An Enhanced Accuracy Method for Determining Forming Temperatures in Warm Deep Drawing Process

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Abstract

Temperature is the main effective physical variable in warm deep drawing (WDD) process due to characteristic role in activating the shear bands in material. This feature requires determination of temperatures in high accuracy for failure free deep drawn cups. Forming temperatures have been measured from blank holder, die and punch sets in the literature. However, differences in tool geometries and assembly of heating and cooling units were caused measurement of different temperature values in forming units. To address this issue, material based measurement method was developed. In this study, a developed method for measurement of forming temperatures in high accuracy from work piece material was discussed. At first, the preparation of index material and assembly of thermocouples from index material were described. Secondly, variation of temperatures in material based on blank holder, die and cooling temperatures was determined and discussed. Measurements were demonstrated that there were considerable differences between literature temperatures and work piece material temperatures determined according to tool set temperatures.

Key words: Forming temperatures, warm deep drawing, accurate temperatures

1. Introduction

Determination of process parameters (PP) has crucial importance in manufacturing. To achieve robust and reliable process, PPs and parameter ranges should be determined carefully. Otherwise, manufacturing failures such as tearing, wear, fracture, undesired output parameters etc. would be occurred and defective analyzes about PPs would be done.

The importance of determination of PPs have been realized in investigations of formability of light-weight engineering materials by WDD process in Karabuk University warm forming laboratory by authors of this paper. Deep drawing is a type of sheet metal forming process which converts two dimensional parts into three dimensional parts (Fig. 1). However, some type of light-weight engineering materials such as 5xxx, 6xxx and 7xxx series aluminum alloys and magnesium alloys are needed temperature effect for drawability due to poor formability properties (effect of alloying elements and atomic structures) at room temperature. Hence, deep drawing with thermal effects has been investigated since 1940's and this process has been called as WDD (Fig. 1). WDD process has two different applications, namely, isothermal and non-isothermal conditions. In isothermal conditions all tooling elements (blank holder, punch and die) are heated to the same temperatures. In non-isothermal conditions, not only heating but also cooling are applied by using cooling channels in punch and heating elements are used in blank

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holder – die set. Non-isothermal application is important for enhancing formability by the way of decreasing flow stress at flange region by temperature effect and keeping constant flow stress at the cup wall region by cooling effect.

