Research Article

An investigation of the effect of temperature variability of the tools on FEA of the warm hydromechanical deep drawing process

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Abstract
Warm hydromechanical deep drawing process is an innovative manufacturing technology that offers considerable increase in the formability of the materials. However, the weakness of the process lies in its complexity. For a successful process, the optimum temperature distribution of the material must be achieved. In addition, optimum loading profiles (pressure of fluid and force of blank holder) should be applied according to the punch position. These conditions can most easily be determined with the proven finite element analysis (FEA). In this study, the effect of the temperature variability of the tools on the results of the FEA was investigated. Namely, the study aims at investigating whether the temperature variability of the tools needs to be modeled or not in FE analysis. For a simple and fast analysis, it is generally accepted that the tools have a homogeneous temperature distribution and the temperature is constant throughout the process. However, in the experiments in this study, the temperatures of the tools changed considerably. The temperature variability of the tools was first measured in the experiments and then modeled in the FEA. In the analysis performed for the AA 5754 aluminum alloy, the thickness distribution of the deep drawn part was compared with the results of an FEA performed at a constant and same temperature condition. Results in both conditions were very close to each other and indicated that there is no need to obtain and model the temperature distribution or temperature variability of the tools throughout the process. It was possible to perform the FEA with acceptable accuracy by assuming a constant and homogeneous temperature distribution in the tools throughout the process.

Keywords Warm hydroforming · Sheet metal forming · FEA

1 Introduction

The warm hydroforming process has been investigated since the early 2000s in order to combine the advantages of hydroforming and warm forming [1, 2]. These advantages include: further increase in formability and part consolidation; more robust manufacturing of parts at reduced weight; a decrease in the production steps; and a reduced press capacity, and allow to form at lower temperatures. These advantages resulted in reduced production costs and the ability to form materials with lower ductility like titanium alloys. Warm hydroforming can be divided into two groups according to the tool used. In warm hydroforming with die process, a female die is used, while in warm hydromechanical deep drawing (WHDD) process, a male die is used as shown in Fig. 1.

The sheet is heated to a certain temperature and then pressed into the die with a hot fluid in warm hydroforming with die. In this process, the sheet is formed by stretching it after it was clamped by blank holder [3]. For this reason, the parameters affecting the process are temperature and fluid pressure. Hence, the effect of temperature fluid pressure on the formed parts was generally investigated in the literature. Modeling of the process in FEA and performing

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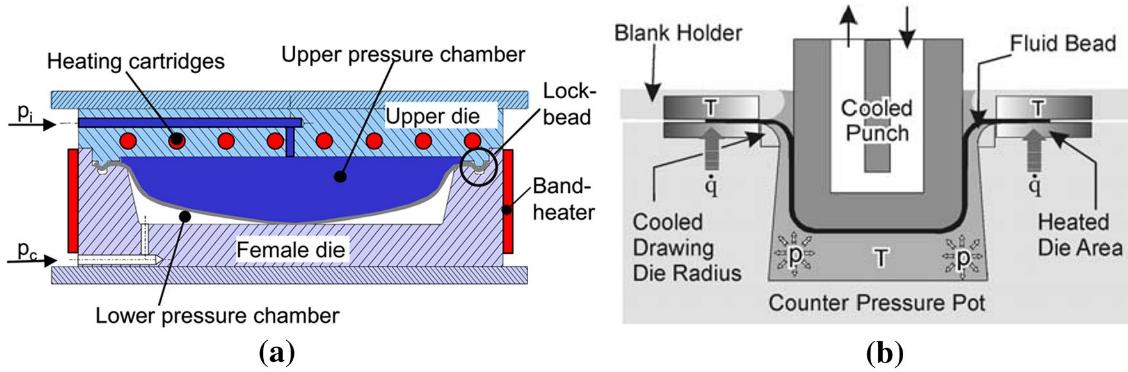

Fig. 1 **a** Warm hydroforming with die [1], **b** warm hydromechanical deep drawing [2]

experiments is simple. Because all tools, the hydraulic medium and the blank have the same temperature, only the maximum pressure level is important for the process.

Keigler et al. [4] heated the complete construction in a furnace and used nitrogen as forming medium. They found that 40 bar internal pressure and 450 °C sheet temperature are the best forming conditions. With these values, the desired cup height and radius could be obtained.

