Investigation of the Effects of Process Parameters on the Welding Line Movement in Deep Drawing of Tailor Welded Blanks

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Abstract: In this paper, the deep drawing process of tailor welded blanks is simulated using the finite element modelling and verified using the experimental results available in the literature. Then the effect of die and material properties on the welding line movement is investigated. It is seen that the most effective material parameters on weld line movement are the differences between sheet metal thicknesses and strength coefficient of two welded sheets. Also it is seen that the most effective die parameter on weld line movement is the friction coefficient between punch and blank. Finite element simulations show that in the wall section of the drawn cup, the welding line moves toward the material with smaller thickness and lower strength coefficient while in the bottom of the drawn cup, the welding line moves toward the material with larger thickness, and higher strength coefficient. Based on the results, increasing the friction coefficient between blank and die, decreases the welding line movement considerably.

Keywords: Deep drawing process, Tailor welded blanks, Welding line movement

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1 INTRODUCTION

Tailor welded blanks (TWB) are made of two or more sheets with different materials, thicknesses or surface coatings which are welded together before the forming process. This technology facilitates the use of lightweight materials like aluminium, titanium, magnesium and the steel sheet metals with different thicknesses. The technology of tailor welded blanks not only considerably reduces the weight of the designed products in aerospace and automobile industries, but also can fulfil the other design factors including increasing the safety, increasing the strength to weight ratio and decreasing the production cost. TWBs make it available to use the required and sufficient material or thickness in the designed sheet metal component. However, beside the mentioned advantages, the tailor welded blanks suffer from lower formability, because they have non-uniform strain distribution due to the difference in thicknesses or materials of the used sheet metals. Also the welding line movement during forming process is one of the unwanted happenings.

Due to the advantages of the TWBs, the research interest in this field is continually increasing. Choi et al. investigated the effect of welding line location in deep drawing of square cross section cup [1]. They studied the effect of thickness ratio of welded sheets and suggested a minimum thickness ratio for TWBs to eliminate fracture. Kinsey et al. proposed a new clamping method along the welding line of the TWB for increasing its formability [2]. In this method hydraulic cylinders apply an extra force to the welding line which reduces the maximum strains along the welding line by approximately one-fifth. Meinders et al. investigated the effect of initial welding line location of TWB in welding line movement of cylindrical and hemispherical components [3]. They suggested that the weld displacement can be minimized by placing the weld in a region where low strains are perpendicular to the welding line. Also welding line movement can be minimized by equalizing the load bearing capacities of the applied base materials. Heu et al. studied the effect of size of drawbead on the welding line movement of TWB in deep drawing of square cups [4]. They used the drawbead in thinner side of the TWB and showed that the welding line movement decreases as the size and height of the drawbead increases. Therefore welding line movement can be controlled by appropriate drawbead installation. He et al. proposed a strategy to control the welding line movement, using the control of the blankholder force [5]. Kinsey and Cao presented an analytical model to predict the welding line movement and forming height for a given tailor welded blank geometry [6]. Good agreement between the analytical model and numerical simulations in both welding line movement and forming height is observed. Bravar et al. proposed an initial welding line position using an analytical model in order to decrease the welding line movement [7]. Ku et al. applied the backward tracing scheme for the rigid-plastic finite element method to design the initial tailor-welded blank for net-shape production and verified it by a rectangular example [8]. Chan et al. studied the effects of thickness ratios on the formability of tailor welded blanks [9]. This study revealed that the higher the thickness ratio, the lower the Forming Limit Curve (FLC) level. Also the experiments show that Failures were usually initiated at the thinner sides of the TWBs near the step. Padmanabhan et al. studied the effect of the anisotropy of the blank sheets in deep drawing of TWBs [10]. They claim that thinning along the weld-line is more in isotropic material combination than anisotropic tailor-welded blank. Also they suggested using appropriate combination of rolling direction orientation to significantly improve the formability of tailor-welded blanks. Tang et al. developed a one-step finite element code InverStamp which can be used to design TWBs [11]. This one step code gets the desired welding line position in the formed part and predicts its initial position in the blank. This code also evaluates the welding line movement during deformation process. Wang et al. used the finite element simulation to analyse the welding line movement behaviour of deep drawn TWB sheet with different thickness [12]. They found that high strain fields are concentrated around the welding line of TWBs. Padmanabhan et al. used a two-segments blank holder for deep drawing of aluminium–steel tailor-welded blanks and investigated the effect of steel material on the welding line movement [13]. Padmanabhan et al. used the finite element simulation to investigate the stress distribution and its effect on springback in tailor welded blanks [14]. Abbasi et al. proposed the FLD for tailor-welded blanks and verified it experimentally [15]. Abbasi et al. [16] analyzed the wall wrinkling tendency of a TWB, analytically, numerically and experimentally. Rojek et al. [17] presented some experimental and experimental-numerical methods which can be used to determine mechanical properties of the weld zone in tailor-welded blanks. Fazli determined the optimum blank shape for tailor welded blank and investigated the effect of welding line location in the optimum blank shape [18]. Mohebbi and Akbarzadeh, proposed a new model to predict the Forming Limit Diagrams (FLDs) of TWBs [19].In this model, they modified the Marciniak and Kuczynski (M-K) analysis and imposed the weld constraints to deformation state of each blank at each strain increment. Safdarian et al. investigated the influence of thickness ratio of TWB on its formability and FLD [20]. Their study reveals that the higher the difference of thickness of welded sheets, the lower is its formability. Masumi et al. introduced a novel numerical method to determine the FLD for TWBs and validated it experimentally [21]. They determined the start of necking in FLDs by this criterion that necking starts when the second derivative of the thickness strain, major strain or plastic strain reaches its maximum value.

