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A New Test Method for Sheet Metal Deformation subject to Tension under Cyclic Bending and Compression (TCBC)

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Abstract: A new test method for sheet metal deformation, *Tension under Cyclic Bending and Compression (TCBC)*, is developed in this study. The TCBC method is capable of testing material deformation under tension, bending and compression with cyclic loading. The effect of each deformation mode can be independently controlled by adjusting corresponding parameters. Using the TCBC test rig developed, aluminium alloy AA5251-H22 is tested under four different testing conditions: simple tension, tension under cyclic compression, tension under cyclic bending, and tension under cyclic bending and compression. The maximum elongation of the tested specimen at fracture and the tensile force required for material plastic deformation are evaluated. The results show that the maximum elongation increases significantly under TCBC condition due to localised plastic deformation under compression that delays the fracture. Finite Element modelling of the TCBC test is developed to obtain stress distributions to explain the enhanced formability. The new TCBC method may be used for testing material formability that resembles double side incremental forming.

Keywords: Incremental sheet forming, Formability, Material testing

1 Introduction

Incremental sheet forming (ISF) is a flexible, cost effective and energy efficient process, particularly suitable for high value manufacturing of small-batch and prototype products. In ISF process, a simple tool with a hemispherical head moves along predefined tool paths to deform a sheet blank incrementally into a desired geometry. ISF does not require any dedicated forming moulds or dies thus it is flexible to manufacture small-batch products of different geometries and dimensions. Forming forces required in ISF are relatively small because the material is deformed locally and incrementally thus there is no need to use heavy duty forming equipment which further improves manufacturing flexibility. Furthermore, it has been widely reported that a variety of materials, when processed under ISF, have exhibited greater formability than that obtained by conventional sheet forming processes. Double side incremental forming (DSIF), firstly reported by Meier et al. [1] and Smith et al. [2], has been developed to further enhance the material formability and to improve the process accuracy, comparing to the conventional ISF using single point incremental forming (SPIF). Figure-1 shows the basic concepts of single point incremental forming (SPIF) and double side incremental forming (DSIF). DSIF uses two simple tools at each side of the sheet blank; one tool acting as a master tool moves along predesigned tool paths to deform the material incrementally while another tool moves synchronously acting as a support tool.

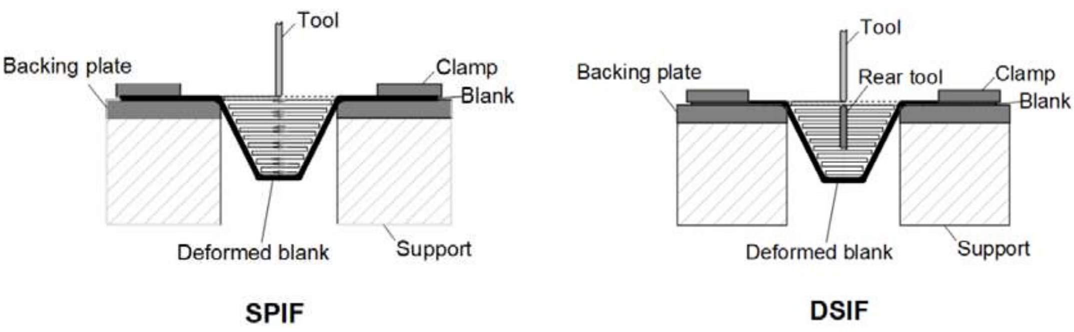

Figure-1 Illustrations of single point (SPIF) and double side incremental forming (DSIF)

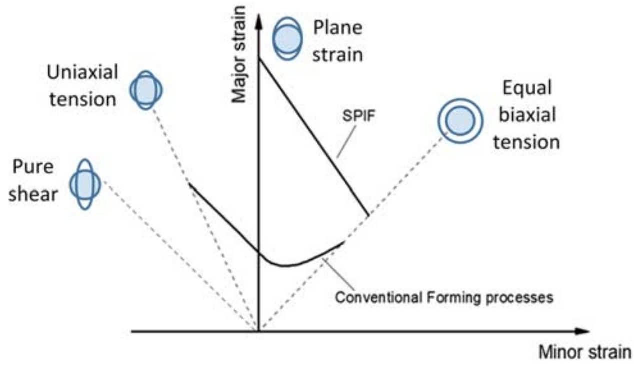

Figure-2 Comparison of forming limit curves in conventional forming and SPIF processes