Koç et al. [5] determined optimal process conditions in warm hydroforming of AA 5754 alloy by measuring thickness strain, cavity fill ratio and radius of curvature. Optimal forming conditions were found to be a pressure of 25 MPa, a pressurization rate of 0.22 MPa/s and a temperature of 268 °C. They found that temperature had a greater effect on the measured properties than pressure and pressure rate.

Mahabunphachai and Koç [6] investigated the effect of temperature and pressure on formability of AA 5082 and AA6061 aluminum alloys in warm hydroforming with die process. In the experiments conducted at 200 °C and 300 °C temperatures and pressures of 10, 15 and 20 MPa, the cavity filling ratio and the thickness distribution of the part were measured. While the cavity filling ratio increased significantly with pressure at 200 °C, the linear increase in the pressure did not significantly affect the cavity filling ratio nor the thinning of the parts in the case of a uniform temperature of 300 °C. It was found that formability of AA5052 was better when compared to AA6061 under the investigated forming parameters. However, they were concluded that using a uniform temperature and linearly increasing pressure profile may not be the most efficient approach to increase formability. Optimal process conditions like variable pressure and blank holder force profiles and temperatures require using an FEA tool.

Koç et al. [7] evaluated the theoretical models to calculate bulge radius and blank thickness. They determined the best combination of theoretical models to obtain accurate flow curves models both at room and elevated temperatures by comparing an FEA of hydraulic bulge test with experimental results. They found that the best combination to predict flow curves was Kruglov's method for thickness and Panknin's method for bulge radius calculations.

Gedikli et al. [8] aimed to determine the optimal conditions such as solvent, material model and element type in the FE model of warm hydroforming with die process. They used AA 5754 sheet metal as material. FEA was evaluated by comparing numerical and experimental results at different temperatures and strain rates. The thinning and cavity filling ratio was taken as the comparison parameter. They found that using an implicit solution technique, shell elements and isotropic material model was appropriate for better prediction of experimental results.

Palumbo et al. [9] investigated optimal forming conditions to manufacture an aluminum sheet part by warm hydroforming with die process. In their numerical study, blank holder force, oil pressure and blank temperature were used as input variables, while output variables were die filling and maximum oil pressure. The optimization was performed by numerical simulations. They used two different yield criteria and obtained different optimal conditions for isotropic von Mises and anisotropic Barlat '89 criterion. Conducted experiments showed that the FEA was valid when the anisotropic criterion was used.

Choi et al. [10] stated that formability in warm hydroforming increases due to reducing the stress with high temperature in the flange area, an increase in material strength via contacting the sheet metal with cooled punch and having the frictional force between the punch and the sheet.

Although the warm hydroforming with die process is simple, it is not a suitable technique for manufacturing deep parts. The WHDD process offers significant advantages in the production of parts with significantly higher heights in one stage. In the WHDD method, the sheet is formed by a cooled punch after its flange region is heated and compressed with certain blank holder force. Performing WHDD is harder than warm hydroforming with die because blank holder force and fluid pressure should be arranged sensitively according to the punch position, and the blank should have a temperature gradient. Although the process has many important advantages, it was generally implemented at a laboratory scale. That is because manufacturing a successful part requires solutions to problems such as insulating and sealing of the tools and using the pressurized medium at high temperatures. In addition, optimized fluid pressure profiles and blank holder force profiles must be used at a proper temperature distribution. The optimization procedure of the parameters requires the use of FEA in the process.

The first studies on WHDD [11, 12] did not deal with FE analysis of the process, and generally, the effect of the temperature and the limiting drawing ratio (LDR) was investigated experimentally in these studies. LDR of SUS304 stainless steel material was obtained as 3.3 [11], and it was obtained as 2.8 for AZ31 magnesium alloy [12].

In a recent study by Liu et al. [13], they attempted to form a part with special-shaped bottom from aluminum alloy using the WHDD process. They applied an independent circumferential pressure on the periphery of the flange of the sheet and improved fittability accuracy of the part. Non-isothermal FE analyses were conducted to determine the effect of different temperature ratios of punch and die on the drawing depth. It was found that the excessive decrease in the punch temperature and the increase in the die temperature did not contribute to the increase in the part depth.