Based on the review of the researches performed on the forming of tailor welded blanks, it can be seen that a comprehensive study which represent the effect of various material and die parameters on the forming of TWBs is not performed. This is an important knowledge in the selection of the materials and the design of the drawing die for tailor welded blanks. So in this study, the effect of process parameters on the welding line movement is studied. The deep drawing process of tailor welded blanks is simulated using the finite element modelling. The FE simulation is verified using the experimental results available in the literature. Then the effect of die and material parameters in welding line movement is investigated and the parameters which have the most important role in welding line movement are determined.

2 MODELLING AND SIMULATION

The deep drawing process of TWB is simulated using the finite element software ABAQUS/Explicit. The blank is modelled with a four-node linear shell element (S4R) and the tools are created using the rigid elements (R3D4). Since the width of the welding line to the overall size of the blank is relatively small, the difference between the material properties of Heat-Affected Zone (HAZ) and the base materials is neglected [7]. The FE model is shown in Fig. 1. The material of the blank is considered to be elastic-plastic and the flow stress-strain relation is considered to be according to the Swift equation as Eq. 1 [22]:

$$\sigma=K(\varepsilon+\varepsilon_0)^n \tag{1}$$

In this equation, σ and ε are the flow stress and equivalent plastic strain respectively, K is the strength coefficient and n is the strain hardening index. The constant ε_0 is the pre-strain constant which can be determined using initial yield stress σ_y using Eq. 2 [22]:

$$\varepsilon_0=(\sigma_y/K)^{1/n} \tag{2}$$

Material is assumed to be planar isotropic and have normal anisotropy $\bar{R}$. Also it is assumed that the material yields according to the Hill's anisotropic criteria.

