VERIFICATION OF JOHNSON-COOK MATERIAL MODEL CONSTANTS OF AA2024-T3 FOR USE IN FINITE ELEMENT SIMULATION OF FRICTION STIR WELDING AND ITS UTILIZATION IN SEVERE PLASTIC DEFORMATION PROCESS MODELLING

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Abstract

Friction Stir Welding (FSW) is a solid state joining process which is gaining significance in many joining applications. The increased use of various commercial Finite Element (FE) packages are also aiding in widening the applicability of FSW by simulating the process for better understanding. However, reliability and accuracy of estimated results depend much on the selected modeling approach and governing equations. The principal equations that govern modeling of FSW are the material model and the friction model. This paper aims in discussing the influence of Johnson–Cook material model constants reported in literature on results obtained from FE simulations of FSW using ABAQUS. The current study also helps in extending the screened and identified constants of Johnson-Cook material model to processes undergoing severe plastic deformation.

Key Words: *FE modeling, FSW, Coupled Eulerian Lagrangian, Johnson-Cook Material Model, ABAQUS*

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1. INTRODUCTION

Friction stir welding is a modification of the traditional friction welding. It is a process patented by The Welding Institute in Cambridge, England in 1991. It is a mechanical process whereby solid-state welding is performed using heat generated from the friction of a rotating tool and plastic deformation of weld material [1, 2]. Two metals that are to be welded together are held in place against a backing plate using a clamping system. The rotating tool is then slowly plunged with a downward force into the weld joint. It dwells for a few seconds while enough heat is generated due to friction that the welded material would begin to flow around the tool. Once this point is reached, the tool is traversed along the joint forming the weld behind the tool as it moves along. The schematic representation of basic principle of the FSW process illustrated in Fig-1. The main benefit of friction stir welding is that the base materials to be welded would not be reaching their melting points. FSW was initially applied to aluminum alloys. Since then FSW has rapidly evolved and has opened up a variety of research channels. It is being touted as the most significant development in metal joining in the last decade [1, 2]. Many alloys, including most aerospace Al alloys (e.g., Al 7xxx) and those regarded as difficult to weld by fusion processes (e.g., Al 2xxx), can be welded by FSW [3, 4].

Since FSW process is solid state welding, it offers metallurgical advantages over conventional fusion welding processes. Invention of the FSW process made a number of aluminium alloys, especially the copper containing 2000-series and 7000-series, receptive to welding, which were previously considered to be non-weldable primarily because of their sensitivity to cracking due essentially to a wide freezing range during solidification coupled with the formation of partially melted zones in the heat-affected zone near the fusion line. The significant advantage of FSW is that it is an environment friendly process, which does not make use of flux and consumable electrodes thereby minimizing and avoids the generation of fumes, formation of slag and ultra-violet radiation thus minimizing the level of health hazards [5].

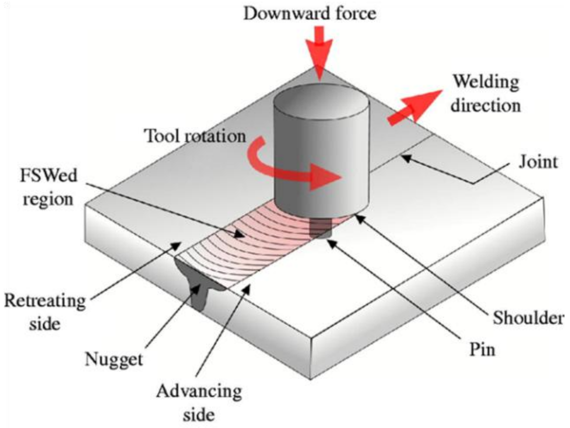


Fig- 1: Schematic of friction stir welding process [6]

In the analysis of FSW using FE simulations, reliability and accuracy of estimated results depend much on two major factors. The first is the flow stress characteristics of work materials to be welded and the second is the contact condition at the interfaces.

The influence of work material flow stress upon FE simulations may be less or even none when there is a constitutive model for work material that is obtained empirically from high-strain rate and temperature deformation tests [7]. Johnson–Cook material model [8] is most commonly used model to represent the thermo-visco-plastic behavior of workpiece material. However, the difficulty arises when one needs to implement accurate material model and their constants for welding simulations using a particular FE formulation. In this study, a Coupled Eulerian Lagrangian finite element formulation is used to simulate FSW of 2024-T3 aluminium alloy. The effects of using various Johnson-Cook material constants are discoursed.

