detonation velocity explosives. It can not only reflect the attenuation of detonation pressure, but also characterize the yield strengthening, thermal softening and compression response of metals under high strain rate.

2.2.1. Main parameters of constitutive model and equation of state for metallic materials

SUS304 flyer plate: ρ = 7.93 g/cm³, A = 0.007, B = 0.013, n = 0.75, C = 0.021, m = 0.90, c = 0.458 cm/μs, γ_0 = 1.93

Q345R base plate: ρ = 7.85 g/cm³, A = 0.00792, B = 0.0051, n = 0.26, C = 0.014, m = 1.03, c = 0.4595 cm/μs, γ_0 = 2.17

2.2.2. Explosive model and initiation conditions

Explosive material model: MAT_HIGH_EXPLOSIVE_BURN + EOS_JWL

Explosive density and detonation velocity: ρ = 0.65 g/cm³, D = 0.24 cm/μs, approximately 2400 m/s

JWL parameters: A = 1.3275, B = 0.00439, R1 = 5.3, R2 = 1.2, ω = 0.21, E0 = 0.0248

Case A: Initiation point at (-19.0977, 0.3, 0) cm, single-end edge initiation

Case B: Initiation point at (2.5, 1.8, 0) cm, off-center initiation

In the contact definition, automatic surface-to-surface contact and erosion surface-to-surface contact are applied simultaneously. The contact between explosive layer and flyer plate is used to transmit detonation driving load, while the contact between flyer plate and base plate is adopted to capture large deformation collision and correct potential local separation or penetration. MAT_ADD_EROSION is attached to all three types of materials, and the equivalent failure strain is set as 0.5 to maintain calculation stability under extreme local distortion conditions.

2.3. Boundary conditions and initial conditions

Two main initiation working conditions are set in the model. The initiation point of Case A is at (-19.0977, 0.3, 0) cm, near the left edge of the explosive layer, which is a typical single-end edge initiation. The initiation point of Case B is at (2.5, 1.8, 0) cm, located at the partial central area of the explosive surface. This condition is more applicable to exploring the influence of local loading path change on the uniformity of interfacial formation.

In terms of process parameters, the collision front of Case A tends to advance continuously along the plate length direction. After accelerating within the 14 mm gap, the flyer plate collides with the base plate in an inclined form, which is consistent with the typical process path of flat stainless steel/steel explosive welding [2]. For Case B, the detonation wave presents a stronger trend of local diffusion on the plate surface, which may lead to more obvious differences in collision angle and collision point velocity at different positions.

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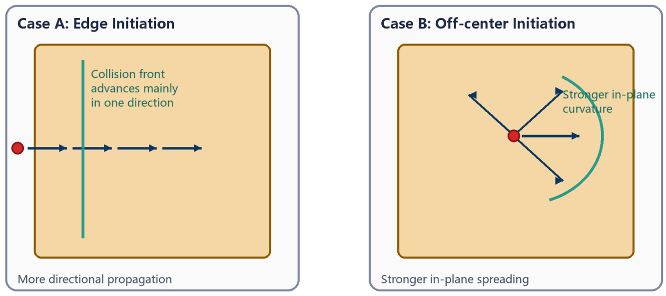
Fig. 3 Schematic Detonation Paths for the Two Initiation Cases



Case A is more suitable for a stable long-range advancing front, while Case B is more suitable for loading-path sensitivity analysis.

Figure3. Schematic detonation paths for the two initiation cases

2.4. Numerical solution settings

According to the keyword file, the model termination time is set to 500 μs. The output time interval of glstat and matsum is 0.1 μs, and the output time interval of d3plot and d3thdt is 10 μs. This output strategy takes into account the overall energy conservation check and observation of macroscopic deformation process, and is suitable for extracting typical results such as the time history of flyer plate velocity, interfacial pressure distribution, material energy conversion and propagation velocity of welding zone in the follow-up work.

Since explosive welding is a problem with strong transient effect and large deformation, the explicit integral solver can well adapt to the rapid switching of contact state and propagation of shock waves. From the existing settings, this model can be taken as a basic example to verify the collision path and carry out further parameter expansion.

3. Simulation results and analysis

3.1. Macroscopic interfacial evolution characteristics

According to the geometric relations and initiation positions, the detonation wave of Case A propagates from the left end to the right. It first drives the local acceleration of the flyer plate below the explosive, and then a continuous inclined collision front is formed in the inter-plate gap. As the thickness of the flyer plate is only 6 mm while the base plate reaches 26 mm, the flyer plate bears most of the macroscopic bending and plastic deformation, and the base plate provides strong inertial constraint and support. The combination of thin flyer plate, thick base plate and low detonation velocity explosive is conducive to forming a stable compression zone near the initiation end at first, and then expanding it into a continuous bonding zone along the welding direction.