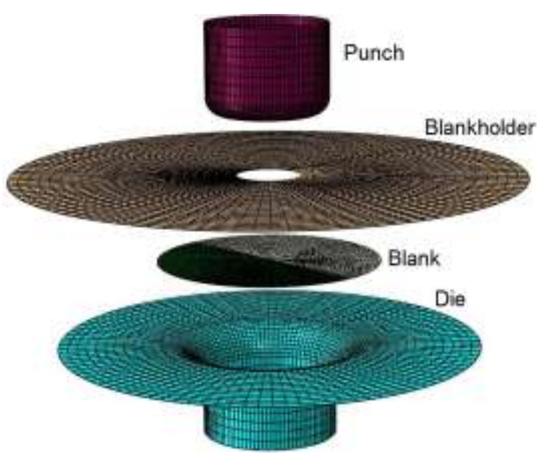

Fig. 1 Tools used in finite element simulations

3 VERIFICATION OF THE FE SIMULATION

In order to verify the FE simulation of deep drawing of TWBs, the experimental results reported by Meinders et al. is used. The sheet metals in these experiments were laser welded together and had thicknesses of 0.7 and 0.98mm. The material properties of welded sheets were according to Table 1 and the die properties were according to Table 2. Due to the difference in the sheets thicknesses, the blankholder force is applied using a stepped blank holder.

Table 1 Material properties of the sheet metals used in the verification of FE simulation [3]

Parameter	First sheet	Second sheet
Sheet thicknes, t (mm)	0.7	0.98
Strength coefficient, K (MPa)	544	549
Yield strength, σ_y (MPa)	168	173
Strain hardening index, n	0.221	0.234
Anisotropy		
R0	1.842	1.971
R45	1.302	1.277
R90	2.077	2.114

Table 2 The die parameters used in the verification of FE simulation [3]

Die Parameter	Value
Punch diameter	293mm
Die diameter	295mm
Punch arc radius	20mm
Punch arc radius	20mm
Friction coefficient between blank and die components	0.12
Blankholder force	20kN

The comparison of welding line movement in experiments and FE simulations for three different drawing depths of 50, 75 and 100mm are shown in Fig. 2 a-c, respectively. As shown in these figures, the finite element results are in good agreement with the experimental results. The finite element simulation has good accuracy for determination of welding line movement in the bottom and wall of the drawn cup. The most difference between the FE simulation and the experimental results are near the punch arc region.

4 THE EFFECT OF MATERIAL PROPERTIES OF WELDED SHEET METALS IN WELDING LINE MOVEMENT

In order to study the effect of material properties of welded sheet metals in the welding line movement, the deep drawing process of TWBs are simulated using the die geometry shown in Fig. 3. The material properties of one of the welded sheet metals were considered to be as the first values in Table 3. The material properties of the other sheet metal are considered to be the same as it except for the parameter that is being studied. In three different simulations the studied parameter is considered to be 85%, 70% and 50% of the value of the first sheet metal (second, third and fourth value in Table 3).

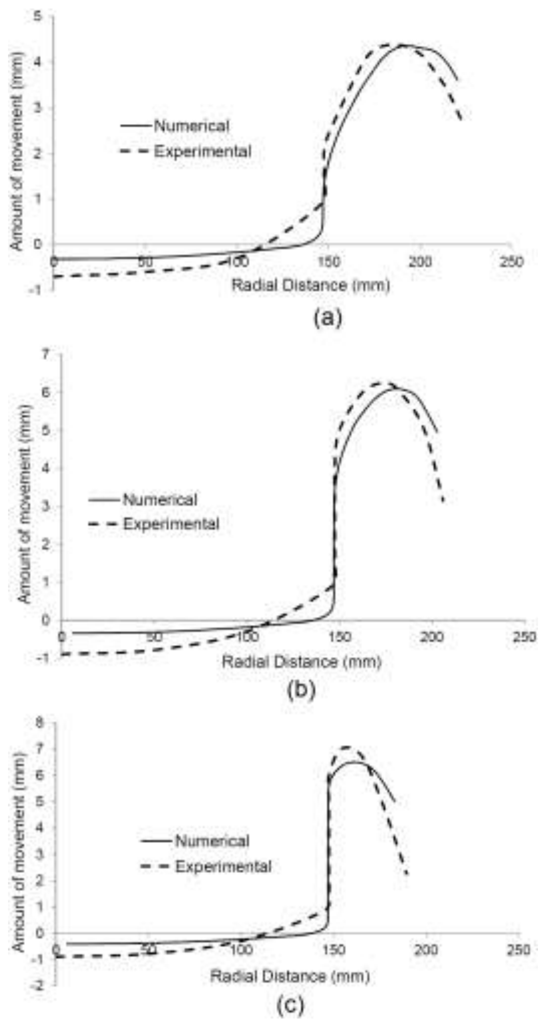

Fig. 2 The Comparison of welding line movement in experiments and FE simulation. Drawing depth of a) 50 mm b) 75mm c) 100mm

The die parameters which are not changed in the parameter study are as shown in Table 4. At the final drawing depth, the maximum welding line movement in bottom and wall of the drawn cup is determined for each parameter. Comparing the results, the material parameters which have the most effect on the welding line movement are determined.