Forming Limit Curves (FLCs) are widely used to evaluate the material formability in conventional sheet metal forming processes. Banabic [3] reported that the dome test, hydraulic bulge test, and the Nakajima test were the commonly adopted testing methods to obtain the FLCs for various materials in industry. A FLC defined the boundary of the stable deformation and unstable deformation of a material under various strain paths, such as uniaxial tension, plane strain, and equal biaxial tension. Materials generally exhibit much higher formability in ISF processes than that in the conventional forming processes. The FLCs obtained from SPIF experiments also show very different strain limit values and distributions upon the fracture occurrence, as illustrated in Figure-2. The significantly enhanced formability in SPIF was demonstrated by testing various materials, including aluminium alloys used by Shim and Park [4] and Filice et al. [5], copper, steel, and aluminium alloys used by Fratini et al. [6]. For DSIF, both Malhotra et al. [7] and Lu et al. [8] reported that the material formability was further enhanced due to the compressive loading employed in DSIF in comparison with SPIF.

Emmens et al. [9] stated that FLCs could only be an effective method to predict the formability under the pre-condition that the material deformation is plane stress with a linear strain path, without bending and through thickness shear. In the conventional forming processes, the critical areas of the deforming part are generally under simple deformation conditions. However, the strain paths of SPIF deforming parts are generally between plane strain and equal biaxial tension [4, 10], where the material deformation is accumulated incrementally. It is widely acknowledged that the material deformation in SPIF is limited to the contact area between the tool and deforming sheet. Both experimental study and finite element (FE) simulation confirm that the material deformation in SPIF is a combination of stretching, bending, and shearing. Smith et al. [2] confirmed the effect of these deformation modes in ISF by comparing stress and strain distributions of the material elements in the thickness direction obtained from FE simulations. Eyckens et al. [11], Jackson and Allwood [12] investigated the influence of through-thickness-shear of the ISF formed parts on the material formability and identified the existence of stretching, bending, and shearing deformation modes. Furthermore, progressive toolpaths in ISF create cyclic and non-monotonic loading conditions. Consequently, the ISF formability can be affected by specific tool paths and process parameters, which makes it difficult to predict the onset of the fracture accurately. Emmens et al. [13] explained the stabilized deformation mechanisms in SPIF and concluded that the fracture could eventually occur at the weak spot of the material under continuous tensile loading. As a result, any deformation mode that suppresses the damage propagation at the weak spot improves the material formability. By applying a loading condition of cyclic bending onto the material, Emmens and von den Boogaard [14] performed the continuous bending under tension (CBT) test, in which the weakest spot in the test specimen changed constantly, leading to a significantly increased maximum elongation of 430% for material DC04.

Published studies on ISF material deformation, fracture and formability are mostly conducted by performing the ISF test itself, as reviewed by Li et al. [15], Gatea et al. [16] and Sheng et al. [17]. However, owing to the complexity of the ISF process, including the complex loading conditions and localised contact and cyclic deformation, it is not easy to evaluate the individual and interactive effects of different deformation modes as well as the cyclic loading condition on the material deformation and fracture by simply conducting SPIF or DSIF tests. The traditional formability evaluation methods, such as FLCs as shown in Figure-2, are unable to explain the experimental observation of material formability enhancement achieved in ISF processes.

In this study, a new test method named as *tension under cyclic bending and compression* (TCBC) is developed to investigate the material deformation in incremental forming processes, such as SPIF and DSIF. This test method is a further development of the CBT test method [14] owing to the introduction of compression deformation mode in addition to the deformation modes of tension and bending with cyclic loading. Using the developed TCBC test rig, four different testing conditions, simple tension (ST), tension under cyclic compression (TCC), tension under cyclic bending (TCB), and tension under cyclic bending and compression (TCBC) are performed to investigate the bending effect, compression effect, and combined effect of bending and compression on the formability enhancement. Finite Element Models of TCB and TCBC tests are also developed to explain the effect of the localised material deformation and interaction of bending and compression on the formability enhancement.

2 TCBC test concept development

The focus of this study is to develop a material testing method capable of applying various loading conditions such as tension, bending, and compression, with cyclic loading effect. In the CBT test developed by Emmens and van den Boogaard [13, 14], the sheet specimen was stretched in the longitudinal direction while the cyclic bending was also applied thus the material deformation under tension and bending with cyclic effect was investigated. To facilitate the superimposed compressive loading generated by the additional tool employed in DSIF, the new test method needs to provide a compressive force from the other side of the sheet specimen, moving synchronously with the bending tool. Figure-3 illustrates the different deformation zones at the contact between the master and slave tools because of the introduction of the compressive loading in DSIF.

