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Numerical Modelling of High Energy Density Beam Assisted Machining of Hardened Armour Steel

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Abstract: High energy density beam assisted machining (HEDBAM) finds huge applications in machining of difficult to machine materials such as hardened steels, superalloys etc. Among these materials, Armour steel is widely deployed in military and civil applications where resistance to ballistic protection is essential. In the present work, a numerical model is developed to investigate HEDBAM of high hardness Armour steel. A fully coupled thermo-mechanical analysis model is developed for predicting the cutting forces and thrust forces using commercial software Abaqus/Explicit. The developed model for orthogonal cutting is validated with previously published literature on Thermally assisted machining of titanium alloy with maximum error of 9 %. Further, the model is extended to of Armour steel at four different temperature levels (20 - 620°C) and a maximum reduction of 19% and 24 % in the cutting and thrust force, respectively is obtained at 620° C. The work paves way for HEDBAM of different hardened high strength materials.

Keywords**:** High energy density beam assisted machining, Armour steel, FEM, 2D Orthogonal cutting

1. Introduction

High hardness Armour steel (HHAS) is used for the resistance to ballistic protection in military and civil applications due to its high hardness (~500 HB) and high ultimate tensile strength (~ 1640 MPa) [1]. Due to its high strength and hardness, machining of HHAS is difficult resulting in low material removal rates (MRR), large cutting forces and reduced tool life. High energy density beam assisted machining (HEDBAM) finds key application in the machining of such difficult-to-machine materials.

HEDBAM is a hybrid machining process in which high energy source such as laser, plasma etc. is used for localized heating of the material before the material removal takes place. Temperature at which material removal takes place governs the machining performance. The material heating results in increased material removal temperature of work piece thereby reducing the strength and hardness of the material. This can increase the MRR and improve the tool life. It is observed from literature that HEDBAM can considerably improve the machinability of titanium alloys [2-5], Nickel alloys [6,7] and ceramics [8].

Xi et.al. [4] developed a 2D model for thermally assisted machining of Ti-6Al-4V at four different machining temperature (20°C,150°C, 250°C, 350°C) and predicted the chip formation behaviour and cutting force reduction. A very good correlation between the predicted cutting forces and experimental results was observed. Singh et. al. [9] developed a 3D orthogonal laser assisted machining (LAM) model to predict the temperature profile, cutting forces and stress generated during machining of D2 Tool Steel. It was observed that flow stress and cutting forces reduced by 28% and 32%, respectively after LAM. Tian et. al. [10] developed a 3D thermal model for LAM of silicon nitride and found good agreement between experimental results and surface temperature from thermal.

Thus, it is observed that there is limited literature available in the public domain on HEDBAM of HHAS. In the present work, a 2D orthogonal machining model is developed and the effect of different workpiece temperature on the cutting forces and thrust forces is estimated.

2. Finite Element Modelling

An orthogonal machining process is simulated using a plain strain 2D thermo-mechanical model in the commercially available finite element Abaqus/Explicit software. A plastic deformable workpiece of size 6 x 3 mm2 is used for the analysis. Cutting tool is modelled with rake angle ὰ = 0 and clearance angle ɤ = 7º. In metal cutting process two main phenomenon generate heat in the materials-heat produced by friction between cutting tool-workpiece interaction and heat produced by plastic deformation. It is assumed that all the frictional energy is converted into heat and 50% of its total heat is distributed into chip region. Heat generated by plastic deformation in the materials is 90%. Adiabatic boundary condition is applied on the workpiece. Further, the workpiece temperature considered for the study is assumed to be equal to the temperature generated by the high energy beam source on the workpiece surface at different energy levels. Machining parameters such as cutting speed, feed and depth of cut are kept constant during the simulation. The cutting speed, feed and depth of cut selected for the simulation are 100 m/min, 0.20 mm/rev and 1 mm, respectively for all values of workpiece temperature. Workpiece temperature values of 20 º C, 220 º C, 420 º C, and 620 º C are used for analysis.

2. 1. Material properties and constitutive models

HHAS is used as the work piece material and Tungsten Carbide (WC) is used as the tool material. Mechanical and thermal properties of work piece and tool are presented in table 1.

Table. 1 Material property of HHAS and WC [1, 4]

Material Properties	HHAS	WC	Material Properties	HHAS	WC
Density (Kg/m^3)	7860	14500	Specific Heat (J/kg-°K)	452	220
Young Modulus (GPA)	205	640	Thermal expansion coefficient	9 x 10^{-6} /K	-
Poisson's Ratio	0.293	0.22	Thermal Conductivity(W/m-°K)	20	75.4

During the cutting process, material undergoes high strain rate deformation and hence Johnson cook constitutive model is used [1]. Flow stress of material during the process is presented in Eq. (1)

$$\sigma = (A + B\varepsilon^n)(1 + Cln(\frac{\acute{\varepsilon}}{\acute{\varepsilon}_o})\left(1 - \left\{\frac{T-T_r}{T_m-T_r}\right\}^m\right) \quad (1)$$

Where, A is the yield strength, B is the hardening modulus, C is the coefficient of strain rate, n is the hardening coefficient, m is the thermal softening coefficient, Tm is the melting temperature, Tr room temperature, T is the material temperature at an instant and $\acute{\varepsilon}_o$is the reference plastic strain rate. The material constants deployed for the present work are shown in Table 2.