It should be noted that second, third and fourth values mentioned in Table 3 may not be related to an available material and it does not mean that the material with these properties can be found. It is just to determine the relative importance of each parameter. Based on this knowledge it would be possible to compare the material properties of two different sheets which are going to be welded and determine the welding line behaviour during forming process.

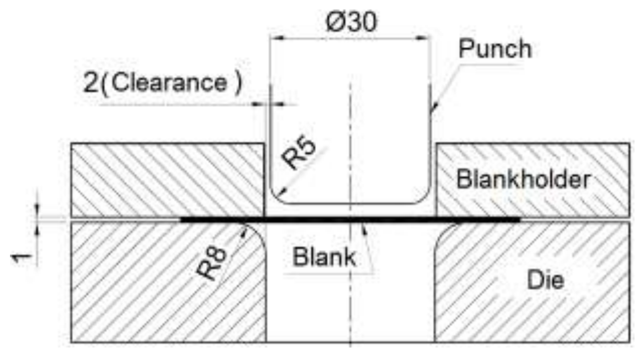

Fig. 3 Geometry of the tools used in FE simulations

Table 3 Material properties used in the parameter study

Parameters	First value (100%)	Second value (85%)	Third value (70%)	Forth value (50%)
σ_y (MPa)	152	129	114	76
K (MPa)	496	422	372	248
$\overline{R}$	1.6	1.36	1.2	0.8
thickness (mm)	1	0.85	0.75	0.5
n	0.29	0.25	0.22	0.15

Table 4 The die parameters used in the parameter study

Parameter	Value
Blank Diameter (mm)	60
Blank holder force (N)	1760
Blank/punch friction coefficient (μ_p)	0.18
Blank/blankholder and blank/die friction coefficient (μ_d)	0.18

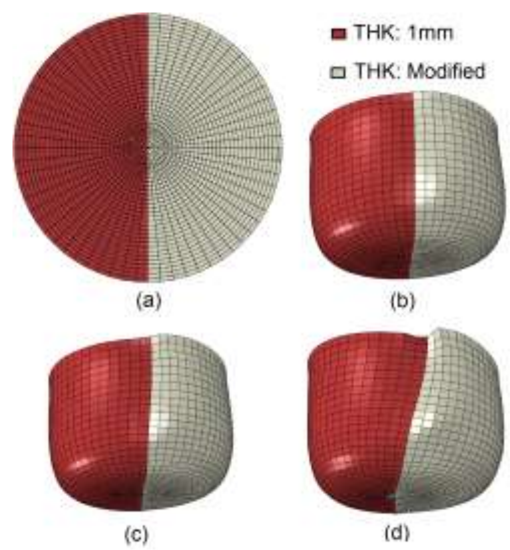

Fig. 4 Initial blank and drawn cups for three different thickness combinations. a) initial blank b) thicknesses of 0.85 and 1mm c) thicknesses of 0.75 and 1mm d) thicknesses of 0.5 and 1mm

4.1. Investigation of the thickness effect

During deep drawing of the TWBs with different thicknesses, due to the difference that is sheet metal thicknesses, the initial blank is stepped. So in order to apply the blankholder force on both half of the sheet metal, the blankholder is also considered to be stepped. In order that the blankholder step does not hinder the welding line movement toward thinner sheet, the step has 5mm distance from the welding line toward the thinner sheet metal. Fig. 4 shows the initial blank shape and the drawn cup for each combination of the sheet metals thicknesses. As it can be seen in this figure, increasing the difference in sheet metal thicknesses increases the welding line movement.