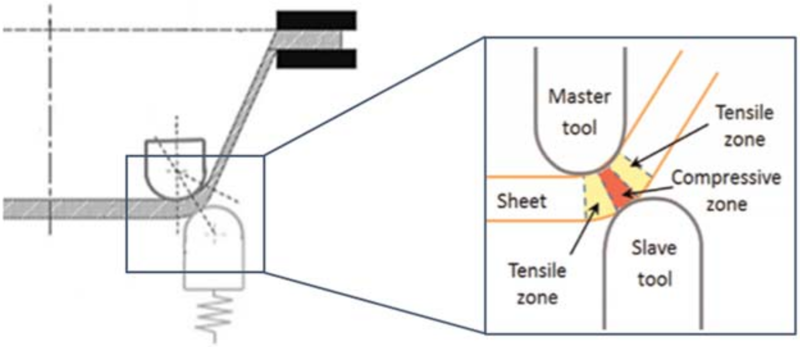

Figure-3 Different deformation zones at the contact between master and slave tools in DSIF

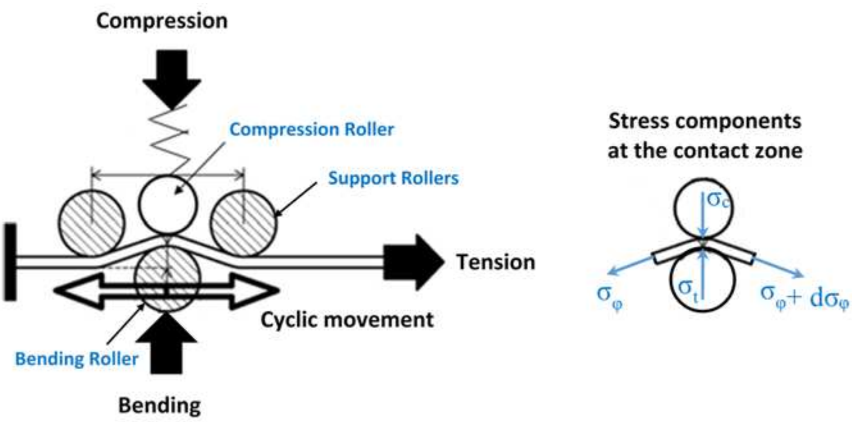

Figure-4 Design concept of Tension under Cyclic Bending and Compression (TCBC) test

Figure-4 presents the design concept of Tension under Cyclic Bending and Compression (TCBC) test. It consists of a bending roller, a compression roller and two support rollers to enable the application of tension, bending, and compression deformation with cyclic loading effect. To develop the detailed design of the test rig, an analytical model based on the elementary plasticity theory is developed to characterise the effect of tension, bending and compression on the initiation of material plastic deformation [18]. By considering an infinitely small element of the specimen material within the compressive deformation zone as shown in Figure-4, based on the force equilibrium condition and the Tresca yield criterion, the contact stress between the specimen and bending roller, σ_t, can be derived as

$$\sigma_t = \frac{\sigma_s + \sigma_c \frac{r_t}{t}}{1 + \frac{r_t}{t}}$$

where σ_s is the material flow stress, σ_c is the contact stress between the specimen and the compression roller, as shown in Figure-4; where r_t is the radius of the bending and compression rollers, and t is the thickness of the specimen under deformation. The tensile stress of the specimen in its longitudinal direction, σ_φ, can be derived as

$$\sigma_\varphi = \frac{(\sigma_s - \sigma_c)\frac{r_t}{t}}{1 + \frac{r_t}{t}}$$