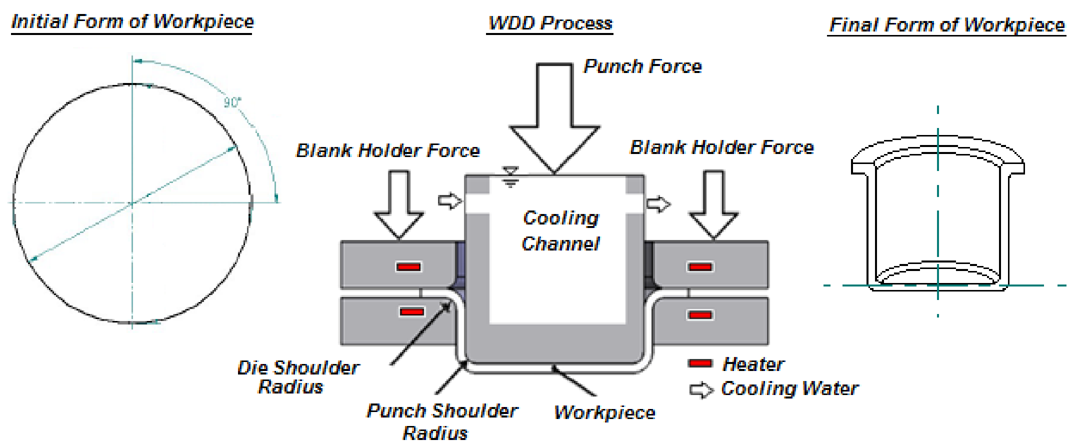

Figure 1. WDD process

Input parameters for WDD process can be classified as temperature, blank holder force, strain rate, lubrication conditions and tool dimensions. Between these parameters, temperature is the main effective PP by activating the additional slip lines in material and makes process realizable. Therefore, determination of forming temperatures becomes more important process stage. In literature, forming temperatures were determined according to tool temperatures (TT) and this temperatures were used in analyzes. However, tooling stage is non-standardization process and all of tooling stage is depend on tool designer. This situation causes assembly of heating-cooling elements and measurement of temperatures from different regions which have variability according to the tooling stage. Therefore, it is difficult to say that obtained temperatures from tools are forming temperatures. This claim can be verified by discussing literature temperatures. Obtained optimum temperatures and temperature ranges from real experiments for warm deep drawing of AA5754-O material according to the literature was presented in Fig. 2. Optimum formability temperature was found 267 °C by Koc et al. [1], 250 °C by Ozturk et al. [2], range of 23-150 °C by Smerd et al. [3], range of 100-175 °C by Bolt et al. [4] and range of 250-300 °C by Kaya et al. [5]. These different values can be explained by using of different tooling systems. In each study, heating and cooling systems and temperature measurement points have differences. Because of the fact that, determining measured TTs as a forming temperature causes incorrect analysis and inconsistency. To address this issue, work piece material based temperature measurement can be used under closed and heated tool conditions. Suggestive study for measurement of temperatures from material surface was studied by Kaya et al. [1]. In their study, special index material (4.5 mm thickness) was developed to determine the required dwell time and to understand the effect of interface pressure on temperature increase. However, thickness differences between work piece material which has 1.3 mm thickness and index material results in decreasing of measurement sensitivity. On the other hand, index material approach can be applied for determining surface temperatures.

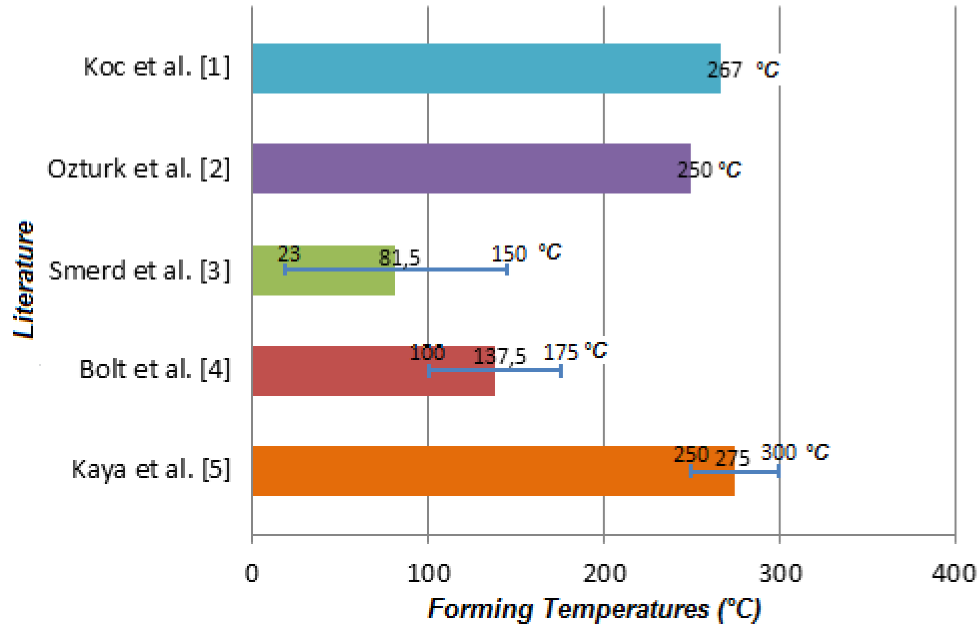

Figure 2. Forming temperature ranges according to the literature

In this study, index material approach was investigated for determining forming temperatures accurately from material surface to solve aforementioned problems. In first stage of the study, preparation of index material for determining forming temperatures and assembly of thermocouples was described. As the next step, forming temperatures were measured form material surface by using TTs as a reference temperature. Due to non-isothermal conditions, material temperatures were described by curves which can be interpreted as originality. Additionally, temperature change of cooling water was measured and cooling water behavior under heating tools was described.

2. Development of material based temperature measurement system

In scope of the WDD investigations, 2 mm thickness of AA5754-O aluminum alloy was used as a work piece and index material. The diameter of the work piece and index material is 150 mm. L type thermocouples were used for measurement of TTs. Thermocouples were located inside the tooling elements and location length is 15 mm below and above from the work piece material surface (Fig. 3).