In the study of Cai et al. [14], appropriate forming mediums in the WHDD process were investigated. Different types of forming mediums had different cooling effects on the sheet. The mechanical properties and microstructure of cylindrical cups were analyzed in the WHDD process when using different cooling. They found that different types of cooling slightly influenced the mechanical properties and microstructure of cylindrical cups.

Choi et al. [10] proposed the adaptive-isothermal FEA/DOE approach instead of the costly and lengthy thermomechanical simulations to accurately and quickly determine the optimum temperature condition in a WHDD process. They compared three methods to determine the proper temperature distribution of the blank. They concluded that the accurate modeling of WHDD is possible with thermomechanical FEAs in which the heat transfer between the dies and sheet was calculated. However, due to the complex and nonlinear calculations and iterations, thermomechanical FE Analysis requires both a large amount of resources and a long time depending on the size of the simulated parts. In the isothermal approach, the heat transfer was not modeled, and different temperature levels were assigned to the different regions of the blank. However, in this approach accurate blank temperatures could not be simulated. The proposed adaptive-isothermal approach controls the material location and assigns neighboring tool temperature to the blank. Different levels of punch wall, punch face, punch corner, die corner, flange region and hydraulic medium temperatures were analyzed by two-level fractional factorial design. Optimal temperature distribution of the blank was determined. In the study, it was demonstrated that using an adaptive-isothermal FEA/DOE is suitable for calculating the fast and accurate estimation of the appropriate temperature distribution.

Choi et al. [15] developed a methodology in WHDD to determine the appropriate loading profiles (fluid pressure and blank holder force curves) at different punch speeds. Adaptive FE and a fuzzy control algorithm were developed to determine the loading conditions simultaneously. Thinning, wrinkling and contact with the punch are selected as criteria in this algorithm. Then, regardless of the results in the process, the effects of the mentioned profiles on thickness, stress, strain and temperature distribution were given. They divided the tooling into three segments and optimized each segment temperature to achieve maximum formability. As a result, it was found that optimal process conditions were obtained quickly and accurately with the adaptive FEA method, and the fuzzy control algorithm was developed.

FEA was important place in determining the optimum process conditions in the studies mentioned above. However, in the WHDD process, the variability in the temperature of the tools due to the cooling of the punch and the heating of the die and the blank holder was ignored except for the numerical studies done by Choi et al. [10, 15]. Although a different temperature was assigned to the radius region of the die in the studies performed by Choi et al. [10, 15], the experimental verification of this situation was not made, and the temperature change in the radius during the process was still ignored. In this study, the aim was to determine the need of modeling temperature variability of the tools in the WHDD process. Hence, the temperature variability during the process was analyzed for each region with thermocouples placed in 4 different regions on the die/blank holder and in 2 different regions on the punch. Then, in FE analysis, the temperature variation occurring in the tools during the process was modeled and the results obtained were compared with those obtained from the analyses made with constant temperature acceptance.

2 FEA and experiments

FE analysis was conducted in Ls-Dyna solver. A quarter-model of the axisymmetric geometry of cylindrical cups was used to take a fast solution as shown in Fig. 2. The punch diameter was 40 mm. The blank holder and the die cavity had diameter of 43 mm. Punch nose and die entrance radiuses were 5 mm. A 3D quadrilateral fully integrated shell element formulation with five integration points through the thickness was used to model the blank. "Belytschko-Tsay" element formulation with three integration points was assigned to shorten the simulation time as for rigid tools. The blank, with a 124 mm diameter and 1 mm thickness, was modeled with 2,655 elements.

Symmetry boundary conditions were applied to the edges of the blank, and the fluid pressure area was determined by a mask loading condition. In addition, the blank holder force was applied on the blank from the blank holder and the encastered boundary condition was applied to the die.

The blank was modeled as elastic viscoplastic, whereas the punch, die and blank holder were assumed as rigid. Elastic properties for AA 5754-O blank material such as modulus of elasticity and Poisson's ratio are 70 MPa and 0.33, respectively. Flow behavior of the material obtained by bulge test experiments at elevated temperatures was taken from a previous study [16] as shown in Fig. 3. The blank was modelled by elastic visco-plastic constitutive model, whereas the punch, die and blank holder were assumed as rigid. Material model was used by entering the flow curves at different temperatures as tabulated.