Fig. 5 shows the magnitude of welding line movement in each thickness combinations. It can be seen that increasing the sheet thicknesses difference causes the welding line to move toward the thicker sheet in the bottom and toward the thinner sheet in the wall of the drawn cup. The welding line movement in the bottom, up to thickness difference of 30% is negligible, but increasing the sheet thickness difference to 50%, increases the welding line movement in the bottom considerably and it reaches to the value of 2.3mm.

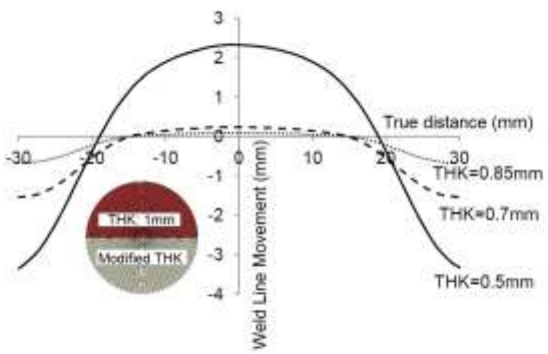

Fig. 5 The effect of difference in sheet metals thicknesses in welding line movement

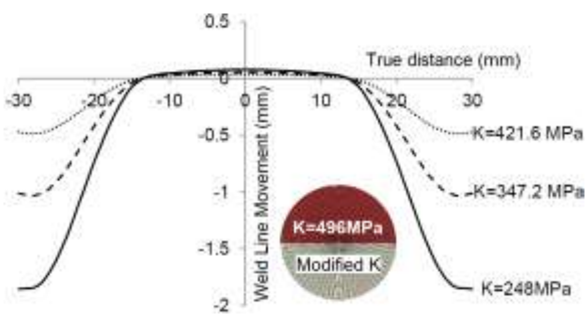

Fig. 6 The effect of difference in strength coefficients (K) in welding line movement

4.2. Investigation of the effect of strength coefficient

The effect of strength coefficient (K) on welding line movement is shown in Fig. 6. As shown in this figure, increasing the difference in K value of the welded sheet metals increases the welding line movement. The welding line movement in the wall of the drawn cup is more considerable than the bottom of the drawn cup. For example when the difference in K value is 50%, the maximum welding line movement in the bottom of the drawn cups is only 0.07mm while it is 1.85mm in the wall of the drawn cup. In the bottom of the blank, the welding line moves slightly toward the sheet with higher K value (stronger material), while in the wall of the drawn cup, it moves considerably toward the sheet with smaller K value (weaker material).

4.3. Investigation of the effect of strain hardening exponent

The effect of strain hardening exponent on welding line movement is shown in Fig. 7. It can be seen that the strain hardening exponent has a negligible effect on the welding line movement. For example, 50% deference in the strain hardening exponent causes a maximum welding line movement of 0.15mm and 0.65mm in the bottom and wall of the drawn cup respectively. The welding line movement in the bottom is toward the material with smaller strain hardening exponent and in the wall is toward the material with larger strain hardening exponent.

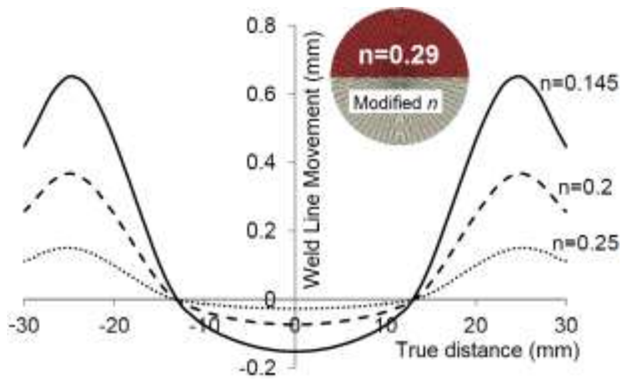

Fig. 7 The effect of difference in stain hardening index (n) in welding line movement

