Drilling process simulation of bainite steel material using FEM-SPG formulation in LS-DYNA

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Abstract. Drilling is one of the most important and common manufacturing processes in the fabrication of critical automotive powertrain components. Efficient drilling operations directly impact product quality and manufacturing productivity in the automotive industry. This research work focuses on simulating the drilling process using LS-DYNA. The simulation combines Lagrange Element Formulation and Momentum-Consistent Smoothed Particle Galerkin (MC-SPG), using the Johnson-Cook material model for material behavior under the effects of strain, strain rate and temperature on the material flow stress. Drilling process generates high mechanical and thermal loading on the drill tool and workpiece. This could significantly impact performance of tool, hole geometry and surface integrity. The research study involves simulation of thermomechanical analysis due to heat generated from mechanical work produced during chip formation. The simulation methodology incorporates the attainment of thermo-mechanical steady-state conditions to ensure stability in temperature distribution and cutting force [1]. The workpiece was made of bainite steel, and the tool was made of coated ISO K10 Hard-metal. Experiments were conducted on the CNC machine to validate the simulated forces and chip shape. This research highlights the importance of advanced simulation techniques in the evaluation of drilling process. The study confirms the reliability of the simulation model by the comparison of simulated data with experiments.

Keywords: Finite Element Method (FEM), Smoothed Particle Galerkin (SPG), Simulation, Machining.

1 Introduction

Drilling is defined as process of making circular holes by material removal process using specially designed tool known as drill bit. Deep hole drilling relies on increased material removal rate travelling over the depth of hole along the axis of the hole. Drilling is a complex machining process because of chip-flow restrictions and poor heat dissipation in a confined space when drill tool is inside the workpiece [2]. Hence simulations offer a valuable alternative to traditional experiments, which are often time-consuming, resource-intensive, and costly to study [3]. The simulation of drilling addresses the intricate demands of precision metal cutting and chip shape formation for realistic cutting parameters and understanding mechanism of drilling**.** Finite element method (FEM) is a traditional simulation method for mechanical and thermal studies [4]. The simulation of drilling processes presents a significant challenge due to the large deformations and material removal involved in the workpiece. Traditional finite element methods often struggle with mesh distortion and element entanglement in such complex deformation scenarios, particularly in metal cutting operations like drilling. Thus, discretization required for finite element method must be updated at each timestep for achieving realistic large deformation studies. This becomes increasingly computationally expensive. Hence the necessity of using alternate numerical strategies to ensure accuracy and computational stability is needed. The solution to excessive deformation would be to switch from traditional FEM to unconventional particle-based simulation. To address this, the research work leverages the Smoothed Particle Galerkin (SPG) method, a particle-based technique known for its ability to simulate large deformation problems without the limitations of mesh-based approaches where particle methods are increasingly being adopted for simulating manufacturing processes [4] [5] involving severe material deformation. To understand the chip formation at the tool-workpiece interface simulation incorporated a thermomechanical analysis [6] using Momentum Consistent Smoothed Particle Galerkin (MC-SPG), steady-state cutting model that accounts for heat generation due to plastic deformation and friction is essential. Bainite steels are high strength steel used in automotive industry for its mechanical properties, which can be categorized as hard to machine material. The aim of this research work involves simulation of drilling bainite steel using coated ISO K10 Hard-metal. Johnson Cook material parameters from previous research works were used to define mechanical property of bainite steel. The tool is modelled as rigid and cutting process parameters

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were assigned to it. The research work employs an experimental methodology to determine cutting force and analysis chips generated involving a series of drilling tests conducted under controlled conditions.

1.1 Smoothed Particle Galerkin

In computational mechanics, especially when simulating processes like metal cutting that involve excessive deformation, two prominent numerical approaches are often considered: the Finite Element Method (FEM) and the Particle Method. Particle method being more robust in scenarios involving fragmentation or severe distortion which eliminates the need of structured grid as in FEM. There are several differences between traditional FEM and unconventional particle-based approaches like use of stabilization term can boost numerical accuracy and prevent instabilities, use of smoothing kernels instead of shape function in FEM. Overall, while FEM remains a powerful tool for many engineering applications, the Particle Method offers a compelling alternative for problems where traditional meshing becomes a limitation. Its ability to handle extreme deformation and failure makes it particularly useful in advanced manufacturing simulations. In order to overcome limitations of general particle methods like difficulty in applying boundary conditions due to lack of structured mesh and tension instability, Momentum Consistent Smoothed Particle Galerkin [7] is widely used. A unique smoothing algorithm tied to linear momentum helps eliminate low-energy modes without the need for additional stabilization terms. Furthermore, the method incorporates a bond-based failure criterion, allowing for more accurate analysis of material separation behavior.