In order to determine contact behavior between the blank and tools, "Forming One Way Surface to Surface" contact algorithm was used. The Coulomb friction model was determined with a friction coefficient of 0.05 for the interacting interfaces between the blank and heated tools (die and blank holder). A friction coefficient of 0.25 was determined for the interacting interfaces between the blank and punch. The coefficient of friction was selected lower at high-temperature testing/zone as the contact region of the blank between the die and blank holder was lubricated by copper paste except for the contact region with punch, yet no lubrication was performed at the blank–punch interface as the friction is useful at that region in terms of increased formability. So the friction between the blank and die/blank holder became less although they were at higher temperatures. The fluid pressure and blank holder force (loading profiles) according to position of the punch shown in Fig. 4 were used in the FE

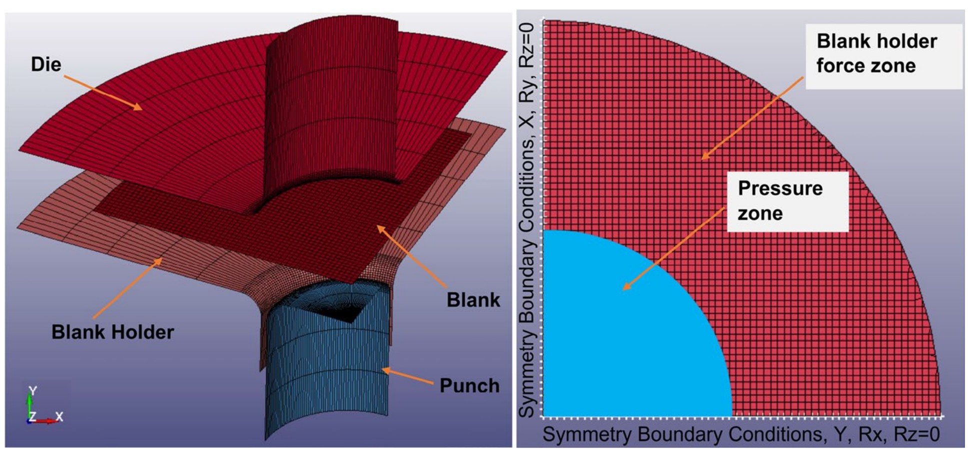

Fig. 2 **a** A quarter of 3D model of the process, **b** boundary conditions of the blank

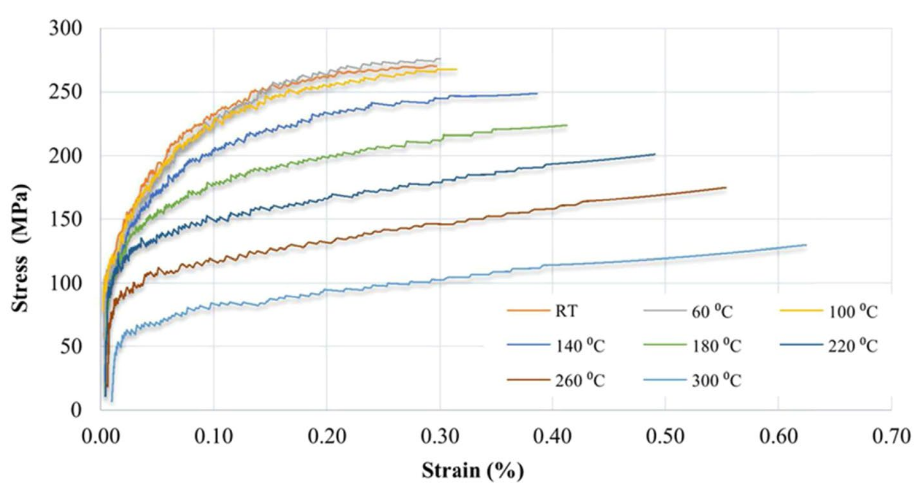

Fig. 3 Flow behavior of AA 5754 at elevated temperatures [16]

analysis of the WHDD process. Using optimized loading profiles was important for forming the blank successfully. Therefore, optimal loading profiles were determined by adaptive FEA coupled with fuzzy logic control algorithm (aFEA-FLCA). Implementing an aFEA-FLCA was explained in the study of Türköz et al. [17].