4.4. Determination of the most effective material properties on welding line movement

The effect of normal anisotropy ratio and initial yield strength are also investigated, and compared to the other parameters. Fig. 8 and Fig. 9 compare respectively the maximum welding line movement in bottom and wall of the drawn cup for various material parameters. As it can be seen in these two figures, the difference in normal anisotropy ratio and initial yield strength of welded sheets has negligible effect on welding line movement. Also it can be seen in Fig. 8 that the welding line movement in the bottom of the drawn cup is only related to the difference in sheet metal thickness and the effect of other parameters are negligible. Also as shown in Fig. 9, the most effective parameters in welding line movement in the wall of the drawn cup are the difference in sheet thickness, strength coefficient and strain hardening exponent respectively.

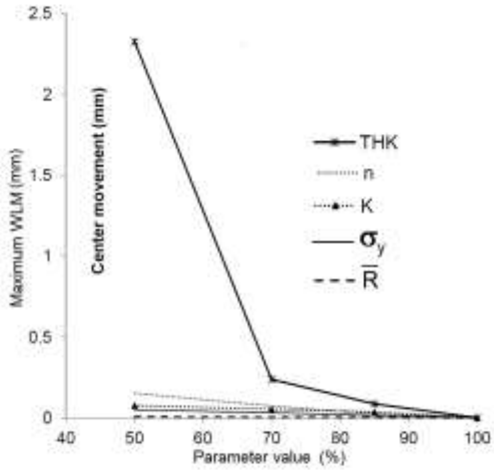

Fig. 8 Comparison of the maximum welding line movement in bottom of the drawn cup for various material parameters

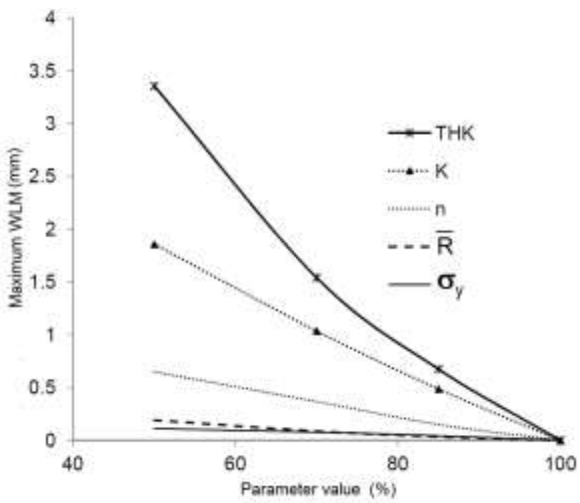

Fig. 9 Comparison of the maximum welding line movement in the wall of the drawn cup for various material parameters

5 INVESTIGATION OF THE EFFECT OF DIE PARAMETERS ON WELDING LINE MOVEMENT

In order to study the effect of die parameters, the properties of two welded sheet metals are considered to be as the first and forth value of Table 3, respectively. To study the effect of each parameter, all the die parameters are considered to be constant as Table 4 and only the studied parameter is changed. In three different simulations, the studied parameter is considered to be 75%, 100% and 125% of the values in Table 4. At the final drawing depth, the maximum welding line movement in bottom and wall of the drawn cup is determined. Comparing the results, the die parameters which have the most effect on the welding line movement are determined.

Fig. 10 shows the effect of various parameters in maximum welding line movement in the bottom of the drawn cup. It can be seen that increasing the friction between blank and punch, decreases the welding line movement in the bottom of the drawn cup considerably. Increasing the punch arc radius increases the welding line movement slightly. Also it can be seen that the blank holder force, die arc radius and friction coefficient between blank/blankholder and blank/die has no considerable effect on welding line movement in the bottom of the drawn cup.

The effect of die parameters on maximum welding line movement in the wall of the drawn cup is shown in Fig. 11. As shown in this figure, increasing the friction coefficient between blank and tool components, decreases the welding line movement in the wall, while increasing the punch arc radius increases it. Also it can be seen that the blank holder fore and die arc radius has no considerable effect on welding line movement.