Combined with contact settings and material models, the macroscopic evolution of the interface generally experiences several stages: acceleration of the flyer plate, initial impact, cleaning of local interfacial jet, continuous collision propagation and gradual stabilization of interfacial waveform. There is an obvious spatiotemporal coupling relationship between the detonation wave and the collision front. A high-pressure compression zone is firstly formed near the initiation end. As the collision front moves forward, the velocity of the free surface of the flyer plate gradually decreases, and the interfacial formation expands from local area to continuous region.

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3.2. Distribution of key mechanical parameters

In terms of key mechanical parameters, the peak value of normal interfacial stress generally appears near the collision front. The high-value area of equivalent plastic strain is mostly distributed at the rear edge of collision points on the flyer plate side, the areas where wave crests and troughs will form, and the adjacent shear bands. Due to the larger thickness, the base plate is mainly subjected to combined compression and shear action below the interface, with a relatively narrow range of plastic deformation. Combined with Johnson-Cook parameters, it can be concluded that the strain concentration and material flow on the flyer plate side are the dominant factors for the formation of interfacial jet and wavy bonding interface.

For subsequent supplementary calculation, the following results deserve priority attention: (1) variations of collision velocity and collision angle of the flyer plate along the welding direction; (2) locations of high-value areas of normal interfacial pressure, equivalent plastic strain and temperature rise; (3) conversion relationship between kinetic energy and internal energy in glstat and matsum. These results can directly support the graphic and textual discussion of the sections about macroscopic interfacial evolution characteristics and distribution of key mechanical parameters in student papers.

3.3. Analysis of the influence of initiation conditions

Different from Case A, the initiation point of Case B is close to the inner area of the plate surface, making the detonation load expand radially locally rather than advance in a single direction. This loading mode increases the curvature of the collision front on the plate surface and reduces the consistency of collision parameters at different positions. For plates with finite size, this condition usually leads to a more concentrated initial welding area, more distinct differences in collision angles among different cross sections, and higher susceptibility to interference from edge reflected waves.

From the perspective of industrial plate manufacturing, Case A is more representative if the target is to obtain a long-distance, stable and statistically accessible wavy bonding zone. If the research focuses on analyzing the influence of inhomogeneous charge distribution, local coverage or multi-point initiation on interfacial inhomogeneity, Case B is more suitable for sensitivity analysis. Therefore, it is suggested to take Case A as the main working condition and Case B as the comparative working condition in the paper, so as to highlight the influence of detonation path change on the uniformity of interfacial evolution.

3.4. Reliability verification of simulation results

The reliability of the model can be verified from three aspects. Firstly, the geometric dimensions, explosive density and detonation velocity are consistent with the supporting test system. The flyer plate is made of SUS304 and the base plate is Q345R. The explosive density is about 0.65 g/cm³ and the detonation velocity is about 0.24 cm/μs (approximately 2400 m/s), all of which are in accordance with existing experimental studies [2]. Secondly, the 14 mm inter-plate gap falls within the common process range for 6 mm-thick stainless steel flyer plates of this type, which ensures effective acceleration of the flyer plate.

Thirdly, the combination of Johnson-Cook constitutive model, JWL equation of state, automatic contact and erosion contact adopted in the model is a mature and widely used technical route for explicit dynamic analysis of explosive welding [7-9]. Although post-processing result files such as

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d3plot and glstat are not attached to the provided data, the keyword model has the foundation for further calculation and quantitative analysis in conference papers in view of the consistency of parameters, unit system and modeling method.

4. Conclusions

(1) The simulation data provided corresponds to a three-dimensional LS-DYNA model for explosive welding of SUS304 stainless steel/Q345R steel composite plates, which adopts the cm-g-μs consistent unit system. The physical dimensions of the model are as follows: 400 mm×300 mm×6 mm for the flyer plate, 360 mm×260 mm×26 mm for the base plate, 20 mm for the explosive layer and 14 mm for the initial stand-off distance. All parameters are clear and can be directly used as the modeling basis for conference papers.

(2) The model applies MAT_HIGH_EXPLOSIVE_BURN combined with JWL equation of state to describe explosive detonation, and adopts Johnson-Cook model together with Gruneisen equation of state to simulate high-velocity collision of metals. Combined with automatic contact, erosion contact and material erosion technology to ensure calculation stability, the model can meet the requirements for large deformation analysis of explosive welding interface.

(3) Among the two groups of initiation conditions, edge initiation is more conducive to forming a collision front advancing steadily along the welding direction, so it is recommended as the main working condition of the paper. Off-center initiation is suitable to serve as a comparative working condition for loading path sensitivity analysis. In the follow-up supplementary calculation, priority should be given to extracting results including collision velocity, interfacial pressure, equivalent plastic strain and energy conversion to enrich charts and quantitative discussion in the paper.

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