Modelling the dynamic behaviour of hard-to-cut alloys under conditions of vibro-impact cutting

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Abstract. Industrial applications of titanium alloys have grown significantly over the years primarily due to their high strength, light weight as well as good fatigue and corrosion-resistance properties. Since these alloys are hard-to-machine, there is an obvious demand to develop simulation tools in order to analyse the material's behaviour during machining and, thus, optimise the entire cutting process. Deformation processes in the machining of Ti alloys are typically characterized by high strains, strain rates and temperatures; the material behaviour under such conditions was derived from split Hopkinson pressure-bar (SHPB) tests. In the current study, a computational three-dimensional finite element model of the SHPB test is developed to assess the material’s behaviour at high-strain, strain-rate and temperature regimes. The material behaviour derived for high strain rates was used in three-dimensional finite-element modelling of conventional turning and ultrasonically assisted turning of Ti-15333 alloy. A parametric analysis of the studied alloy was carried out using the developed model. Comparisons of simulations with experimental results demonstrate their predictive capability.

1. Introduction

Beta-titanium alloys have an exceptional combination of low density, high strength and good corrosion resistance properties. These properties make beta-titanium alloys an ideal material for aerospace applications. However, these alloys are hard-to-cut, producing high cutting forces and excessive temperature in various machining processes[1-3]. Since high levels of strains and strain rates accompanied by high temperatures characterize the deformation process in machining, the material behaviour at these extreme conditions is vital for accurate computational modelling of machining processes [4]. There are several experimental methods available to predict the material behaviour at high strain rates and temperatures; the most commonly used is split Hopkinson pressure-bar (SHPB) test. This method is applicable at strain rates between $10^2$ and $10^4$ s$^{-1}$. However, in machining processes, the strain rate can exceed these levels and there is a need to predict material behaviour at such high strain magnitudes to be used in order to model accurately the machining processes.\footnote{To whom any correspondence should be addressed.}

Some basic assumptions are employed in the assessment of stress strain relationship in SHPB tests including the use of a one-dimensional theory of elastic wave propagation, homogeneity of stress and strain fields in the axial direction and neglection of a frictional effect. A thorough assessment of significance of these assumptions the relevance and accuracy of SHPB is available in [5]. The non-
uniformity of axial stress and strain filed was investigated numerically and experimentally by various researchers [6-8]. Thus, there is a need to critically reassess the validity of the assumptions in the determination of the mechanical response of recently introduced advanced alloys such as Ti-15333.

In this study, a thermo-mechanically coupled three-dimensional finite-element (FE) simulation of the SHPB test is carried out to better understand the deformation mechanisms in a specimen during the impact. Various levels of strain rates and temperatures are used to investigate the response of the beta titanium alloys. Additionally, a thermomechanically coupled three-dimensional FE model of oblique turning is developed for conventional turning (CT) and ultrasonically assisted turning (UAT) [9-10]. The models allow investigation of the effect of ultrasonic vibration on machining cutting forces and temperature at the cutting region in turning of Ti-15333.

2. Split Hopkinson pressure-bar technique

A schematic presentation of the SHPB system is shown in Figure 1. The system used for our tests consist of two 1.2 m long maraging steel rods with diameters of 21.77 mm called incident and transmitter bar, a striker bar made of a same material and diameter with a length of 200 mm and a specimen with a length of 6 mm and a diameter of 8 mm. The striker bar is shot against the free end of the incident stress bar, generating a stress pulse that propagates in the latter bar towards the specimen that is sandwiched between the incident and transmitter bars [11]. The stress pulse is divided into two parts after reaching the specimen interface. A part of stress is reflected back to the incident bar as an elastic wave while the rest of pulse transmits through the specimen to the transmitter bar, resulting in plastic deformation in the specimen. Strain gauges were used in the setup to measure the strains on the incident and transmitted bar. The data obtained from the strain gauges were then used to calculate the levels of strain, strain rate and stress in the specimen. The 1-D wave analysis of SHPB data for the strain rate, strain and stress can be expressed as follows [12]:

\[
\varepsilon(t) = -\frac{2C}{L_s} \int_{0}^{t} \varepsilon_R(t) \, dt, \quad (1)
\]

\[
\dot{\varepsilon}(t) = -\frac{2C}{L_s} \varepsilon_R(t), \quad (2)
\]

\[
\sigma(t) = \frac{A_b E_b}{A_s} \varepsilon_T(t), \quad (3)
\]

where \(C\) is the elastic wave velocity, \(L_s\) is the initial length of the specimen, \(\varepsilon_R\) and \(\varepsilon_T\) are the reflected and transmitted strain pulses, respectively, \(A_b\) and \(A_s\) are the cross sectional areas of the bars and the specimen, respectively, \(E_b\) is the Young’s modulus of the bar material, \(\varepsilon(t)\) is the strain, \(\dot{\varepsilon}(t)\) is the strain rate and \(\sigma(t)\) is the time dependent stress level.