Experimentally measured temperature in the work piece, force on the tool and macro structural findings for defects are utilized in investigation and evaluation of the results. The results depict that the use of various values of Johnson-Cook constants have influence in predicting temperature, force and mainly defect formation.

2. FLOW STRESS CHARACTERISTICS

Material flow during FSW is quite complex, it depends on the tool geometry, process parameters, and material to be welded. It is of practical importance to understand the material flow characteristics for optimal tool design and to obtain high structural efficiency welds [1]. Modeling of the metal flow in FSW is a challenging problem, but this is a fundamental task to be understood in developing the process. Flow models should be able to simultaneously capture the thermal and mechanical aspects of a given problem in adequate detail to address the following topics [9].

- Flow visualization, including the flow of similar /dissimilar metals.
- Evaluation of the heat flow that governs the temperature field.
- Tool design to optimize tool profiling for different materials and thicknesses.
- Susceptibility to formation of defects.

The material flow around the probe is one of the main parameters, determinant for the success of FSW [1]. Numerical FSW flow modeling can be based on analyses and techniques used for other processes, such as friction welding, extrusion, machining, forging, rolling, and ballistic impact [1]. As for heat flow analyses, numerical flow models can use either an Eulerian or Lagrangian formulation for the mesh, other solution can be the combination of both (hybrid solution and Lagrangian–Eulerian) [9]. Here in present simulation a coupled Eulerian Lagrangian formulation is used, which is a hybrid solution.

FSW modelers have used a variety of material models (constitutive laws) to characterize material behavior [10]. They are Sellars and Tegart/Sheppard and Wright law, Johnson–Cook plasticity law, Buffa law, Zhang and Chen law, Heurtier law, Arbegast law, Saturated Hart model and Modified Hart model. But Johnson–Cook plasticity law is the only law which can be fit over a wide range of strain, strain rate, and temperature. Several materials, each with its own set of constants, can be characterized by the Johnson–Cook law. However, accuracy for a particular material may be sacrificed for this versatility [8].

Hence, the Johnson-Cook model with variation in constants for aluminium alloy 2024-T3 is analyzed here for accurate results. Also simulations are performed with the flow stress data drawn from the hot working guide [11] and with data as taken by Sonne, et al. [12], to see the effect on FSW modeling.

Table- 1: Material properties of AA2024-T3

Material properties	**Value**
Young’s modulus of elastic. [GPa]	73.1
Poisson’s ratio	0.33
Initial yield stress [MPa]	345
Ultimate tensile strength [MPa]	483
Thermal conductivity [$Wm^{-1}K^{-1}$]	121
Coefficient of thermal expansion [$°C^{-1}$]	24.7×10^{-6}
Density [kgm^{-3}]	2770
Specific heat capacity [$Jk^{-1}g°C^{-1}$]	875
Solidus [°C]	502
Liquidus [°C]	638

2.1 Johnson-Cook material law

The Johnson-Cook model/law [8] was developed by conducting torsion and dynamic Hopkinson bar tensile tests over a wide range of strain rates and temperatures for a variety of engineering materials. The Johnson-Cook equation (1) describes the flow stress as a product of the equivalent strain, strain rate, temperature dependent terms and several parameters to adequate the real behavior of the materials.

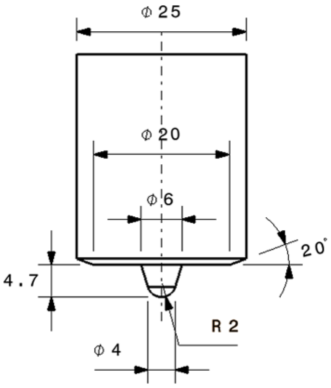
$$\sigma_y = \left[A + B\left(\varepsilon_p\right)^n\right]\left[1 + C\left(\frac{\varepsilon_p}{\varepsilon_o}\right)\right]\left[1 - \left(\frac{T - T_{room}}{T_{melt} - T_{room}}\right)^m\right] \quad (1)$$

where T_{melt} is the melting point or solidus temperature, T_{room} the ambient temperature, T the effective temperature, A the yield stress, B the strain factor, n the strain exponent, m the temperature exponent, $\varepsilon_p/\varepsilon_0$ the plastic strain and C the strain rate factor. A, B, C, n, and m are material/test constants for the Johnson-Cook strain rate dependent yield stress. The Material properties of AA2024-T3, considered for simulations are as per the values taken by Veljic, et al. [13] and are given in Table- 1.

