The study of central cracking mechanism and criterion in cross wedge rolling

Abstract

Cross wedge rolling (CWR) is an innovative metal forming process to manufacture axisymmetric stepped shafts used in the transport industry. Central cracking, also called the Mannesmann Effect, consistently occurs in the central region of the CWR workpiece. This results in reduced product quality and increased costs due to rejected and failed parts. However, the understanding of central cracking mechanism and criterion is limited due to the complex stress states in CWR and the experimental limitations. A large number of CWR tests and different die geometries are required in the identification of the potential mechanistic factors such as the axial tensile stress, secondary tensile stress, shear stress and cyclic loading. Also, there is as yet no efficient method of determining the material constants associated with the central cracking fracture criteria. These problems are addressed in the present study. A physical model was built to reproduce the industrial CWR process. A newly designed model material (plasticine/flour composite) was used to mimic the material flows and internal fracture behaviours found in commercial CWR workpieces. This allowed a variety of die shapes to be rapidly and cost-effectively 3D printed, thereby enabling specific stress states to be achieved within the workpiece. Via experimental observations and the corresponding finite element modelling under different die geometries, the maximum shear stress was identified as the dominant factor for central cracking. The fracture criterion involving the maximum shear stress was quantitatively verified to be accurate and robust in predicting central crack moment and locations. A novel approach using simplified die geometries to determine the associated material constants was proposed and validated. The high accuracy and cost/time efficiency of this new approach will be a significant benefit to fundamental research and also in industrial applications.

Keywords: Cross wedge rolling; central cracking; fracture mechanism; fracture criterion; physical model.

1 Introduction

Cross wedge rolling (CWR), an innovative metal forming process whereby a cylindrical billet is plastically deformed into a stepped shaft under the action of two dies with wedges moving tangentially to each other, is mostly used in manufacturing steel products such as camshafts and connecting rods in the automotive industry [1]. It has been promoted to other industries such as high-speed railways [2] and nuclear reactors [3] where materials such as titanium alloys [2,4], aluminium alloys [5] and 42CrMo/Q235 laminated materials [6,7] are used. It was reported that the annual production of CWR parts in China reached over 2 billion pieces with a gross weight of over 400,000 tons in 2018 [8]. The market demand for this novel technique is expanding rapidly because of new technological developments. For example, hollow parts such as engine valves or railway axle can be manufactured efficiently using CWR [9,10]. CWR of threaded shafts and shafts of non-circular cross-section is also being subject to intensive investigation [11,12]. Multi-materials such as steel and aluminium are used in producing tailored products [13,14]. More knowledge about the theoretical, experimental and technical development of CWR is reviewed by Pater [15] and Tofil and Pater [16].

A critical problem with CWR is central cracking, which occurs in the centre of the workpiece and impedes the adoption of this technique in safety-critical industries, such as aerospace [17]. A wide range of damage models and fracture criteria have been introduced and applied to predict and prevent central crack formation in the drive to produce high-quality products. For example, by comparing two CWR cases with different die geometries, a plastic strain criterion was used to predict the central cracks in pure aluminium AA1100 H16 [18]. The Cockcroft and Latham model [19] and the Oyane model [5] also showed a degree of accuracy in predicting the cracking location. Jia et al. [20] applied a density change model of porous materials to characterise the internal voids in terms of density in multi-wedge-multi-pass CWR. Pater et al. [21] compared ten existing damage models in predicting central cracks in C45 steel, but found none of them demonstrated a high degree of accuracy. The difficulty in determining a robust damage model is attributed to insufficient understanding of the complex fracture mechanism. Recently, Zhou et al. [22] proposed a physically-based fracture criterion integrating the maximum shear stress and first principal stress, and were able to validate the accuracy quantitatively through 27 CWR tests on pure aluminium using various die geometries. The determination of the material constants used in this fracture criterion does, however, require a large number of CWR tests using dies of various shapes, and this is a high-cost and

1 time-consuming process. To overcome this, it is necessary to develop a new method for the efficient and
2 practical determination of the material constants.