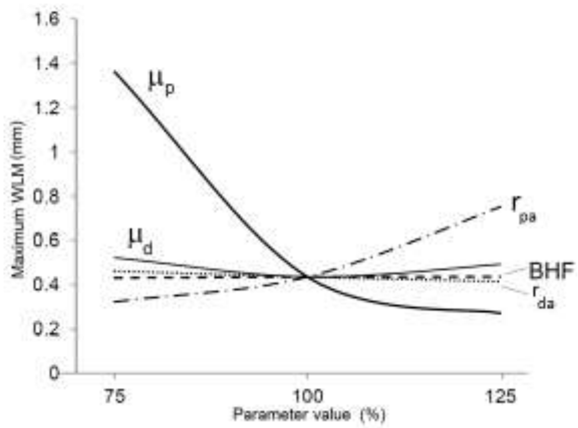

Fig. 10 Comparison of the maximum welding line movement in the bottom of the drawn cup for various die parameters

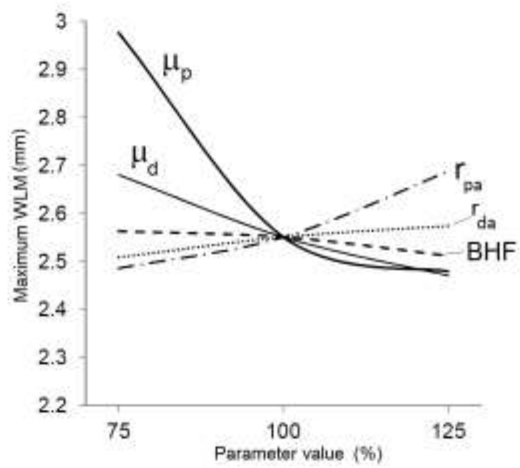

Fig. 11 Comparison of the maximum welding line movement in the wall of the drawn cup for various die parameters

Further investigations of Fig. 10 and 11 show that the most effecting die parameter in welding line movement is the coefficient of friction between blank and punch. The welding line movement for three different punch/blank friction coefficients is shown in Fig. 12. As it can be seen, increasing the punch/blank friction coefficient decreases the welding line movement in the bottom and the wall of the drawn cup and its reduction in the bottom is more considerable.

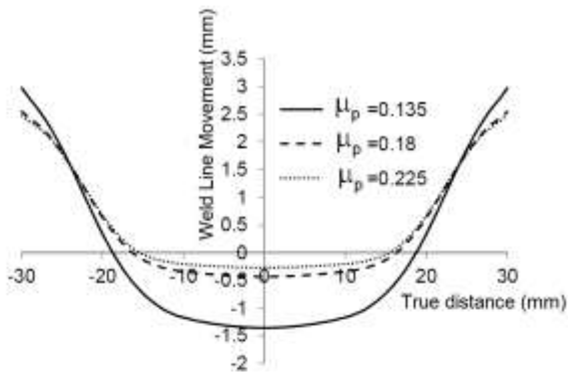

Fig. 12 Effect of friction coefficient between blank and punch on the welding line movement

6 CONCLUSIONS

The deep drawing process of tailor welded blanks is simulated using the finite element modelling and verified using the experimental results available in the literature. The effect of die and material properties on the welding line movement is investigated. The results are as following:

• Among the material parameters, the difference in sheet thickness and strength coefficient of welded sheets has the most effect on the welding line movement, while the difference in initial yield strength and normal anisotropy has no considerable effect on welding line movement.

• Among the die parameters, the blank/punch friction coefficient has the most effect on welding line movement, while the punch arc radius, blank holder force, blank/blankholder and blank/die friction coefficient has no considerable effect on welding line movement.

• The difference in sheet thickness causes the blank to move toward the thicker sheet in the bottom of the drawn cup and toward the thinner sheet in the wall of the drawn cup.

• The difference in strength coefficient causes the blank to move toward the stronger sheet in the bottom of the drawn cup and toward the weaker sheet in the wall of the drawn cup.

• Increasing the punch/blank friction coefficient decreases the welding line movement.

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