3. MODELING DETAILS

FE model is developed in the commercial code ABAQUS/Explicit using the Coupled Eulerian-Lagrangian Formulation, the Johnson-Cook material law, and Coulomb's Law of friction.

The tool dimensions considered are 25 mm shoulder dia., frustum shaped pin with 6/4 diameter at base and tip, pin length is 4.7 mm. Material of tool is Hot Die Steel (HDS). The workpiece of 200 X 100 mm area and thickness of 5 mm is considered in model. The Fig- 2 shows the geometry of tool and workpiece. The Eulerian domain is meshed with multi-material thermally coupled 8-node EC3D8RT Eulerian elements [14, 15] and the void region thickness is taken as 1 mm. The friction coefficient of one is considered for all simulation conditions from the previous findings.



(All dimensions are in mm)

Fig- 2: Geometry of tool employed [16]

The simulation and experimental welding conditions considered are; Plunge velocity of 10 mm/min, Dwell Time of 10 sec, Welding speed of 60 mm/min, Plunge depth is 0.2 mm, tool tilt angle of 0^0 and varying the rotational speed.

4. RESULTS AND DISCUSSION

In the literature various values of constants for the Johnson-Cook were considered for an AA2024-T3 [17-22]. The simulations were performed for the values shown in Table- 2 and validation is done using results of temperature and macrographs obtained from experiment conducted on aluminium 2024-T3 alloy.

Here, for all the cases considered the melting temperature of material and room temperature are 502°C and 25°C respectively. From the literature it is found that, working temperatures in FSW should be around 0.8-0.9 T_{melt} [23] for obtaining defect free welds with any set of parameters used in welding. The temperature range from literature, macrographs obtained from experiment and temperature readings measured during experiment using thermocouples are considered in studying the effect of Johnson-Cook material constants at different cases.

It can be comprehended from the simulation results (Fig- 3) that, use of incorrect Johnson-Cook material constants have a major effect on material flow, temperature predicted and in capability of model in predicting defect formation. The same effects may be realized in modeling of other manufacturing processes undergoing severe plastic deformation.

Table- 2: Material constants for the Johnson-Cook strain rate dependent yield stress

	A (MPa)	**B (MPa)**	**n**	**C**	**m**
Case-1	345	780	0.17	0.0083	1.7
Case-2	265	426	0.34	0.015	1
Case-3	245	414	0.8	0.015	1
Case-4	325	414	0.2	0.015	1
Case-5	369	684	0.73	0.0083	1.7