Table. 2 Johnson Cook material model [1]

A(MPa)	B(MPa)	C	m	n	$\acute{\varepsilon}_o$	T_m(K)	T_m(K)
1200	300	.003	1.17	0.8	1	1783	293

2. 2. Chip Separation Criteria & Contact Law

A plastic strain criterion is used for the chip separation from workpiece. Johnson and cooks damage model considering the sensitivity of the material to temperature, strain rates and hydrostatic pressure is used for the analysis (refer Eq. 2 and Eq.3).

$$D = \sum \frac{\Delta\varepsilon}{\varepsilon f} \tag{2}$$

$$\varepsilon^f = \left(D_1 + D_2 e^{(D_3 \sigma\sigma^*)}\right)\left(1 + D_4 \ln(\frac{\acute{\varepsilon}}{\acute{\varepsilon}_o})\right)\left(1 + D_5 \left\{\frac{T - T_r}{T_m - T_r}\right\}\right) \tag{3}$$

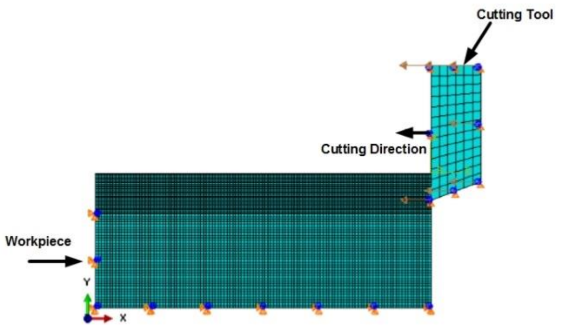
Where, $\Delta\varepsilon$, ε^f and σ^* denotes increment in equivalent plastic strain at each incremental step, equivalent plastic strain at fracture points and ratio of average of normal stress to the von misses stress, respectively. The fracture initiates when the variable D=1 for each element. The material parameters Di are determined by tensile and torsion tests. The value of constants D_1, D_2, D3 D4 and D5 for Johnson cook damage model for HHAS are 0.1, 0.93, -1.08, 0.000014 and 0.65, respectively.

Surface-to-surface contact method is employed to define the interaction between tool and workpiece. It is assumed that the friction coefficient μ=0.4 is constant throughout the cutting process. To avoid penetration between element, kinematic contact method is used. Coulomb friction law is assumed to model the friction between tool and work piece as presented in Eq. 4.

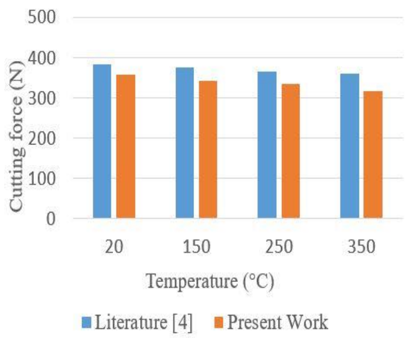
$$\zeta < \mu\sigma \tag{4}$$

2. 3. Element types and boundary condition

Four node plain strain thermo-coupled quad elements (CPE4RT) integration is used for the chip parts. Hourglass control and reduced integration is used for the large element deformation. For tool and bottom surface of workpiece, a three node plain strain thermally coupled triangular element (CPE3T) is used. For the chip region the element size is 10 µm and for the rest of the workpiece a courser mesh is used. The workpiece consist of 7574 element and tool consists of 79 elements. Nodes on the bottom edge and left side of workpiece is constraint in X and Y direction. Displacement of cutting tool is constrained in Y direction and rotation and velocity boundary condition is applied on it. Fig. 1 shows the mesh and boundary condition applied on the workpiece and tool.



(a)



(b)

Fig 1. HEDBAM modelling a) Mesh model and boundary condition b) Model Validation

3. Results and Discussion

The developed model is validated with previously published work on Titanium alloy [4] and the cutting force is estimated. Fig. 1b presents the cutting force obtained at different temperatures (20 – 350 °C) and maximum error of 9 % is observed from previously published literature.