1.2 Johnson Cook Material model

Material undergoes extreme mechanical and thermal conditions during manufacturing process [8]. Johnson-Cook (JC) material model is particularly effective when materials undergo rapid deformation, elevated temperatures, and strain-induced strengthening [9]. It integrates multiple physical effects into a single stress expression, making it suitable for dynamic applications like machining, forging, or impact analysis. It integrates multiple physical effects into a single stress expression, making it suitable for dynamic applications like metal cutting. In addition to stress modeling linear polynomial equation of state (EOS) describes how pressure changes as the material’s volume shifts, particularly under compression. EOS uses parameters like the bulk modulus (a measure of compressibility) and specific volume to compute pressure. This helps in modeling the bulk behavior of materials, such as how material compresses during processing [10].

2 Experimental Setup

The experimental investigations on drilling process were conducted using Computerized-Numerical Control machine (CNC) - DMG DMC 80 HL. The workpiece material was made of high strength bainite steel 40CrMoV4-6. The experimental setup of tool and workpiece which is placed on worktable of CNC machine is shown on Fig. 1. The drilling process involved creating an 18mm diameter hole using an ISO K10 Hard metal tool with mid layer coating of 3 micrometer made up of AlTiN and outer coating layer of 3.5 micrometer made up of TiSiN. The drilling process was carried out with process parameters such as spindle speed of 860 RPM and worktable moves with feed rate as 280 mm/min towards the drill tool. The drilling process had been carried out in dry conditions as no lubrication and cooling was used. To capture the cutting forces, high precision dynamometer was attached to the fixture.

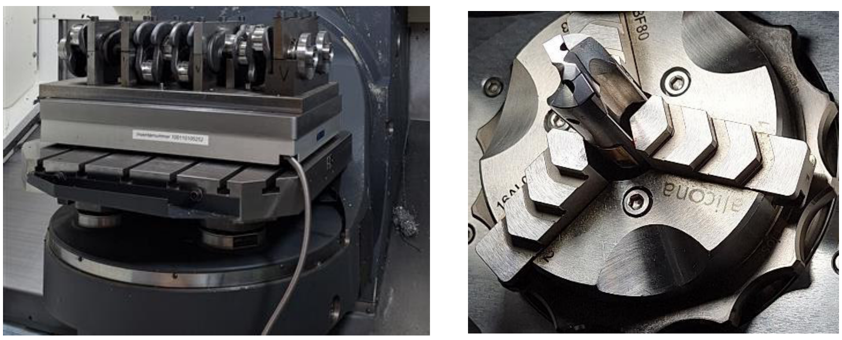

Fig.1: Experimental setup

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3 Simulation Setup

The simulation setup involved developing a 3D drilling simulation model using a combined Lagrange Element Formulation and Momentum-Consistent Smoothed Particle Galerkin (MC-SPG) .LS-DYNA was chosen as simulation software for setting up, calculating, and evaluating the numerical model. The .key or. k file was created in LS-PrePost 2025 R1 (v.4.12.5) version. The workpiece was modelled with SPG particles in the drilling zone of the workpiece and Lagrange element in the rest of the workpiece. The Lagrange element formulation was used to replicate the actual physical geometry of model and to apply boundary conditions to constrain the motion of the workpiece. The machining parameters were defined using **`*DEFINE_CURVE`** for rotation speed and feed rate. The tool and the coating layers though defined as separate parts to assign different material properties are as one rigid bodies with the help of keyword **`*CONSTRAINED_RIGID_BODIES`**. The static and dynamic coefficients of friction were set to 0.65 for the contact between outer coating of the tool and workpiece.