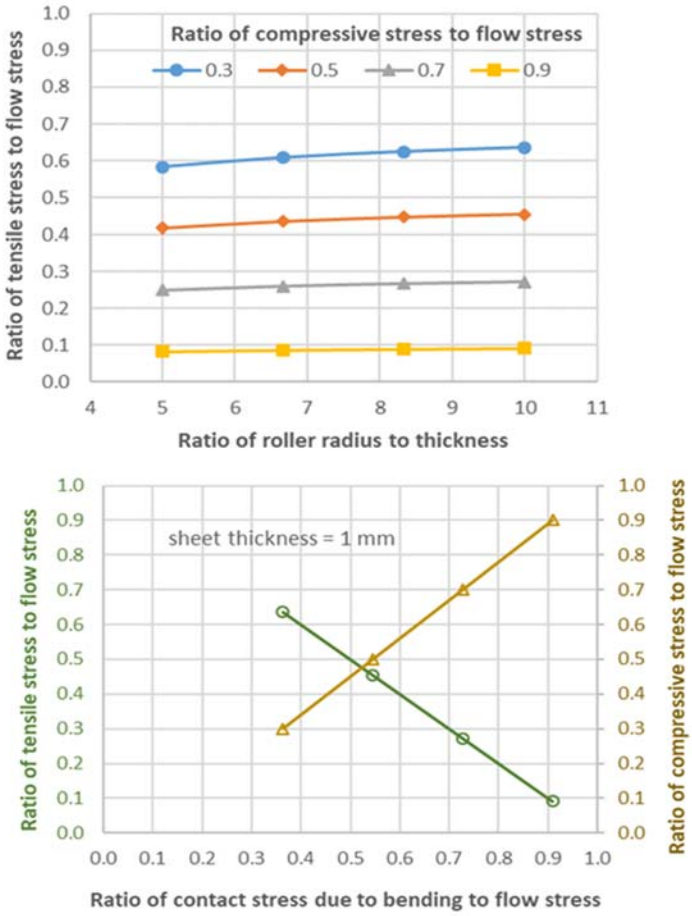

Figure-5 Effect of compressive stress ratio (σ_c/σ_s) and bending contact stress ratio (σ_t/σ_s) on tensile stress ratio (σ_φ/σ_s)

By varying the radius of the rollers from 8 to 12 mm, using sheet thickness from 1 to 2 mm, it has been shown that the ratio of roller radius to sheet thickness only varies from 4 to 12. To illustrate the effect of compressive stress σ_c and contact stress due to bending roller σ_t on the variation of the tensile stress σ_φ, the rollers with radius of 10 mm and the sheet blank thickness of 1, 1.2, 1.5 and 2 mm are tested. The ratio of the compressive stress to the flow stress, σ_c/σ_s, is varied as 0.3, 0.5, 0.7 and 0.9 to evaluate the variation of the tensile stress to the flow stress ratio, σ_φ/σ_s, as shown in Figure-5. The analysis clearly shows that a higher compressive stress will result in a much lower tensile stress required to reach the desired plastic deformation of the material thus delaying the occurrence of fracture. Using the roller radius and sheet thickness values tested, the ratio of roller radius to sheet thickness only shows minimal effect on the variation of the tensile stress ratio. As also shown in Figure-5, the tensile stress ratio σ_φ/σ_s reduces proportionally while the contact stress ratio due to bending σ_t/σ_s increases; however, the compressive stress ratio σ_c/σ_s also increases with the increasing contact stress ratio due to bending σ_t/σ_s, which may result in high stresses in the localised areas of the specimen-tool contact thus leading to early fracture.

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3 TCBC test rig design and manufacturing

Based on the TCBC test concept developed and the analysis of the effect of the bending and compressive loading on the material plastic deformation, a test rig is designed and manufactured. The CAD model and completed TCBC test rig are shown in Figure-6.

Various loading conditions can be applied onto the sheet specimen by using the developed loading device, mounted on a uniaxial tensile test platform as shown in Figure-6. Both ends of the sheet specimen are clamped and the specimen is stretched from one end by the movement of the linear screw mechanism driven by a DC motor. Bending and compression loadings onto the specimen can be applied by the loading device where the specimen can be inserted through and bent from the below by the bending roller and compressed from the above by the compression roller. The compression roller is supported by two cylindrical springs to provide the required level of the compression force as well as to maintain the contact between the compression roller and the specimen. In order to ensure the bending being applied to the target deformation zone and maintain the bending effect during cyclic loading, the specimen is kept in position by two supporting rollers positioned with a constant distance. All rollers can rotate freely around its own axis to reduce friction. The loading device can move along a slider track that is mounted on the base of the uniaxial tensile test platform and driven by another DC motor. On both ends of the slider track, a micro switch is placed; once the loading device hits the switch, the rotating direction of the DC motor will be reversed, creating a cyclic movement of the loading device. Using the motor controlling system, the stroke speed of the slider, the tensile speed, the bending depth and the compression force can be independently controlled and varied. These correspond to the effect of each deformation mode in DSIF, including cyclic effect, tension effect, bending effect and compression effect.