2.1. Development of index material

For determining forming temperatures from material 4 different measurement points were used. Distance of measurement points from outer diameter to inner diameter is 2 mm, 25 mm, 50 mm and 75 mm, respectively. Point of 75 mm distance from outer diameter coincides with the center of the index material. For assembly of thermocouples, milling process vertical to the thickness direction at 1 mm depth and different distances towards the center of the material surface was performed. As the machined view of the index material with distances was presented in Fig. 4. Channels are machined for making guiding to thermocouples

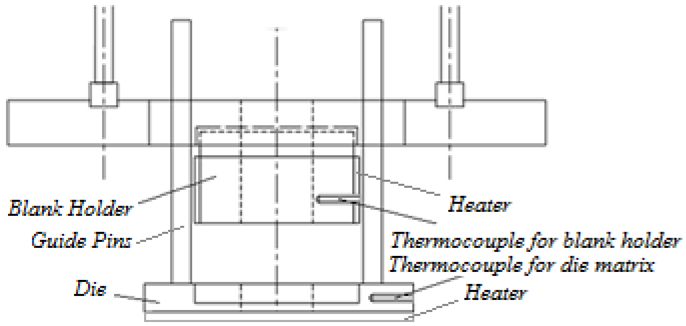

Figure 3. Schematic diagram for thermocouples location

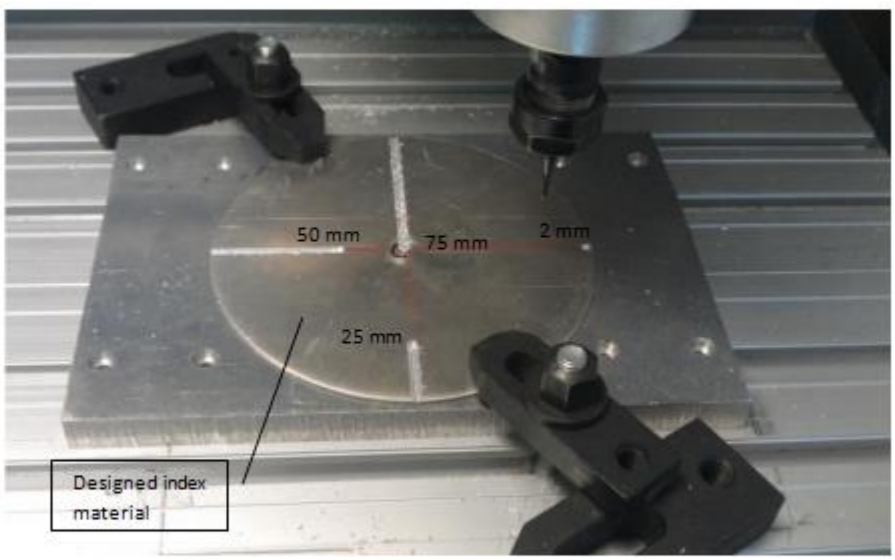

Figure 4. Milling process of index material

2.2. Assembly of thermocouples

For determining forming temperatures from index material, have a 1 mm thickness and 100 mm length of mineral insulated thermocouples were used with 8 channel data logger. K type thermocouples were attached to the index material at contact position of the end of the related channel by using aluminum foil adhesive. Aluminum foil adhesive has 0.1 mm thickness and this value is on a negligible level for effecting heat transfer between tool and material surfaces. On the other hand, lubricator was applied to the material surface to ensure experimental conditions entirely. Teflon based lubricant was used in experiments. Photograph of measurement conditions was presented in Fig. 5.

Figure 5. Photograph of temperature measurement system

3. Results

Sequence of experimental methodology for determining forming temperatures was described in Fig. 5. Before measurement of forming temperatures, cooling water behavior is needed to be defined. In non-isothermal warm deep drawing process, enhancing formability was fulfilled by using punch cooling systems. Enhancing formability of cooling process was analyzed in literature but not enough study was performed about cooling water temperature (CWT) behavior under heated tool conditions [6]. However, CWT is one of the system parameter and its behavior should be described for analyzes. In this study, CWT behavior was investigated according to TTs and obtained values were used as a system parameter in defining forming temperatures from index material. In Fig. 6, output temperature of cooling water from the 16 liter cooling tank was presented. For mathematical modeling of CWT behavior, quadratic model was applied due to the characteristic of temperature curve. The polynomial regression model is presented in Eq. (1). According to the coefficient of determination values (R^2 and Adj. R^2), mathematical models are sufficient to describe behavior of CWT.