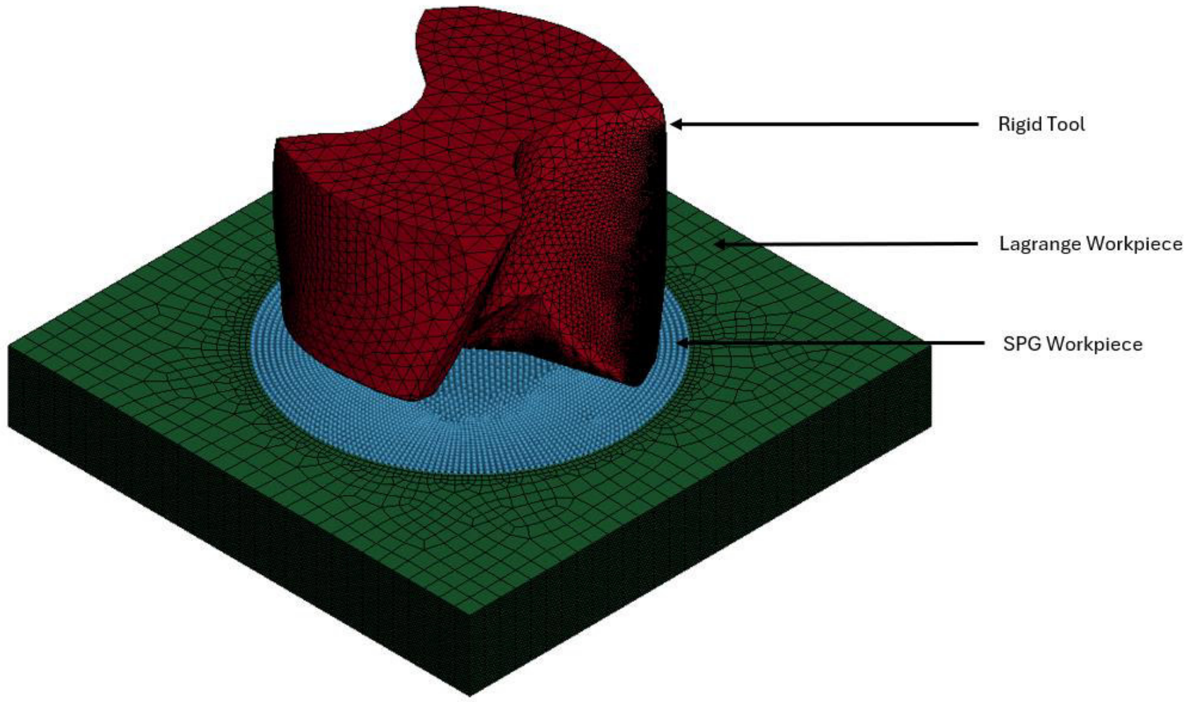

Fig.2: Simulation setup

Fig. 2 depicts the simulation setup in LS-DYNA in which the tool was meshed with approximately 500000 tetrahedron elements, the drilling zone was meshed as approximately 200000 FEM elements, and the rest was meshed with default solid elements in **`*SECTION_SOLID`**. Each node of the solid element will be treated as particles with selection of element formulation as Smoothed Particle Galerkin (SPG) method under **`*SECTION_SOLID_SPG`**. This approach offers better performance than adaptive remeshing during extreme deformation applications. The tool was made of ISO-K10 hard metal and structural material properties of the tool were applied using *MAT_RIGID. It had prescribed motion as boundary conditions in which translation and rotation in the axial direction were defined using feed rate and rotational speed curves in **`*BOUNDARY_PRESCRIBED_MOTION_RIGID`**. The workpiece was modeled as a plastic deformable material using the Johnson-Cook material model [9] with Elform 47 for SPG formulation. The Johnson–Cook (J-C) constitutive model is widely employed to model the thermo-viscoplastic behavior of workpiece materials in machining simulations [11]. The Lagrange workpiece was modeled using Elform 2 to avoid hourglass stabilization issues, with boundary conditions applied to fix the workpiece.

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4 Results

The output files of the simulation, d3plot, and binout file were obtained using ***DATABASE** keyword at specific timesteps using ***CONTROL** keywords. Fig. 3 shows von-mises stress generated during the drilling process simulation using coupled Lagrange elements with SPG particles. The SPG method allows for continuous evolution of particle information even after material failure, offering a more robust simulation framework compared to traditional FEM.