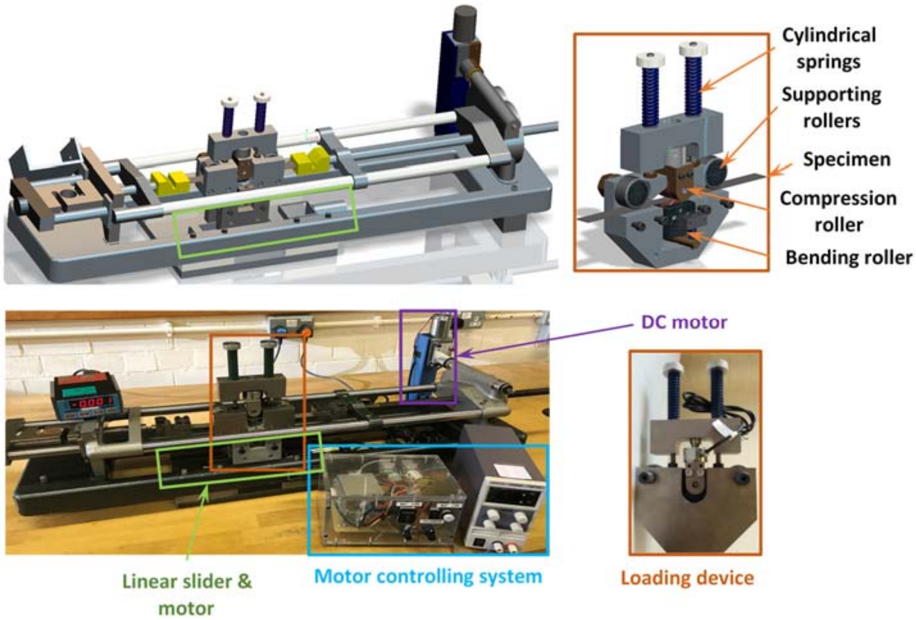

Figure-6 Tension under Cyclic Bending and Compression (TCBC) test rig and loading device

4 TCBC experiment and results discussion

Using the test rig developed, four different types of experiments, representing various loading conditions, are performed. These include tests of simple tension (ST), tension under cyclic compression (TCC), tension under cyclic bending (TCB), and tension under cyclic bending and compression (TCBC). Material AA5251-H22 is used and sheet specimens with thickness of 1, 1.2 and 1.5 mm are tested. Five test parameters are investigated where the compressive force is varied from 0 to 1700 N, bending depth from 1 to 13 mm, stroke speed from 0 to 2.5 mm/s, and stretching speed from 0 to 4 mm/min.

4.1 Effect of various loading conditions on material deformation

Figure-7 shows the tensile force time history when the sheet thickness is 1.5mm, the compression force 906N, bending depth 9mm, stroke speed 1.5mm/s, and stretching speed 3.2mm/min. Significant tensile force reduction is recorded under TCC, TBC and TCBC conditions when compared to that under simple tension. The maximum tensile force under TCBC condition is only 50% of that required under simple tension. Figure-8 shows the maximum elongation ratio at fracture of the specimens tested under these conditions. The maximum elongation ratios of the specimen under TCC, TCB and TCBC are significantly higher than that under simple tension. The specimen elongation is the greatest under TCBC while the elongation under TCB is higher than that under TCC. The fracture behaviour of the specimens is also different under different testing conditions. In the simple tension test, the crack of the specimen occurs at an approximate angle of 45° to the elongation direction of the specimen. While in other tests of TCC, TCB and TCBC, the cracks of the specimen are all perpendicular to the elongation direction. The difference of the cracking orientation of the specimens is resulted from the difference in stress distributions due to different loading conditions as discussed in Section 4.3.