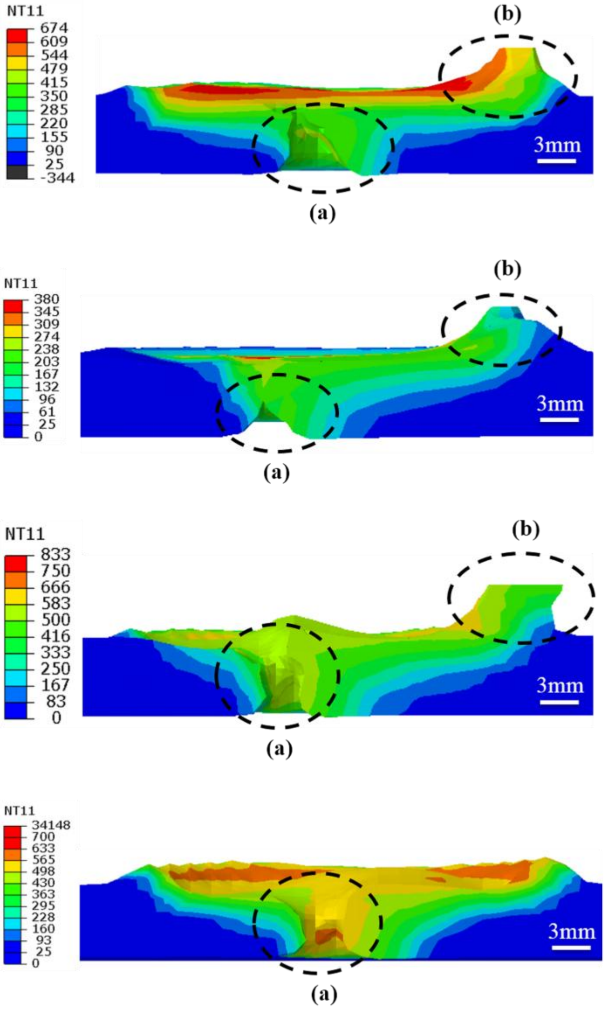


Fig- 3: Effect of Johnson-Cook material constants at case 1, 2, 3 and 4 respectively; (a) Improper flow of material around the tool and poor formation of weld zones, (b) High flash

With considering μ=1 and with right Johnson-Cook constants (i.e. case-5 values) for AA2024-T3 work material, the Fig- 4 and 5 shows the capability of model in simulating defect and defect free welds for particular process parameters. Here the only rotational speed is varied and all other parameters are as stated under modeling details. The results show that a defect is generated at 850 rpm and it reduces as the rotational speed increases. The same effects were also observed in the experimental conditions. Also after considering appropriate Johnson-Cook material constants, the temperature, torque and force on tool predicted by FE model were close to experimental results.

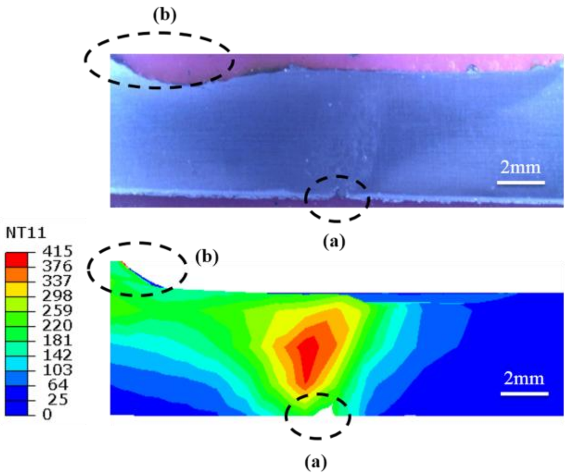


Fig- 4: Experimentally seen and numerically predicted defect at 850 rpm; (a) Root flaw defect, (b) Surface galling

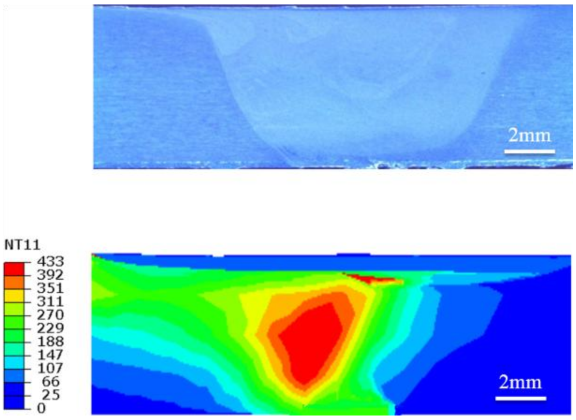


Fig- 5: Experimentally and numerically seen weld zones at 950 rpm with no defects

5. CONCLUSIONS

Based on the results and discussion, the following conclusions are drawn:

(i) With Johnson-Cook material constants, A=369 MPa, B=684 MPa, n=0.73, C=0.0083, m=1.7, T_{melt} = 502 °C and T_{room} =25 °C for AA2024 help in obtaining results close to experimental outputs.
(ii) The simulation results showed that the effect of change in Johnson-Cook material constants have a major role in accurate simulation of FSW.
(iii) The selection of correct numerical values of Johnson-Cook material constants for a particular material demonstrates the FE modeling capable in getting required results and predicting processing conditions successfully.
(iv) The study can be performed on modeling of other manufacturing processes undergoing severe plastic deformation, to see the effects in particular process and conditions with variation in Johnson-Cook material constants.
(v) FE modeling with plastic data also have the effect on the results and it will be taken up as future study.

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