The thermal condition of the blank was affected by the thermal coefficients used in the FE model for contact surfaces of the blank and tools. These are heat transfer conductance (HTC), thermal conductivity of the fluid between the two sliding surfaces (CF) and critical gap distance GCRIT under which HTC is constant. The maximum gap above which no thermal contact is assumed is GMAX. These properties were applied as contact conditions. Moreover, thermal conductivity (TC) and heat capacity of the blank and tools (HC) were determined as thermal isotropic material properties of the blank and tools. Thermal coefficients are shown in Table 1.

The simulations were conducted for two temperature conditions of the tools. In the first condition, only one fixed temperature value was attained for each die, blank holder and punch. In the process, the die and blank holder were heated to the same temperature. So the temperature of these tools was taken as the same. While a temperature of 300 °C was assigned to the blank holder and die, the temperature of the punch was taken as 20 °C. At the beginning of the FE analysis, the temperature of the blank was also 20 °C in the WHDD process. By conducting coupled structural thermal analysis, heat transfer between the blank and tools was calculated, and the blank had a temperature gradient. While the center of the blank was cold, the flange region of the blank was heated up to the temperature of the blank holder and die. In the second condition, the die and blank holder were divided into four and the punch

Table 1 Thermal coefficients used in FE Simulations

HTC (W/m2.K)	CF (W/m.K)	HC (J/kg.K)	TC (W/m.K)
1400	10	Tools = 4200 Blank = 900	Tools = 50 Blank = 220

was divided into two regions and the temperature values, which are variable throughout the process, were assigned to each zone. The real temperature values throughout the process were measured with thermocouples, the locations of which are shown in Fig. 5. The K-type thermocouples made measurements from the channels shown in Fig. 6, with a depth of up to 2 mm from the die and blank holder surfaces where the blank is placed. Thermocouples channels had a diameter of 6.5 mm.

Temperature variability measurements were carried out at the target die and blank holder temperature of 300 °C and target punch temperature of 20 °C, with the blanks measuring 125 mm diameter as three repeats. The experiments were conducted at the test setup shown in Fig. 6. The tools were heated by an induction coil placed around the tools. More details about conducting the experiments and about the experimental setup were given in a previous study [17].

3 Results and discussion

In the three experiments conducted, the mean temperature values measured at each time were calculated as referenced in Table 2. In the analysis of the forming of the sheet with a diameter of 125 mm, the temperature change curves in Table 2 are assigned to the regions of

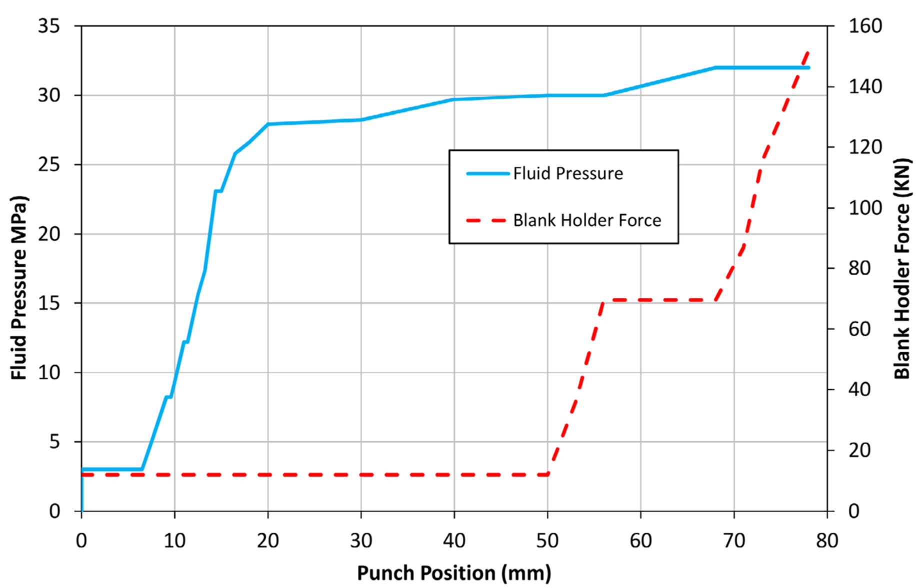

Fig. 4 Loading profiles used in WHDD process FEA [18]