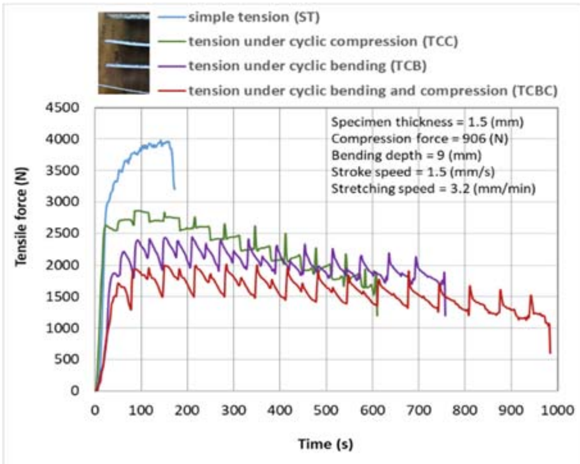

Figure-7 Tensile force time history under four different testing conditions

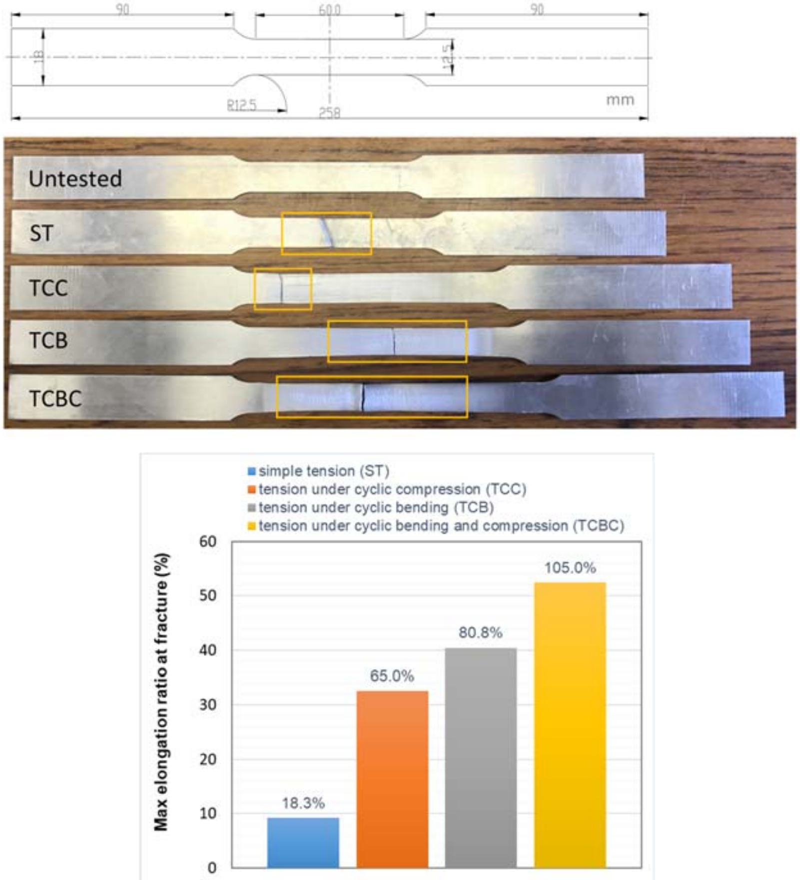

Figure-8 Maximum elongation of tested specimens under four different testing conditions (thickness 1.5mm, compression 906N, bending 9mm, stroke speed 1.5mm/s, stretching speed 3.2mm/min)

4.2 Effect of bending depth and compression force on material deformation

To investigate the bending effect on material deformation, different values of the bending depth, varied from 1 to 13 mm, are used under the TCB testing condition while all other parameters remain constant. Figure-9 shows variations of the maximum elongation ratio and maximum tensile force when different values of the bending depth are applied. It shows that the maximum elongation ratio increases with the increasing bending depth; at bending depth of 12 mm, the maximum elongation ratio achieved is 70%, i.e. equivalent to an increase of 42 mm elongation from original gauge length of 60 mm. However, when the bending depth is further increased to 13 mm, the maximum elongation ratio starts to reduce which was explained by Emmens et al. [19] as a fracture mechanism under cyclic loading effect. Figure-9 also shows that the maximum tensile force reduces considerably when the bending depth is increased. The tensile force reduction trend levels out and remains almost constant after the bending depth reaches to and is greater than 10mm.