The SHPB tests were carried out for Ti-15333 at strain rates ranging from 600 s\(^{-1}\) to 3300 s\(^{-1}\) at room temperature. An ingot of Ti-15333 was wire cut into specimens with dimension requested for the tests. The ratio of the length to diameter was 0.75 (within the established range of 0.5-1.0) in the current tests. The material properties of the specimen and the setup used in both experiments and
simulations with relative dimension are listed in Table 1.

| Material   | Length, mm | Diameter, mm | Young’s modulus, GPa | Passion’s ratio | Density, kg/m³ |
|------------|------------|--------------|----------------------|-----------------|----------------|
| Striker    | 200        | 21.77        | 198                  | 0.329           | 8470           |
| Bars       | 1200       | 21.77        | 198                  | 0.329           | 8470           |
| Specimen   | Ti-15333   | 6            | 8                    | 0.3             | 4900           |

3. Oblique turning test

A Harrison 300 lathe machine was suitably modified to mount a transducer on the tool post, which imposed vibrations on the tool in the primary cutting direction. The system is capable of carry out conventional machining and UAT on the same setup. A Kistler dynamometer was used to record cutting forces at various cutting conditions. A FLIR ThermaCAM™ SC3000 camera was employed to carry out thermal analysis in real time during the cutting operation. The new Stirling-cooled Quantum Well Infrared Photon (QWIP) photo-detector enables the system to capture images with a spectral response between 8 and 9 µm, temperature range of -20°C to 2000°C, 320 × 240 pixel resolution, low noise detection and high image stability and uniformity. In our experiments, a temperature resolution of 30°C to 650°C was used. The ThermaCAM® QuickView™ software was used to analyse the data of the FLIR ThermaCAM™ SC3000 system. The experimental setup used for turning experiments is shown in Figure 2.

![Figure 2. Experimental setup for turning experiments](image)

A workpiece material was an ingot of Ti-15333, and a commercial tungsten carbide insert, PVD coated with TiAlN (DNMG-150608 supplied by Seco) was employed as a cutting tool. All experiments were carried out in dry-cutting conditions without the use of any lubricants or coolants. The experiments and simulations were carried out for a cutting speed of 10 m/min, depth of cut of 300 µm and feed rate of 0.1 mm/rev. A series of tests for conventional turning (CT) and UAT were performed, and the tangential and radial components of cutting forces (see Figure 2) were measured. Each experiment was repeated at least five times to get good repeatability. The measured cutting forces reduced significantly during ultrasonically assisted turning when compared to those obtained with CT.
In addition to force reduction, other substantial benefits were observed, in particular, elimination of the chatter noise during operations and better surface finish of the machined workpiece [2, 9, 13].

4. Finite-element modelling
A part of deformable workpiece with the following dimensions: a length of 5 mm, width of 1.3 mm and height of 0.5 mm + \( \Delta p \) (depth of cut) was modelled in oblique turning of Ti-15333 (Figure 3). Initially, 8-node hexahedral elements with a minimum length of 0.05 mm were used to model the workpiece. Later on, 5-node tetrahedron elements were used due to lack of support of global re-meshing for 8-node elements in simulations. A rigid cutting tool with a nose radius of 0.8 mm, rake angle of 14.5° and end relief angle of 0° was modelled reflecting the experiments conducted. Four-noded tetrahedral elements were used to discretise the cutting tool. A constant velocity (\( V \)) was imposed on the workpiece in the tangential direction. The tool was made to move in the feed direction with a feed rate of 0.1 mm/rev. In UAT, vibration was superimposed on the cutting tool in the tangential direction with an amplitude of 8 µm and frequency of 20 kHz.

![Figure 3. Oblique turning model](image)

5. Material model
A piecewise linear material model was used to represent the material behaviour at high strain rates and elevated temperature in FE simulation of SHPB and oblique turning. The data comprised a combination of four different strain rates (0.1 s\(^{-1}\), 1 s\(^{-1}\), 3300 s\(^{-1}\), 10\(^5\) s\(^{-1}\)) and four different temperature values (20°C, 200°C, 600°C, 950°C) (Figure 4). Details of the material data are available elsewhere [14]. The data were obtained from a series of the SHPB tests carried out at the Tempere University of Technology, Finland. In order to account for higher strain rates beyond the experimentally characterized ones, the stress-strain data for a higher strain rate level (10\(^5\) s\(^{-1}\)) need to be assumed based on the corresponding values for the highest strain rate in experiments 3300 s\(^{-1}\) (Figure 4b). The extrapolation was introduced assuming a 20% offset from the stress levels observed at 3300 s\(^{-1}\) and was verified using FE modelling of the SHPB setup.