3 In addition to the maximum shear stress and the first principal stress integrated with the fracture criterion
4 mentioned above, a number of other mechanistic factors are considered to be critical for central cracking.
5 These include the shear stress, the axial tensile stress, the secondary tensile stress and low cyclic fatigue.
6 Tselikov et al. [23] concluded that the accumulated tensile stress in the central region of the workpiece
7 during the rolling was key. However, by analysing the stress state in rotary compression, Smirnov and
8 Lunjev [24,25] suggested that the secondary tensile stress generated by the normal compression was the
9 main cause. From experimental observation, Guzavichus et al. [26] found that the strong velocity gradient
10 between workpiece flanges and steps led to strong torsional forces which increased during rotation,
11 generating strong shear stress and causing the final fracture. This finding was backed up by Makushok
12 and Shukin [27] and Shukin [28], who demonstrated that the micro-cracks occurred when a critical shear
13 intensity was reached. These micro-cracks grew under successive load cycles, where the low cyclic fatigue
14 effects were investigated. The micro-cracks finally joined up to form large cracks in the central regions.
15 More recent studies, however, have found that the combined shear and tensile stresses are critical for the
16 central crack formation. Li et al. [29] proposed a fracture mechanism considering the main effects of the
17 normal stress and shear stress. Yang et al. [30] evaluated the strong shear and tensile deformation in the
18 central region of the CWR parts by finite element (FE) modelling. By numerically analysing the stress
19 invariants on the C45 steel workpiece, Pater et al. [31] revealed that central cracking involved void
20 formation and shear fracture. They considered that the first principal stress facilitates void formation,
21 while the shear stress accelerates shear fracture. Nevertheless, the individual roles of the tensile and shear
22 stresses, as well as the cyclic reversal loading, on central crack formation have never been compared and
23 clarified due to the high cost and long lead time of manufacturing the various-shaped dies required to
24 achieve specific stress states. Thus, to identify the individual roles of all the potential mechanistic factors,
25 it is of great importance to adopt a novel practical method to create specific CWR stress states at low cost
26 and with a short lead time.

27 To tackle this challenge, a combination of in-lab die manufacturing and the use of modelling materials,
28 i.e. plasticines, was proposed for this CWR study. Although model materials and metal alloys are different
29 in structure, they exhibit similar mechanical behaviours such as stress-strain relationship, yield criterion,
30 plastic strain hardening, strain rate sensitivity and fracture, but with a flow stress difference of one or two

orders of magnitude [32]. These characteristics of model materials enable lab-scale reproduction to be achieved. Previous flow visualization studies on the friction stir welding were conducted using plasticine based on its similarities to hot metals in constitutive behaviours [33]. Recently, plasticine was also applied for the feasibility study for a new differential velocity sideways extrusion process [34]. The application of model materials in CWR can be traced back to the year 1984 when the internal defects were simulated in rotary side-compression tests on plasticine [35]. Fu and Dean [36] used plasticine to study the formation of necking and twisting. Soft metals such as pure aluminium and copper were used to study uncontrolled slipping and internal defects [29,37]. More recently, the close similarity in terms of mechanical properties and defect features was achieved between commercial plasticine and hot steels (1150 °C) under CWR [38,39]. From this, it is interesting to observe that central crack formation appears to be material independent and occurs in a variety of solid materials such as steels [31,38], aluminium [5,29] and plasticine [35,38]. Hence, central cracking during CWR is a general mechanistic problem rather than specific to metals. As a result, it is considered reasonable to build a fundamental understanding of the process through the use of the soft model materials. The lower forces involved allows the dies (rollers) to be formed by rapid prototyping techniques. Dies of various geometries can therefore be manufactured quickly and at low cost. This facilitates the investigation of a wide range of CWR stress states without the usual budget and timescale limitations.

This work aims to identify and clarify the dominant mechanistic factors for central cracking from a wide range of potential factors. Specific stress states are generated through the change of die geometries in physical models. The fracture mechanism is revealed by the comparison of the stress/strain evolution in FE model with the experimentally observed cracking behaviours. A physics-based central crack criterion is re-examined with the specifically designed model material (plasticine/flour composite). A novel method of calibrating material constants is also proposed and validated.

2 Methodology

The physical lab-scale plasticine CWR tests and the FE CWR numerical modelling were conducted simultaneously to reveal the underlying fracture mechanism and validate the proposed fracture criterion. The physical model was used to observe the damage/fracture evolution, and the FE model was adopted to track the corresponding stress/strain distribution.

2.1 Physical model

2.1.1 Sample preparation

CWR test samples and uniaxial tensile test samples were manufactured as presented in Fig. 1. The white powder observed on the sample surface, especially in Fig. 1(b), is flour and was applied to prevent sticking during the sample preparation stage. Plasticine from Flair Company was selected due to its stable feature (never dries out). The plasticine from the same batch was selected to avoid any differences in mechanical properties between different batches. For the central cracking observations, flour was added and uniformly mixed with the plasticine so as to reduce its ductility. Green and pink plasticines were used to study the material flow due to their sharp colour contrast.

The sample preparation process was carefully designed and controlled to keep high consistency in homogeneous structure, stable mechanical properties and geometry accuracy. The plasticine for each sample was hammered and folded for more than ten times to homogenise the structure and achieve consistent mechanical properties. For the observation of the material flow during CWR, the cylindrical samples were mixed with regular green and pink plasticine layers that were formed by using a pastry maker to ensure constant thickness. Plasticine with the same colour was used for the same series of tests. A press forging process was applied to guarantee geometry accuracy. The forging moulds were 3D printed by a Fortus 400mc using the plastic material, acrylonitrile butadiene styrene (ABS).

The plasticine/flour composite was blended so as to have properties capable of presenting central cracking behaviour. Flour was added to the pure plasticine to reduce the material ductility and accelerate the occurrence of central crack formation for better experimental observations. The weight ratio of flour to plasticine was designed as 7.5%. At levels above this, the material gets too crumbly to form the sample shapes, and at levels below 7.5%, it is difficult to generate central cracks.