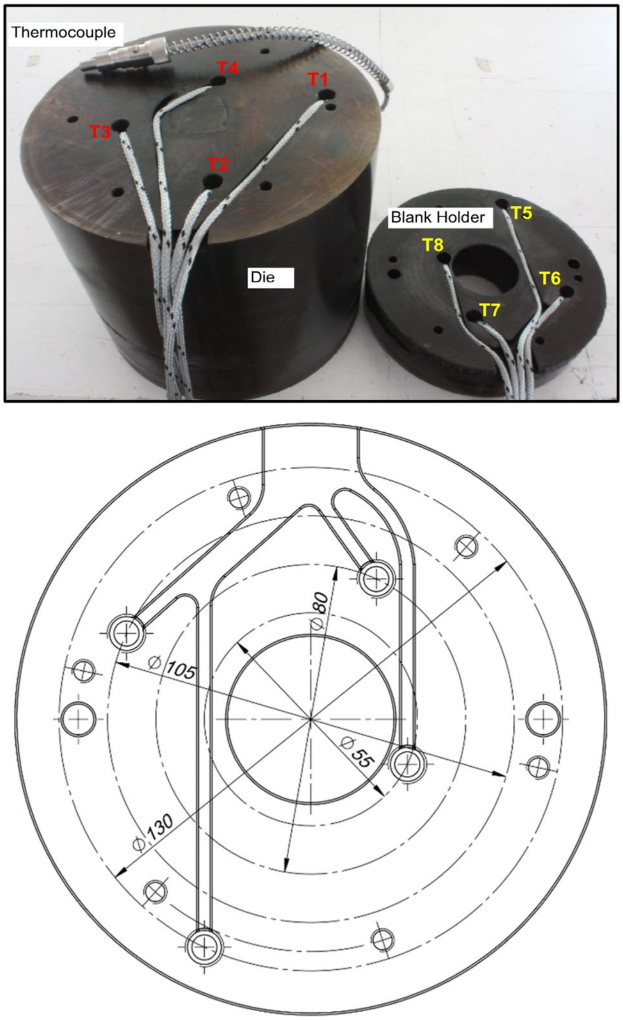

Fig. 5 Thermocouples and their locations used to measure the temperature distributions of the tools

the tools. Thus, the regional temperature changes of the tools during the process were modeled. As a result of this analysis, the value of the temperature change during the forming process of the tools was determined according to the analysis that the temperature was considered constant throughout the process. Thus, the effect of the temperature change of the tools on the WHDD process was also obtained. As seen in the table, the temperatures of the regions on the tools are very different, and they changed significantly during the process. When the tools were heated to the 300 °C target temperature, there was a temperature variance about 316–292 = 24 °C at the beginning of the process, and the difference increased to 60 °C at the end of the process. But as the blank slides to inside of the tools while it is being formed, measuring the temperature of the outer regions is not important. It is more practical to take reference of inner thermocouples T4 and T8. If the temperature change of these thermocouples is observed, the temperature has decreased to approximately 20 °C throughout the process. Temperature of the blank holder is less than the die because its mass is less than the die and the cooling effect originated from the cooled punch, which significantly decreased the inner regions of the tools. In addition, the temperatures of the outer regions increased due to the heating effect from the induction coil. Although the punch cooled by circulated water at 5 °C in the punch, as the punch under contact was under high pressure with the blank, its temperature increased up to 55 °C from 13 °C.

The results obtained in the case of the regional modeling of the change in the tool temperatures during the process are shown in Fig. 7. In the graph, the thickness distributions obtained at the temperature conditions of constant and variable throughout the process were compared with the thickness distributions of the cylindrical part manufactured in the experiments under the same conditions. The parts were measured in rolling and transverse to rolling direction. In the analysis, the thickening tendency of the part in the flange region was much higher than in the experiments. However, the thickness distributions obtained from the analysis were similar to the experimental results in other regions. In the experiments, the temperature difference between different regions of the tools was 24 °C at the beginning of formation and increased up to 60 °C at the end of formation. Again, the temperature of the punch increased to approximately 40 °C during the process. This temperature variability in the tools did not cause a significant difference in material behavior compared to the constant temperature condition. That is because the results of FE analysis performed under two different temperature conditions were very close to each other. Thus, the analysis of results, in which the tool temperatures were considered constant throughout the process with all regions, could make successful predictions with sufficient accuracy. Therefore, it was concluded that the modeling of the temperature change of the tools in the FE analyses of the WHDD process is not needed. Accepting that the temperatures of the tools are the same and do not change during the forming process is an acceptable approach.