A thermomechanically coupled finite-element model for SHPB test was developed using commercially available code MSC Marc/Mentat [15]. Eight-noded, isoparametric, hexahedral elements (Element type 7) were used to discretize the striker, incident bar, transmitted bar and specimen (see Figure 5). The incident and transmitter bars were discretized with 5760 elements each and the striker bar with 960 elements. The initial number of elements used to mesh the workpiece was 75600. Global remeshing and rezoning technique was used to avoid any distortion in element of the
workpiece material. The right hand side of the transmission bar is constrained in all directions to model the end stopper used in the experiments.

The modified shear-friction model was used to simulate friction between the materials of tool, chip and workpiece in FE simulation of oblique turning process,

$$
\sigma_{fr} \leq -m_{fr} \bar{\sigma} \frac{2}{\sqrt{3} \pi} \text{sgn}(\nu_r) \arctan \left( \frac{\nu_r}{\nu_{cr}} \right),
$$

where \(\sigma_{fr}\) is a friction stress, \(\bar{\sigma}\) is the equivalent stress, \(\nu_r\) is the relative sliding velocity, \(\nu_{cr}\) is the critical sliding velocity below which sticking is simulated, \(m_{fr}\) is the friction coefficient and \(\text{sgn}(x)\) is the signum function.

\[\text{Figure 4. Experimental stress-strain curves for various strain rates (a) experiment; (b) modified flow stresses used in simulations}\]

\[\text{Figure 5. FE model of SHPB test}\]

The extrapolated data for two high strain levels 10^5 and 10^{10} s^{-1} assumed in simulation was used to interpolate the observed experimental data at lower strain rate level (at 1300 s^{-1}), as shown in Figure 6. The observed stress levels obtained from simulations demonstrate that the interpolated flow stress level 10^{10} s^{-1} was lower to that observed in SHPB tests. On the other hand, a good agreement between the experimental data and calculated results was for the 20%-offset assumption for a strain rate of 10^5 s^{-1}. The results obtained in FE simulation of the SHPB test, verified our assumption that was used in the FE modelling of CT and UAT. In addition to that, the SHPB model was used for additional studies that will be discussed in the following section.
6. Results and discussions

6.1. Numerical results of SHPB test

The values of the axial strain calculated for locations of the strain gauges at the middle span in tests on the incident and transmitted bar was calculated with the FE model (see Figure 7a). A compressive wave pulse propagating in the incident bar resulted from an impact of the striker bar with it. This response of the bar was achieved before compression of the specimen, while a dynamic plastic response of the workpiece was gained through the transmitted and reflected pulses measured from the transmitted and incident bars, respectively. The transmitted pulse was compressive whereas the reflected pulse was tensile. The flow stresses for Ti-1533 were analysed for a strain-rate 3300 s⁻¹ and room temperature (see Figure 7b). The stress-strain relations obtained from simulations were in reasonably a good agreement with experimental stress magnitudes.

An inhomogeneous deformation of the specimen was observed at the start of the compression process in the FE simulations; at 3% plastic strain, a homogeneous stress state was reached. After the first contact between the incident bar and the specimen the levels of equivalent and the axial stresses varied from 138 MPa to approx. 400 MPa as shown in Figure 8. The same was observed in the equivalent plastic strain rate (1350 s⁻¹ to 3000 s⁻¹) at the same cross-sectional plane of the workpiece.
This may be of some concern when deriving the relevant stress-strain relations from the experimental procedure since one of the fundamental assumptions of the SHPB theory was that of a homogeneous stress state in the body during the entire deformation evaluation.

A temperature increase in the specimen was observed due to low thermal conductivity and adiabatic heat condition of the studied cases. A rise of 117°C was caused by plastic deformation of the workpiece material; the thermal history of the midpoint of the workpiece material is shown in Figure 9c. The effect of adiabatic heating should be included in the materials stress-strain response in actual experiments. On the other hand, including this effect may cause non-negligible errors in the data and could ultimately affect the accuracy of numerical simulations. The same discussion can be extended to the reference strain-rate value, which was found to be non-constant during the initial stages of the test. Using a reference strain-rate value for experiments conducted without accounting for its variability during the compression may also lead to errors.