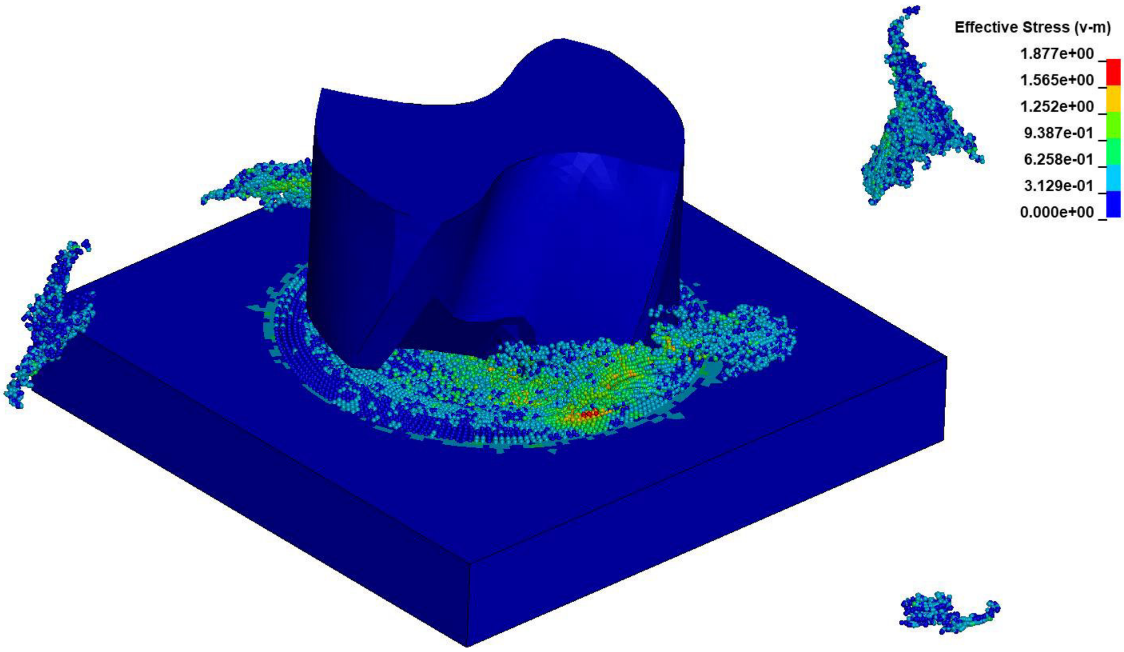

Fig.3: Drilling process simulation using coupled Lagrange elements with SPG particles

Chips collected after experiments were qualitatively analyzed for chip shape formed during metal cutting process using KEYENCE VHX-5000 as shown in Fig. 4, which is an 2D image and measurement capturing device. It is evident that Smoothed Particle Galerkin simulation in the drilling zone can produce realistic chip shape compared to experiments. The realistic chip flow is essential for contact between chip and tool surface.

Fig.4: Chip morphology from experiment (left) and simulation (right)

The force experienced by the tool along the axis of hole on the workpiece during drilling was measured with a 3-component dynamometer, Kistler 9121, and analyzed using NI DIAdem software as shown in Fig. 5. The value of cutting force remains zero until the tool encounters the workpiece. It maintains 6500 N when both lips of the drill cutting edge encounters the workpiece until the tool leaves the workpiece after 15 seconds of drilling during experiment. In simulation, the value of cutting force also remains zero

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until tool encounters the workpiece. The simulated cutting force reaches around 5000 N at 300 milliseconds when lips of the cutting edges encounter the workpiece and maintain on average of 5000 N for rest of the drilling simulations.

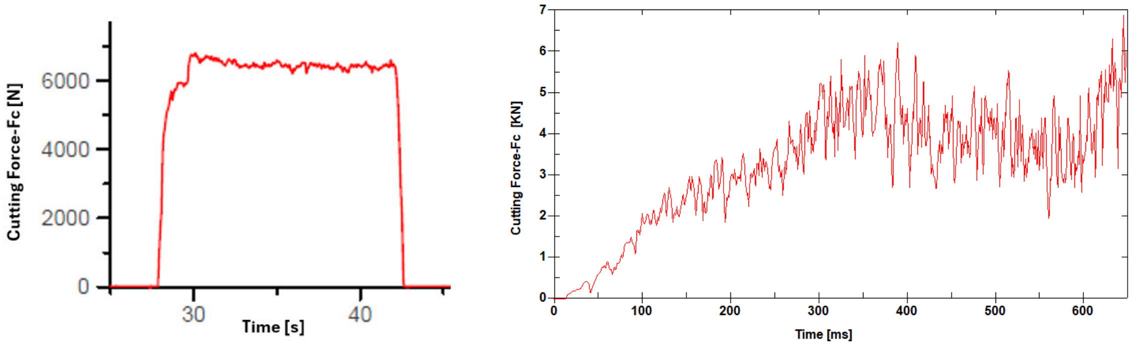

Fig.5: Comparision of Cutting force from experiment (left) and simulation (right)

5 Summary

The integration of the Coupled Lagrange Element approach with the Momentum-Consistent Smoothed Particle Galerkin (MC-SPG) method has shown strong potential in accurately replicating the drilling process in simulations. This hybrid modeling technique not only captures the physical behavior of chip formation and cutting forces but also aligns well with experimental observations, validating its reliability. The simulation results seemed to be in good agreement with the experimental results. Such advancements are particularly valuable in industries like automotive and precision manufacturing, where accurate prediction of tool performance and material response is critical. The upcoming research work will be incorporating dynamic tool wear modeling based on chip-tool interaction will further enhance the realism of simulations, enabling adaptive tool geometry updates. This paves the way for more predictive manufacturing systems that can optimize tool life and machining efficiency in real time

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