Fig. 1 Structures of plasticine specimens for (a) cross wedge rolling test, (b) uniaxial tensile test (unit: mm).

2.1.2 Mechanical properties of plasticine

Uniaxial tensile tests were conducted to characterise the mechanical properties of the pure plasticine (green and red) and the plasticine/flour composite. Pure plasticine samples were used to observe the material flow and the samples made in plasticine/flour composites were used in the study of the fracture mechanisms and criteria. Figs. 2(a) and (b) show the true stress-strain curves of plasticine at different strain rates. These were obtained on an Instron test machine, as shown in Fig. 2(c). A 1000 g load cell was used to ensure high measurement accuracy. The specimen grips were 3D printed on a UP Mini2 using the plastic material, polylactic acid (PLA). Steps were designed into the grip face to ensure effective clamping of the sample without slippage during the test. Each test was repeated at least three times, and average values were taken to ensure the accuracy of the results.

Fig. 2 True stress-strain curves of plasticines at various strain rates: (a) pure plasticine (green, pink and their average value), (b) green plasticine with 7.5 wt% flour; and (c) the uniaxial tensile test setup with 3D printed rigs.

2.1.3 Cross wedge rolling prototype and test

Fig. 3 illustrates the configuration of the CWR prototype and details the die structure. In Fig. 3(a), a cylindrical billet is placed in the middle of two dies. The upper die is fixed on the frame, while the bottom die is driven by the step motor at a speed of 20 mm/s. The speed and the moving distance of the bottom die are precisely controlled by the electronic step motor system. The upper and lower dies share the same geometry. During the test, the billet rotates along its axis and moves forward at approximately 10 mm/s, driven by the dies. As shown in the inserted figure, the cylindrical billet is deformed into a stepped shaft after rolling. Fig. 3(b) describes the die geometry, showing forming angle α , stretching angle β and area

1 reduction ratio η . The area reduction ratio η is defined as $\eta=1-(D_f/D_0)^2$, where D_0 is the initial sample
 2 diameter, and D_f is the final diameter of the workpiece. The dies with various geometries were rapidly
 3 manufactured by the 3D printer Fortus 400mc with ABS. Only ~ 2 hours is required to manufacture one
 4 pair of dies at the cost of $\sim \text{£}20$. In total, nine pairs of dies with different geometries were manufactured.
 5 The specific stress states of the workpiece central region were generated. CWR tests under each geometry
 6 were performed at least three times to guarantee the result accuracy.

Fig. 3 Illustrations of (a) cross wedge rolling test setup and (b) die geometry and samples with plastic strain distribution under the condition that $\alpha=15^\circ$, $\beta=7^\circ$ and $\eta=44\%$.

2.2 Finite element model

2.2.1 Cross wedge rolling finite element model

The CWR FE model was developed in QForm, which is computationally efficient and highly robust in simulating metal forming processes due to the dual mesh method used [40]. This method is particularly suited to analysing cases involving severe plastic deformation and strong shear effects. The QForm FE configuration is displayed in Fig. 4. For high computational efficiency, and because of the symmetrical nature of the specimen, it was possible to analyse half of the model, assuming suitable boundary conditions at the centreline. To create the material database for the pure plasticine and the plasticine/flour composites, the experimentally derived true stress-strain data for various strain rates (shown in Fig. 2 (a) and (b)) was input. Material properties such as the density, Young's modulus and Poisson's ratio were input, as listed in Table 1. The density of the material was calculated by the measured weight and volume of the manufactured samples. The Young's modulus was calculated from the stress/strain curves, while the value of the Poisson's ratio was averaged from data in previous investigations of plasticine materials in the literature [41,42].

Table 1. Material properties for the new plasticine materials.

	<i>Density (kg/m³)</i>	<i>Young's modulus (MPa)</i>	<i>Poisson's ratio</i>
Pure plasticine	1868	2.6	0.4
Plasticine/flour composite	1714	5.8	0.4

The visco-plastic deformation was considered in the constitutive model of plasticine and the Lévy-Mises equation was applied, as given by:

$$\dot{\epsilon}_{ij} = \frac{3\dot{\bar{\epsilon}}}{2\bar{\sigma}} \sigma'_{ij} \quad (1)$$

where $\dot{\bar{\epsilon}}$ is the effective deformation rate, $\dot{\epsilon}_{ij}$ is the strain rate tensor, and σ'_{ij} is the stress deviator.

Due to the shortage of ABS material data, a rigid material, H13 steel, was selected from the QForm material library to describe the die deformation behaviour. This was considered reasonable because the deformation of the ABS die observed during CWR was minimal.