6.2. Numerical results of oblique turning process

The developed model of oblique turning provides all the three components of cutting forces in FE simulations. The tangential cutting force ($F_x$) of magnitude 110 N was observed as shown in Figure 10a. A cutting velocity of 10 m/min, feed rate of 0.1 mm/rev and depth of cut of 300 µm were used for these simulations. A radial component ($F_y$) of 48 N and an axial component of ($F_z$) 20 N were calculated.

Application of ultrasonic vibration to the cutting tool produced a significant reduction in average cutting force. In the process of vibration, the cutting tool separated from the workpiece in each cycle, resulting in considerable reduction of the average cutting force. During the penetration stage of the tool in UAT, the tool experiences a higher magnitude of cutting force in the tangential, radial and axial...
directions. However, during the retardation stage, the cutting forces in all three directions started to decline, ultimately vanished at complete tool disengagement (see Figure 10b). The average cutting force component $F_x$ declined from 110 N to 35 N (68%). Also, a considerable reduction of 68% (from 48 N to 15 N) was observed for average $F_y$ in UAT. In addition to this, ultrasonically assisted turning yielded a significant reduction of 55% (20 N to 9 N) in average $F_z$. The simulations of CT and UAT were carried out for various depths of cuts, and a considerable reduction in forces was consistently observed in UAT when compared to CT. The obtained results of simulations were in good agreement with experimental data (Figure 11).

![Figure 10](image1.png)

Figure 10. Cutting forces in CT (a); and UAT (b)

The temperature in the process zone was also investigated with the developed 3D FE model of oblique turning in both CT and UAT, as shown in Figure 12. In UAT, a relatively higher temperature was observed along the contact area of the tool-workpiece interface. Temperature in UAT was higher at the maximum penetration of the tool; the possible reason for that was application of extra energy to the cutting tool in the form of vibration. The application of vibration to the cutting tool increased its relative velocity causing high plastic deformation of the workpiece material, resulting in high temperature (approx. 105°C) when compared to CT. The process zone temperature in both CT and UAT was higher in magnitude when compared to experimental results; this could be due to a limitation of the infrared thermography in measurements. There was often an obstruction to the clear line-of-sight due to chips, which ultimately yielded a lower estimate of the process zone temperature. However, the temperature magnitudes in regions visible to the thermal camera were in a good agreement with the obtained simulation results. Hence, the FE models have the added advantage of elucidating the temperature characteristics in regions of the workpiece not visible to thermal imaging.

A distribution of von-Mises stress in the cutting region of the studied region in both CT and UAT was investigated with the developed oblique turning model (Figure 13). A uniform distribution of stresses in the primary and secondary deformation zones was observed in CT, while in UAT, a distribution of stresses was transient during each cycle of vibration, as expected. The stress magnitude in the process zone at maximum penetration in UAT was 1050 MPa which reduced significantly at the retardation stage when the tool separated from the workpiece as shown in Figure 13c. The stress level in CT was nearly the same as the peak stress in UAT. The average levels of the von-Mises stress in the cutting region for one cycle in UAT was significantly lower than that of CT.

Similarly, the strain rate calculated in CT and UAT in oblique turning was also studied. The strain rate in UAT was significantly higher almost four-times when compared to CT (see Figure 14). The high strain rate in UAT was due to the vibro–impact interaction of the cutting tool with the workpiece material resulting in strain hardening of machined surface.
Figure 11. Comparison of cutting forces calculated in experiments and simulation

Figure 12. Process zone temperature in CT and UAT

Figure 13. Stress distribution (a) CT; (b) UAT at penetration stage; (c) UAT at retardation stage
7. Conclusions
In this study, a 3D thermo-mechanically coupled finite-element model was developed for SHPB test. The model was used to validate the FE simulations of CT and UAT based on assumptions of the deformation behaviour of the studied beta titanium alloy (Ti-15333). In the FE simulation of the SHPB experiment, an inhomogeneous deformation behaviour was observed in the specimen at the initial stages of compression contrary to a standard assumption of homogeneity employed in stress-strain calculations in SHPB. Thus, the validity of such assumptions should be critically assessed for each combination of material and high-strain-rate loading conditions. The adiabatic heating regime and variable strain rate during the compression process should also be taken into consideration in the identification of the material model’s parameters, since this can result in non-adequate extrapolation of the future real-life material properties.

The validated SHPB tests data were used in the FE models of CT and UAT of Ti-15333. The models were capable to analyse all the three components of cutting forces in both CT and UAT. The reduction in the radial and the axial components of cutting forces was explained with the help of the developed models. The level of cutting forces in UAT was significantly lower when compared to that in CT; this reduction can be attributed to the tool separation from the workpiece material in each cycle of vibration. A relatively high temperature of the process zone was observed in UAT together with changing in the process zone due to the tool movement. However, the level of average stress was lower in UAT when compared to CT.

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