4 Conclusion

The warm hydromechanical deep drawing (WHDD) method is a complex process because the success of the process depends on the geometric and material parameters, as well as on the optimum temperature distribution of the sheet, the optimum fluid pressure and the blank holder force profiles, which vary according to the punch position. Therefore, it is essential to investigate the most

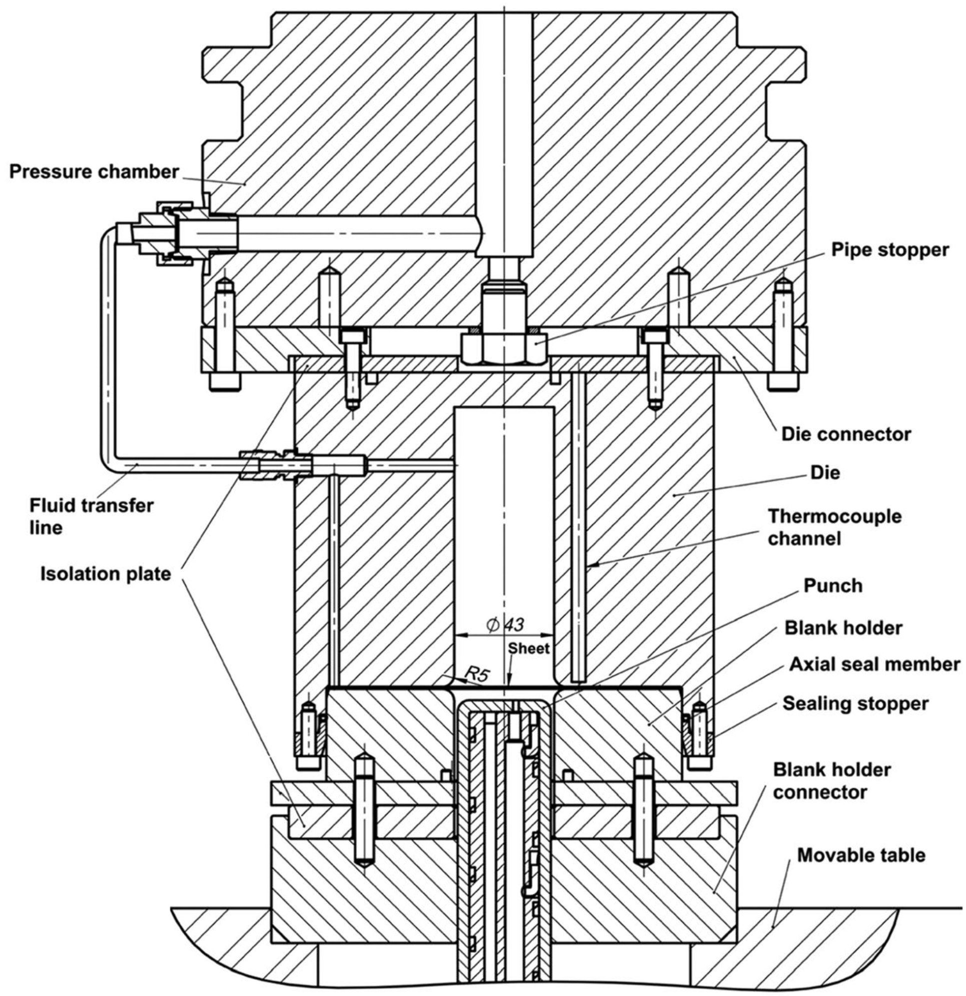

Fig. 6 WHDD experimental setup [17]

appropriate conditions with FE analysis before the process is implemented. The die and blank holder, which are heated to the warm forming temperatures, and the punch, which is cooled to the room temperature, cause a temperature gradient at the blank, and this causes a strong heat conduction between the tools and the sheet. So it is not possible that all regions of the tools have a constant temperature. In the FEA of the process, however, the temperature is set to be the same for all regions of the tools and it remains unchanged throughout the process. In this study, the difference between constant and variable assignment of temperature to each region of the tools during the WHDD process was investigated by modeling the temperature condition of the tools using real experimental temperature measurements. The thickness distributions of the parts obtained with constant and variable temperature conditions were compared, and no important difference between the two conditions was found. Therefore, it was concluded that there is no need to model the temperature change of the tools while forming in the FEA of the WHDD process. Accepting that temperatures of the tools are the same and do not change during the forming process is an acceptable approach.