The Coulomb friction model with a friction coefficient value 0.9 was employed in the FE simulation to prevent the slipping of the soft plasticine workpiece from the dies. However, this high friction value does not cause the frictional stress exceeds the shear yield strength of the materials, because of the automatic shear yield stress correction algorithm embedded in QForm [43]. QForm set the maximum value of the friction resulted shear stress to the shearing yield strength of the material to avoid unphysical stress state. The accuracy of the FE model has been experimentally validated by comparing the final geometries of the rolled workpiece in the FE model and physical model.

For high calculation accuracy, the dual mesh strategy was applied. This automatically refines the regions with complex geometry or intense stress/strain concentration [40]. The main region of interest (a cylinder of 10 mm diameter around the workpiece central line) was further refined with an adaptation factor of 1.5. For example, the total number of elements in one CWR model increased from 162,971 to 169,928 at the end of the CWR process.

Fig. 4 Finite element model for cross wedge rolling process.

2.2.2 Fracture criterion for central crack prediction

The previously proposed physically-based fracture criterion is given as Eq. (2), which was validated quantitatively by 27 cases of CWR tests on pure aluminium [22]. The fracture criterion demonstrates that central cracking occurs when the damage value D exceeds the critical damage value, D_c . Note that the damage in this study presents the stress intensity with a unit of MPa. Eq. (2) can be rewritten to Eq. (3) by defining $D_n = D/A$ and $C = \frac{1-A}{A}$. Then only two material constants, C and $D_{c,n}$, are involved in this criterion, which vary with material properties.

$$D = A\tau_{max} + B\sigma_1 > D_c, \text{ with } A+B=1 \quad (2)$$

$$D_n = \tau_{max} + C\sigma_1 > D_{c,n} \quad (3)$$

2.2.3 A novel method to determine material constants in the fracture criterion

Material constants $D_{c,n}$ and C in the studied fracture criterion can be characterised by CWR tests with simplified dies, as shown in Fig. 5. A new parameter, feed angle γ , is defined as the slope of the inclined plate. By varying the feed angle, various stress states can be achieved. To solve the two variables $D_{c,n}$ and C in Eq. (3), three simple steps are required: (1) determine the cracking nucleation points in two CWR conditions, i.e. under two different feed angles, by interrupted tests. The central crack condition in each sample can be checked by sectioning the rolled sample along the axial line; (2) calculate the stress states (i.e. the maximum shear stress and the first principal stress) at these two specific moments by FE modelling; and (3) solve for the two variables $D_{c,n}$ and C by inputting the acquired maximum shear stress and first principal stress for the two states into Eq. (3). In principle, two groups of data will be sufficient for determining the material constants. The accuracy could, however, be further improved by collecting more test data.

This method is advantageous compared with the conventional ways such as uniaxial tensile or shear tests, because it simulates the actual stress states in CWR and central cracking behaviours, thus ensuring a higher degree of accuracy. The novelty of this method is supported by a recent study on the calibration of the critical damage value using rotary compression tests [44]. Meanwhile, compared with the method used in the previous study [22] which required a high number of CWR dies, only one pair of slopped/flat plates is required, raising one end of each plate to get different slopes for real applications. This method will benefit the industry by its high accuracy and considerable time/cost efficiency.

Fig. 5 Simplified die geometry for the determination of material constants.

3 Results

3.1 Validation of the finite element model

The plasticine CWR FE model was validated by comparing the final geometry and material flow within the rolled sample with the corresponding experimental results. The die with a forming angle 15° , a stretching angle 7° and an area reduction ratio 44% was applied for this comparative study.

3.1.1 Geometry comparison

Fig. 6 illustrates the rolled samples from the FE model and the physical model and defines the geometrical parameters, including the final length L_f , the minimum diameter D_{min} and the maximum diameter D_{max} . The comparative results are presented in Table 2. It shows that the highest absolute deviation (relative to the physical value) of the three parameters is 6.6%, within the 10% range, considered acceptable for the validation of soft materials [45].

Fig. 6 Geometrical comparison between (a) finite element model and (b) physical model.

Table 2. Comparison of the final dimensions in the finite element model and physical model.

	<i>Physical results (mm)</i>	<i>Simulated results (mm)</i>	<i>Absolute deviation (%)</i>
D_{min}	18.7	18.6	0.5
D_{max}	22.8	21.3	6.6
L_f	56.7	59.4	4.8

3.1.2 Material flow comparison

The material flows within the sample before and after the CWR process are compared in Fig. 7. Before the CWR, the green and pink plasticine layers were evenly distributed on both sections, except for the

1 pink layer in the centre of the longitudinal section. Its thickness was nearly doubled, mainly because it
2 was the starting point during the sample preparation process. On the transverse section, some regions were
3 expanded, as indicated by the blue arrows, while other regions narrowed due to the compression during
4 CWR, as shown by the yellow arrows. The S-shape pattern of the layers appeared in the middle of both
5 the physical and FE models, as indicated by the red dashed curves. On the longitudinal section, the
6 thickness of the middle pink layer was increased, especially at the sample ends, as indicated by the blue
7 arrows, while the regions near the surface were narrowed, as the yellow arrows indicate. Central cracks
8 are found in both views. These cracks are located in the central region of the transversal section and along
9 the central line of the longitudinal section. This agrees with the morphologies of CWR central cracking in
10 metals, as observed in previous studies [29–31]. It is noticed that the exterior shape on the transverse
11 section differs slightly between the physical and FE models. This is caused by the sectioning process after
12 the CWR. The slight difference in the exterior shape does not affect the characterisation of the cracks as
13 indicated by the red circles.