$$CWT = (0.000619 * TT^2) - (0.1160 * TT) + 25.91 \quad \text{Eq. (1)}$$

$R^2 = 96.8\%$ Adj. $R^2 = 96.1\%$

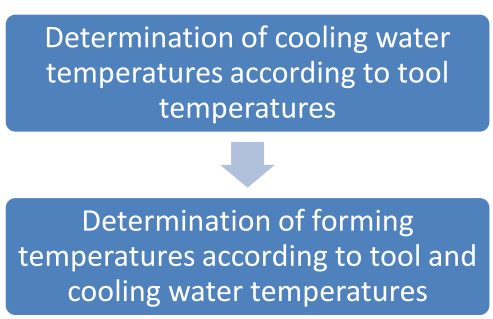

Figure 5. Sequence of experimental methodology

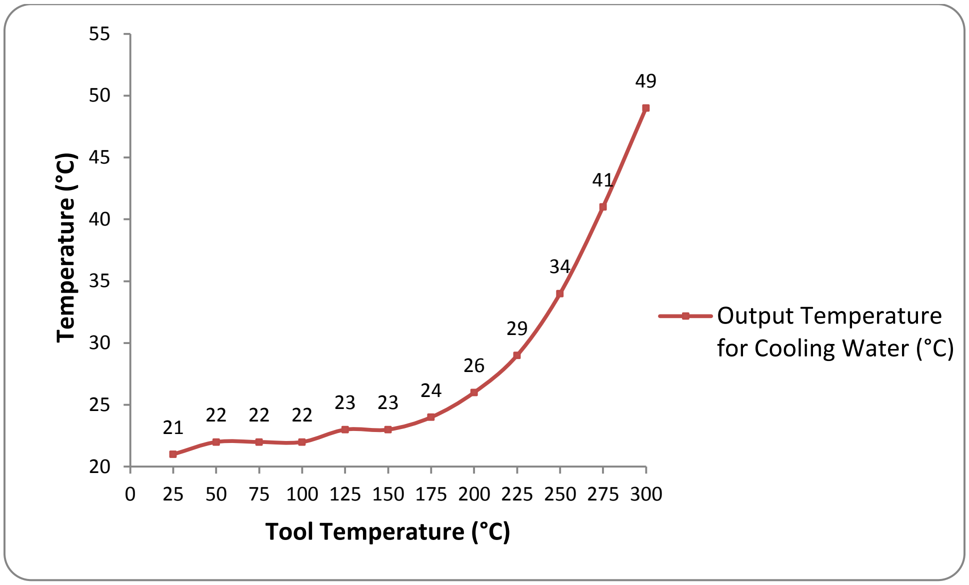

Figure 6. Warming behaviour of CWT

Forming temperatures were determined according to TT range of 25 to 300 °C and CWTs. Behaviour of forming temperatures obtained from work-piece was presented in Fig. 7. Due to the non-isothermal conditions, forming temperatures was measured from 4 different points and characterized by forming temperature curves (FTC). For mathematical modelling of FTCs, quadratic models were chosen due to the inadequacy of the linear model. Polynomial mathematical models were presented in Table 1 with R^2 and Adj. R^2 values.