Table 2 The measured temperature values of the die, blank holder and punch at the experiments conducted for 300 °C target temperature

	Die (T1–T4) and blank holder (T5–T8) temperatures								Punch temp	
Time (s)	T1	T2	T3	T4	T5	T6	T7	T8	Tip	Middle
Place of thermocouples	28	40	53	65	28	40	53	65	6	66
0	316	317	314	309	301	302	298	292	13	15
5	316	317	314	309	301	302	298	292	13	15
10	315	317	314	309	301	302	297	291	13	15
15	314	317	314	308	301	301	298	290	14	15
20	314	316	313	307	301	301	297	290	15	15
25	314	316	313	307	301	301	297	289	16	15
30	315	316	313	306	301	300	297	288	16	15
35	315	316	313	305	302	293	297	286	17	15
40	316	316	312	303	302	299	296	285	21	15
45	318	316	312	301	303	298	296	284	33	15
50	319	316	312	299	303	297	296	283	45	15
55	321	316	312	296	304	297	296	281	61	15
60	323	317	312	293	305	296	295	280	61	15
65	326	318	313	290	306	296	295	279	57	15
70	329	318	313	289	306	295	295	278	58	15
75	331	320	314	287	307	295	295	278	57	15
80	334	321	314	286	308	295	294	277	57	15
85	337	322	315	285	308	295	294	277	55	15

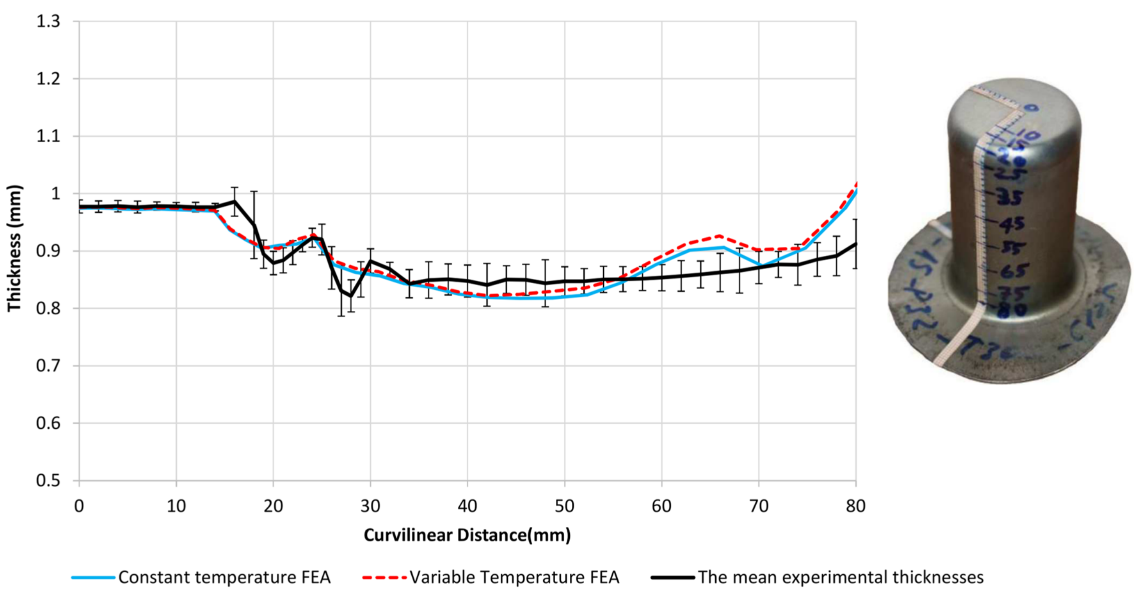

Fig. 7 Comparisons of the thickness distributions obtained from the four repeated experiments and FEA analyses

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Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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