14
15 **Figure. 7** Comparison of material flows on the transverse and longitudinal sections before and after cross wedge
16 rolling in the physical model and finite element model. The red circles indicate the central cracks, with the red double
17 dashed lines the material flows, the yellow arrows the narrowed regions and the blue arrows the expanded regions.

3.2 Cross wedge rolling test under various die geometries

3.2.1 Die description and cross wedge rolling test results

Nine pairs of CWR dies were manufactured for achieving various stress states. Table 3 lists the die geometry parameters and the central crack status after the corresponding CWR processes. The die geometry in the Reference case was selected from the literature [29], in which central cracks were generated in pure aluminium. The other cases were designed to create specific stress states within the workpiece to differentiate the critical mechanistic factors for central crack formation and to validate the fracture criterion and the new calibration method.

Cases 1, 2 and 3 were based on the Reference case, adjusting the forming angle or the stretching angle to the limits. The cracking severity increased from the Reference case to cases 1 and to 3, implying a significant change had occurred in the value of the critical mechanistic factor. This makes it possible to partially differentiate between the critical and non-critical factors. Case 3 was further investigated by adjusting the feed angle, as shown in cases 4 and 5. It is noticed that the cracking severity increased with the increase in feed angle, which enables the confirmation of the critical factor. To clarify the effects of cyclic loading, the total compressive deformation (i.e. the tool wedge height) in cases 3 - 5 was kept constant; thus the total number of load cycles reduced with the increase in feed angle. In these three cases, the dies were stopped at the moment the billet passed the highest point of the die slope, so as to avoid the unnecessary influence of rotation after that point. Cases 6 - 8 were simplified from cases 3 – 5 by widening the wedge out to become a flat plane, and these were used for determining the material constants used in the fracture criterion. This extremely simplified die geometry will offer the industry considerable savings in test die manufacturing.

Table 3. Geometrical parameters of dies for nine cases of cross wedge rolling tests and the longitudinal views of rolled samples.

<i>Case no.</i>	$\alpha/^{\circ}$	$\beta/^{\circ}$	$\eta/\%$	$\gamma/^{\circ}$	<i>Die structure</i>	<i>The longitudinal cross-sectional view of rolled samples</i>
Reference	15	7	44	-

1	15	0	44	-
2	90	7	44	-
3	90	0	44	1.37
4	90	0	44	0.91
5	90	0	44	1.83
6	90	0	44	0.91
7	90	0	61	1.37
8	90	0	75	1.83

3.2.2 Fracture evolution

Cases 6, 7 and 8 were designed to investigate the fracture evolution and determine the material constants in the proposed fracture criterion. The damage process in the central region is divided into four stages; namely, stage I no damage, stage II void nucleation, stage III macro crack and stage IV fully cracked, as shown in Fig. 8. The central region is defined in Fig. 8(a) as a rectangle with a length $1/2$ of the final length L_f along the axial direction and a width $1/4$ of the final diameter D_f along the radial direction. The stage II void nucleation is when separated voids/cracks with a diameter less than 0.5 mm are formed, followed by the stage III macro crack stage when the separate voids coalesce together along the axial direction as shown in Fig. 8(c). In stage IV, the crack propagates along the whole shaft of the workpiece (Fig. 8(d)). The crack formation process, as observed in the plasticine, is consistent with the fracture mechanism of ductile fracture in metals [29–31].

Fig. 8 Definition of damage levels for quantitative analysis : (a) stage I no damage; (b) stage II void nucleation with voids less than 0.5 mm; (c) stage III macro crack when the void coalescence occurs; (d) stage IV fully cracked when the crack propagates across the whole sample.

The damage development in cases 6 - 8 is shown in Table 4. The damage was monitored by conducting interrupted tests that four samples were rolled at each condition but stopped and sectioned at 25%, 50%, 64% and 100% of the whole CWR process. The feed angle shows significant effects on the central cracking formation. As the feed angle was increased, the crack tended to form at an earlier stage.

Table 4. Damage levels on the cross wedge rolled samples stopped at different moments in Cases 6 to 8.