Fig. 2a and 2b shows the chip formation during the orthogonal cutting process and maximum temperature generated in the secondary shear zone, respectively. Cutting forces and thrust forces generated during the contact between cutting tool and workpiece is presented in Fig. 2c. It is observed that continuous chips are formed due to the ductile mode failure of HHAS for all workpiece temperature. Shear stress is the failure criteria in ductile mode failure and as the temperature increases, shear stress inside the materials decreases resulting in reduced cutting forces.

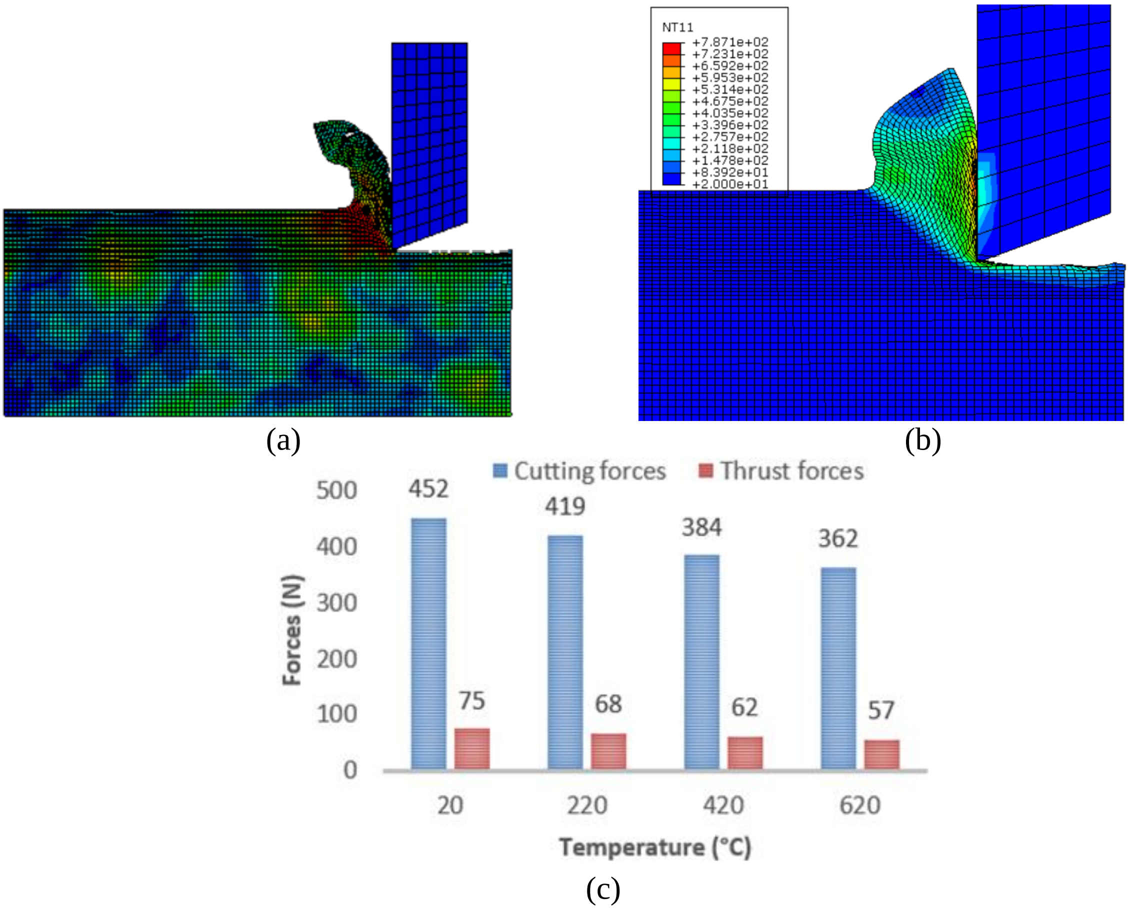


Fig 2 : (a) Chip formation during orthogonal cutting (b) Temperature profile during room temperature machining c) Forces at different workpiece temperature

A reduction of 7 %, 15 % and 19 % is obtained in the cutting forces at 220° C, 420 °C and 620 °C, respectively as compared to the room temperature cutting forces (20 °C). Further, a reduction of 9 %, 17.3 % and 24 % in the thrust forces is obtained at 220° C, 420 °C and 620 °C, respectively as compared to the room temperature thrust force

4. Conclusion

HEDBAM process finds huge applications in machining difficult to machine materials. Finite element model is developed to estimate the cutting forces during HEDBAM of HHAS. The developed model for orthogonal cutting is validated with previously published literature on HEDBAM of titanium alloy with maximum error of 9 %. Further, numerical modelling of HEDBAM of HHAS shows a maximum reduction of 19% and 24 % in the cutting and thrust force, respectively at 620° C. Continuous chips are formed during the machining of HHAS showing ductile failure. The work will be further extended to the experimental studies on the machining of HHAS and ceramic materials.

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