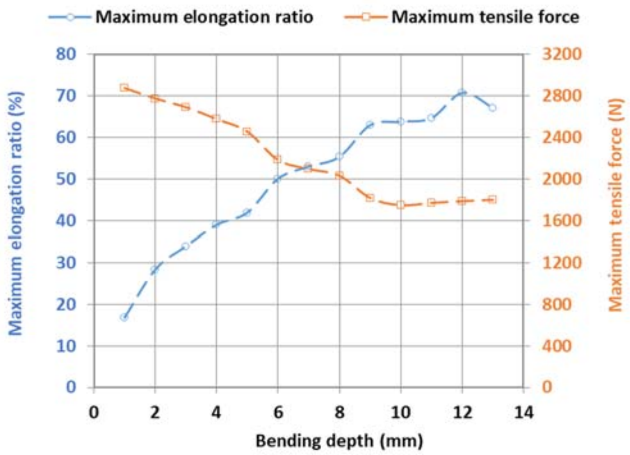

Figure-9 TCB tests with variable bending depth (thickness 1mm, compression force 0, stroke speed 1 mm/s, stretching speed 2.4 mm/min)

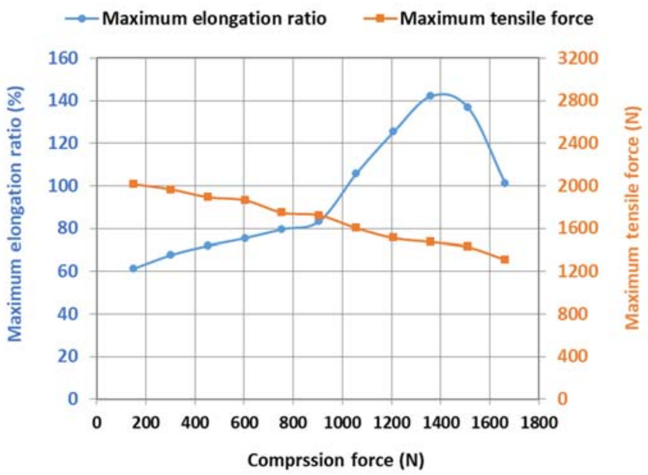

Figure-10 TCBC tests with variable compression force (thickness 1.2mm, bending 9mm, stroke speed 1.5mm/s, stretching speed 3.2mm/min)

To investigate the compression effect on material deformation, different values of the compression force, varied from 100N to 1700N, are applied under TCBC testing condition while all other parameters remain constant. Figure-10 shows variations of the maximum elongation ratio and maximum tensile force when different values of the compression force are used. At the compression force of 906N the maximum elongation ratio reaches 80%; with further increases of the compression force from 906N to 1359N the maximum elongation ratio increases significantly to peak at 142%. However, with further increase of the compression force, the maximum elongation ratio starts to decrease. When the compression force increases, Figure-10 shows a steady decrease of the tensile force required for achieving the material plastic deformation.

4.3 FE modelling of material deformation under TCB and TCBC conditions

To understand the material deformation characteristics of the significantly increased elongation of the specimen under TCB and TCBC testing conditions, FE models of TCB and TCBC tests are generated to simulate the experimental tests using the developed test rig. In FE modelling, a stroke speed of 1.5mm/s and stretching speed of 2.4mm/min are applied to the specimen thickness of 1mm under bending depth of 9mm. For the TCBC model, an additional compression force of 600N is applied; while for the TCB model it is zero. Details of the FE modelling can be found in [18]. Figure-11 and Figure-12 show FE stress distributions on two surfaces of the specimen in the longitudinal direction during the uniform material deformation stage, for the TCB and TCBC testing conditions, respectively. Under both testing conditions, for the surface in contact with the compression roller the material is under tension and subjected to the highest plastic deformation. On the other hand, for the surface in contact with the bending roller the material is under compression. The additional compressive force in the TCBC test reduces the difference of the stresses on these two surfaces leading to a more uniform stress gradient through the specimen thickness. The more homogeneous stress distribution in the specimen thickness allows the material to undertake a greater plastic deformation thus to delay the occurrence of fracture.

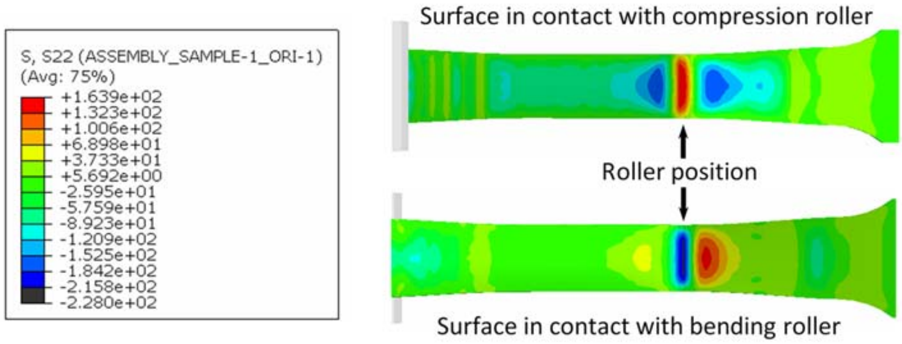

Figure-11 TCB test – stress distributions of deformation zones around compression and bending rollers