<i>Case no.</i>	<i>Feed angle</i>	<i>25%</i>	<i>50%</i>	<i>64%</i>	<i>100%</i>
6	0.91°	No crack	No crack	Void nucleation	Macro crack
7	1.37°	No crack	Macro crack	Macro crack	Fully cracked
8	1.83°	Void nucleation	Fully cracked	-	-

3.3 Finite element results

3.3.1 Stress evolutions under various die geometries

The dominant effect of the maximum shear stress is distinguished by comparing the stress states in the nine cases with the cracking conditions shown in Table 3. Based on the detailed stress analysis of the cases Reference, Case 1 and Case 3, as shown in Fig. 9, it is clear that the critical stress components causing central cracking are the first principal stress (σ_1) and the maximum shear stress (τ_{max}), while the axial tensile stress (σ_{xx}) is not a critical factor. The most severe cracking occurred in Case 3, where the highest principal stress (σ_1) and the highest maximum shear stress (τ_{max}) of all the three cases are found. For the axial direction (x -axis), as seen in Fig. 9 (b), the stress σ_{xx} in the Reference case (no crack) is the highest. Along the y -axis, the highest value of σ_{yy} occurs in Case 3, implying its potential critical effect in central cracking, which will be further examined.

Fig. 9 Comparison of stress components in Ref case and Cases 1 and 3 with experimental observations (Ref case: $\alpha=15^\circ$, $\beta=7^\circ$ and $\eta=44\%$; Case 1: $\alpha=15^\circ$, $\beta=0^\circ$ and $\eta=44\%$; Case 3: $\alpha=15^\circ$, $\beta=0^\circ$, $\eta=44\%$ and $\gamma=1.37^\circ$).

Cases 3-5 investigate the effects of the maximum shear stress on the central cracking further. These cases were designed to generate approximately the same level of the first principal stress, but with different maximum shear stresses in the central region of the CWR samples. Case 4 with the smallest feed angle is crack-free, Cases 3 and 5 with larger feed angles show evident central cracking. Fig. 10 compares the stress states in Cases 3 - 5 in both cartesian and cylindrical coordinate systems. The feed angle increases successively from Case 4 to 3 and to 5. As seen in Fig. 10 (a), with a similar level of the first principal stress, the crack formation trends increased with the increase in the maximum shear stress. For example, Case 5 with the largest feed angle and the largest crack exhibited the highest maximum shear stress of the three cases, while Case 4 experienced the lowest maximum shear stress and no central crack was found. Also, the other tensile stress components such as σ_{xx} and σ_{yy} seem to have little influence on the central cracking process, as seen in Fig 10 (b). The highest values of σ_{xx} and σ_{yy} are found in Case 4, where no central crack is observed. Thus, all three stress variables including the first principal stress σ_1 , the axial stress σ_{xx} and the secondary tensile stress σ_{yy} are excluded from the critical factor, and the significance of the maximum shear stress is distinguished.

The severe extremely low cycle reversed deformation in CWR is a unique feature of the forming process. However, its effect on central cracking is still unclear. Cases 3 - 5 were also designed to investigate the cyclic loading effect on the central cracking process. Fig. 10(c) compares the cyclic loadings in the three cases. Fig. 10(d) shows that P1 instead of the central point was taken for the study of cyclic loadings mainly because the central point could not present the reversal pattern precisely due to its singular position.

Only the radial stress in the three cases is compared because of it has the same pattern as the hoop stress. The cyclic loading in three cases was analysed, and the results are listed in Table 5. It is of great interest to see that in Case 5, both the effective cyclic number and the average loading amplitude are the lowest, but the cracking is the most severe. Whereas, the highest number of cycles and the maximum stress amplitude are found in the crack-free case 4. This is mainly because the total compressive deformation in all the three cases, Cases 3 - 5, was constant. In Case 5, the CWR was completed within half cycle of the workpiece rotation, leading to the high compressive stress (σ_3) in the central region, followed by the high maximum shear stress ($\tau_{max} = (\sigma_1 - \sigma_3)/2$). Therefore, it can be concluded that the cyclic loadings are not the critical reason for central crack formation in CWR.

Fig. 10 Stress components at the central point in Cases 3 - 5 in the cartesian coordinate system: (a) the first principal stress and the maximum shear stress; (b) the stress components along three axes; and at point P1 in the cylindrical coordinate system with the central point as the original point and the x -direction as cylindrical axis: (c) radial stress in three cases; (d) stress components in Case 4.

Table 5. Cyclic loadings at P1 in Cases 3 - 5

Case No.	4	3	5
Effective cyclic number	5	2	1
Average amplitude (MPa)	0.0735	0.0548	0.0469

The effect of the maximum shear stress is further investigated in Cases 6 - 8. Fig. 11 presents the first principal stress and the maximum shear stress at the central point of the workpiece. It is seen that the maximum shear stress in Cases 7 and 8 is much higher than that in Case 6, in agreement with the experimental observation, as shown in Table 3. Meanwhile, the maximum shear stress at the void nucleation point, 4.75 s in Case 8, is at the same level of that in Case 6 at 12.16 s, as the solid green dots show, implying that the potential nucleation point in Case 7 is between 4.75 s and 9.5 s as the hollow green dot shows. This agrees with the experimental observation shown in Table 4. This finding further emphasises the dominant significance of the maximum shear stress and its potential capability to predict void nucleation.

Fig. 11 The first principal stress and the maximum shear stress at the central point in Cases 6 – 8 with solid green dots showing the void nucleation points and the hollowed one showing the potential void nucleation moment.

3.3.2 Material flow, stress and damage analysis

A detailed investigation on Case 6 was undertaken to demonstrate the material flow, stress and predicted damage evolution over the fracture process, from the no damage stage to void formation and then to the macro crack as shown in Fig. 12. According to Table 4, it is known that the void formation in Case 6 occurred at 64% of the whole CWR process, and the macro crack was observed at the end.

Fig. 12(a) and (b) presents the material flows in the radial and hoop directions on the transverse cross-section. Along the radial direction, materials under the dies are flowing into the central region, while the material outside the compressive zone between the dies is squeezed to the surface, leaving the central point a singular point. With the increase of the deformation, the billet ovality is increased, causing the high radial velocity of the material outside the compressive zone. Along the hoop direction in Fig. 12(b), the velocity increases from 0 at the centre to about 10 mm/s on the surface due to the billet self-rotation. A slight distortion is noticed in the areas near the die resulting from the strong tangential stress applied by the dies.

For the stress components in Fig. 12(c) to (e), none of them demonstrates a considerable change in value with the exception of the shear stress on the cross-section (τ_{RH}). This is in accordance with the no damage, void nucleation and macro crack trend. Consistent with the radial velocity, the radial stress of materials under the dies is negative, but it is interesting to notice the positive radial stress (the red region in Fig. 12(c)) is located around the central point, implying the centre is subject to strong tension. The hoop stress experiences a similar phenomenon in that the high and positive stress is located around the central point, and just normal to the red pattern for the radial stress, the combined effects of which contribute to the high first principal stress in the central region as shown in Fig. 12(f). In addition, strong shear bands are noticed on the cross-section, and with the workpiece rotation, these values increase, and the shear bands get wider. This matches the non-crack, void nucleation and macro crack trend. Thus, the predominant effect of the shear stress was demonstrated.

The first principal stress distribution is shown in Fig. 12(f). The highest value occurs in the central region, corresponding to the central cracking location; however, there is no visible difference in the value between the three specific stages, indicating it cannot, by itself predict the central crack formation. It is noticed that

1 the absolute value of the third principal stress is increased with the increase of the deformation (in Fig.
 2 12(g)), leading to the rise of the maximum shear stress (in Fig. 12(h)), given that the first principal stress
 3 is nearly constant. Although the maximum shear stress shares the same trend as the cracking evolution, its
 4 highest value is located around the die contact, making it insufficient to describe the central cracking
 5 location. However, the first principal stress acts to guarantee the fracture location. With the combined
 6 consideration of the maximum shear stress and the first principal stress, applying the proposed fracture
 7 criterion in Eq. (3), shows the predicted damage evolution matches the cracking evolution closely, as
 8 presented in Fig. 12(i), i.e. no damage at 50% CWR, void nucleation at 64% and macro crack at the end
 9 of the CWR. Note that the lower limit of the colour bar is the critical damage value.

10 The comparison of the stress/damage evolution with the experimental cracking evolution demonstrates
 11 the essential role of both the maximum shear stress and the principal first stress in accurately predicting
 12 the central cracking location and moment.

Fig. 12 Material flow, stress and damage distribution on the transversal cross-section in Case 6 at three specific stages: no damage, void formation and macro crack.

4 Discussion

4.1 Determination of critical mechanistic factors for central crack formation

The important roles of the maximum shear stress and the first principal stress in forming central cracks are identified, as shown by the above comparison and analysis of the simulated and experimental results for various die geometries. The axial tensile stress, the secondary tensile stress and the low cyclic fatigue are not considered to be critical factors due to the lack of correlation between these stress variables and the experimental observations. These non-critical stress variables play different roles for central crack formation. As investigated in literature [26], the cyclic loadings resulting from the rotation of the workpiece accelerated the accumulation of the shear stress in the central region. Without the workpiece rotation (or cyclic loadings), the fracture is more likely to occur on the surface. The value of the axial tensile stress (σ_{xx}) is relatively low in this study compared with the other stress variables along y and z directions, probably because of the low stretching angle β . However, with the increasing stretching angle, the axial tensile stress would increase, resulting in the direction of the first principal stress shifting to the axial direction [22]. The significance of the axial tensile stress would then be reflected. The secondary

tensile stress (σ_{yy}) is generated by the compressive stress (σ_{zz}) applied by the dies, and this contributes to the increase in the first principal stress as well as in the maximum shear stress.

4.2 Determination and validation of material constants

Different cracking levels were defined through three groups of interrupted CWR tests, as shown in Table 4. To achieve the high accuracy of the material constants defined in Eqs. (2) - (3), all ten situations given in Table 4, including four different CWR moments (25%, 50%, 64% and 100%) under three feed angles, were taken into account. The material constant value C was calculated to be 0.22, and the critical damage value was calculated to be 0.1319 MPa, as determined by the average of the minimum damage value for the void formation cases and the highest damage value for the non-cracked cases. Fig. 13 shows the damage value in Cases 6 - 8 for various stages, as shown in Table 4. The x -axis presents the situation number, 1 to 10, while the y -axis shows the predicted damage value at each situation. The critical line, marked as the dashed red line, clearly differentiates the cracked and non-cracked cases. The void nucleation cases are represented by the blue triangles, located just above the critical line.