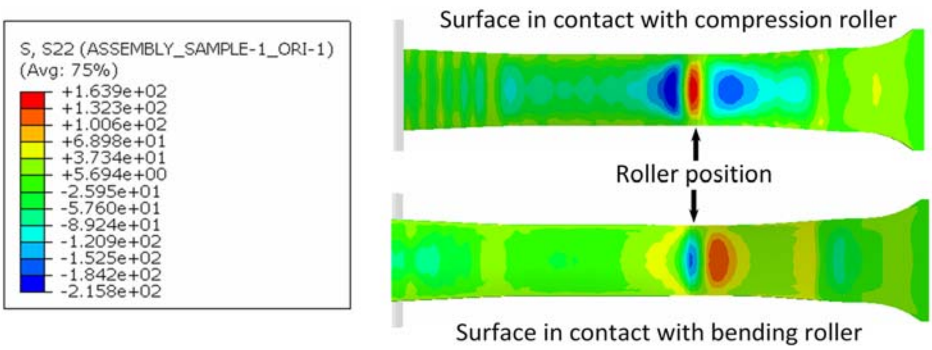

Figure-12 TCBC test – stress distributions of deformation zones around compression and bending rollers

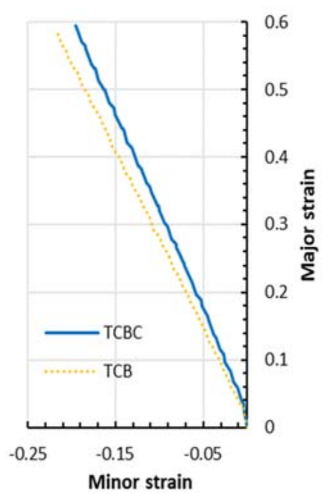

Figure-13 Strain paths of elements in FE modelling of TCBC and TCB tests

Figure-13 shows the strain paths of the elements located on the outer surface in the centre of the specimen of the TCBC and TCB FE models. The strain component in the longitudinal direction of the specimen is the major strain and the strain component in the specimen's width direction is the minor strain. The non-linear strain paths reflects the effect of cyclic loading on the material deformation. For TCBC test, the introduction of the compressive force reduces the material deformation in the lateral direction than that in TCB test while elongations of the specimens in the longitudinal direction are the same. In the TCBC and TCB tests, as shown in Figure-13, the material deformation is approximately between plane strain and uniaxial tension, as illustrated in Figure-2. However, in the ISF processes, the material is approximately under a strain state between plane strain and equal biaxial tension. The difference could be caused by two factors, firstly due to the difference of the geometric constrains between the TCBC tests and the ISF processes and secondly how the tension is applied onto the specimen material. In the TCBC and TCB tests, tension is applied by continuous stretching force from the clamp. By comparison, in the ISF processes, the sheet blank is only clamped on its outer edges, once the tool(s) moves away from the sheet-tool contact area, the tension applied on that area of the material would be partially released. As a result, the strain paths obtained from the TCBC and TCB tests are different from the ISF processes.

5 Conclusions

The new TCBC test method has successfully produced results to evaluate the material deformation under four different conditions: simple tension (ST), tension under cyclic compression (TCC), tension under cyclic bending (TCB), and tension under cyclic bending and compression (TCBC). The following conclusions may be drawn:

- The compressive force shows a significant effect on the increase of the maximum elongation of the tested specimen and a significant reduction of the tensile force required to achieve the material plastic deformation. However, high compression forces greater than a certain limit may reduce the maximum elongation thus have a negative effect on formability.
- The bending depth displays a considerable effect on the increase of the maximum elongation even under a small value of bending depth tested. However, when the bending depth is increased above a certain limit, it may result in higher tensile stresses on the specimen surface in contact with the compression roller thus causing early fracture of the specimen.
- The maximum elongation increases significantly under TCBC condition due to cyclic alternations of localised plastic deformation zone that delays the occurrence of fracture. The experimental testing and FE modelling results also show effects of complex interactions between compression and bending on the material deformation and fracture.

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