Fig. 13 Damage value at the ten situations (including the 25%, 50%, 64% and 100% cross wedge rolling moments in Cases 6 - 8 given in Table 4) with the critical damage line (the red dashed line).

Furthermore, the damage value was calculated in all the other six cases in Table 3, as shown in Fig. 14. The damage value matches the experimental cracking conditions well. The red dots mean the cracked cases, all of which are located above the red critical damage line, while the green squares corresponding to the crack-free cases are all lower than the critical damage value. Note that the distance from the critical value also indicates the crack level; for example, the case 1 is close to the critical line and only minor cracks are observed, as presented in Table 3. This demonstrates the high effectiveness of the new approach to determine the material constants and the robustness of the proposed fracture criterion for predicting central crack formation.

Fig. 14 Comparison of the damage value in Ref case and Cases 1 - 5 with the critical damage value.

4.3 Fracture mechanism

The reliability of the proposed model was further demonstrated through the high degree of consistency between central crack formation in the FE model, plasticine CWR and pure aluminium, as shown in Fig. 15. In all three cases, it can be seen that the most severe damage occurs in the central region of the transverse section and propagates along the axial direction. Both the plasticine and pure aluminium billets present the same fracture features, i.e. cross-shape cracks in the central region and voids ahead of the crack

tips. This also agrees with the central crack features in C45 steel [30]. Note that the central cracking feature keeps consistent even though the simplified dies were applied.

The highest first principal stress (σ_1) occurs in the central region of the billet transverse cross-section, as shown in Fig. 12(f). Due to the increasing compressive stress (σ_3) generated during the die compression, the maximum shear stress (τ_{max}) under the dies increases, as presented in the FE model of Fig. 15. Both the first principal stress and the maximum shear stress accelerate crack formation, but to different degrees, as implied by the proposed fracture criterion. With their combined effects, fracture occurs in the central region when the damage value reaches the critical damage value.

Based on the current study and previous literature [22,29–31,46], the central cracking process in CWR can be summarised as (i) the microvoids/cracks form around the initial defects by interface decohesion driven by the maximum shear stress and the first principal stress; (ii) with the increase of the maximum shear stress and the first principal stress, the voids are strongly distorted and enlarged. The shear stress sharpens the void ends/cracking tips, causing the high stress concentration, while the first principal stress enlarges the voids or opens the crack tips. Both the shear and the principal stress accelerate the coalescence and propagation of voids/cracks, followed by the formation of macrocracks on the transverse cross-section; (iii) the rotation of the workpiece facilitates the formation of secondary cracks perpendicular or close to perpendicular to the initial crack path due to symmetry about the specimen axis, thus generating the cross-shape morphology on the transverse cross-section. Meanwhile, with the increase in the damage value along the axial direction and the sharpening of cracking tips, the cracks propagate along the axial direction quickly, forming the longitudinal cracking as shown in Fig. 15.

Fig. 15 Comparison of central cracks on (1) transverse and (2) longitudinal views (a) predicted by the FE model, (b) observed in plasticine/flour composites and (c) pure aluminium [29].

5 Conclusions

To clarify the effects of individual stress components, cyclic loading and the mechanism of central cracking in CWR, plasticine was used as a model material. The plasticine was cross wedge rolled using a range of shaped dies. These CWR dies were 3D printed using rapid prototyping techniques. A lab-scale CWR prototype was developed such that it could generate the specific stress states found during CWR. An FE model of the CWR process was also developed. The FE CWR models were used to reveal the

distribution and evolution of stress components in the CWR cases analysed, and their results compared.

The following conclusions can be drawn:

(1) The individual effects of the mechanistic factors to central cracking were systematically analysed and compared experimentally and numerically. The dominant effect of the maximum shear stress was verified. The integration of the maximum shear stress with the first principal stress is essential for the accurate prediction of central crack formation. The effects of the low cycle fatigue, axial tensile stress and secondary tensile stress are less significant. This finding is significant in developing a robust central cracking fracture criterion and in explaining the long-lasting Mannesmann Effect occurring in other metal forming processes such as rotary tube piercing process.

(2) The fracture mechanism of central cracking involves the void formation and shear decohesion. This is based on the crack morphologies observed in the experiments and is also applicable to various materials.

(3) A novel method for determining the material constants used in the previously proposed criterion is established. The method involves a limited number of interrupted CWR tests and FE process simulations. Only one pair of inclined CWR plates is required, and this results in great efficiency and convenience in both research and industrial applications. The high accuracy of this technique was demonstrated by six groups of CWR tests. The novelty in this new method is also suitable for the investigations of other complex manufacturing processes.

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