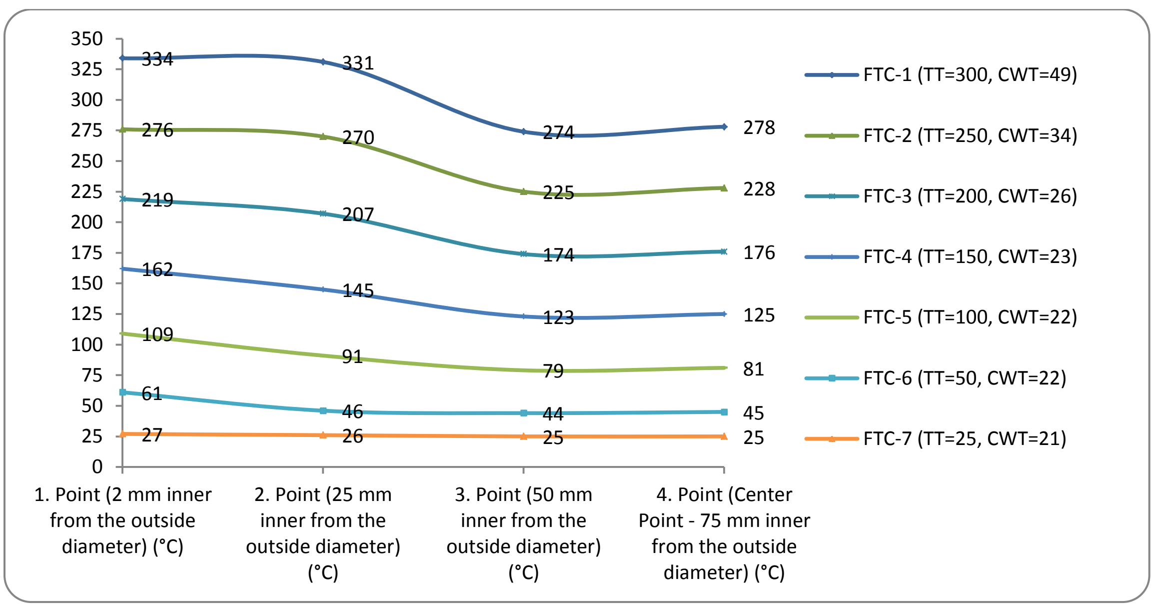

Figure 7. Characteristic behaviour of FTCs

Table 1. Mathematical models of FTCs

Curve	Polynomial Mathematical Models	R-Sq. (%)	Adj. R-Sq. (%)
FTC-1	$0.00438*x^2 - 1.262*x + 342.6$	80.2	40.7
FTC-2	$0.00495*x^2 - 1.158*x + 282.9$	83.6	50.7
FTC-3	$0.00681*x^2 - 1.189*x + 224.3$	90.5	71.5
FTC-4	$0.00870*x^2 - 1.214*x + 165.8$	96.5	89.5
FTC-5	$0.00888*x^2 - 1.075*x + 111.4$	99.7	99.1
FTC-6	$0.00692*x^2 - 0.7359*x + 61.82$	96.6	89.9
FTC-7	$0.00046*x^2 - 0.0637*x + 27.17$	98.6	95.8

Polynomial models of FTCs presented a good fit with the curves due to 80% above R-Sq. values. The lower values of Adj. R-Sq. for FTC 1, 2 and 3 can be explained by higher differences between flange region temperatures and blank centre temperatures.

4. Discussion

In first step of the study, CWT behaviour was described graphically and fitted by quadratic polynomial function. According to results, there is not significant change on CWT till 200 °C of TT; however, significant increase of CWT was measured above 200 °C of TT. Approximately 50 °C of CWT can be considered as a proses parameter and steady state condition of CWT. Palumbo and Tricarico investigated three different water flow rate values (7, 14, 21 ml/s) in order to evaluate the punch cooling efficiency [7]. They found that temperature on blank centre was not affected by the cooling water flow rate. Additionally, the temperature of 110 °C was measured in the central region of the blank when the blank holder temperature reaches at 250 °C. In this study, 110 °C in blank centre was obtained when the flange region temperature reaches approximately at 150 °C. The differences can be explained by using different points for temperature measurement. Palumbo and Tricarico determined flange temperature by considering blank holder temperature as a flange temperature; however, in concept of this study, temperatures were determined from directly related regions. This situation proves that there are significant differences between TTs and work-piece material temperatures and determining forming temperatures should be carried out from work-piece material temperatures. Otherwise, inconsistent analyses were applied due to incorrect designated PPs. Obtained results from FTCs exhibited that there is crucial differences between TTs and work-piece material temperatures. For instance, at 300 °C of TT and 49 °C of CWT conditions, flange region temperature reaches 334 °C and blank centre temperature reaches 278 °C. This result indicates that enhancing accuracy of forming temperatures can be succeeded by using index material approach.

Conclusions

In this paper, an enhanced accuracy method was described for determining forming temperatures in WDD process. The following results were obtained:

- Index material was developed for determining forming temperatures form work-piece material surface under closed and heated tool conditions. Preparation of index material and assembly of thermocouples were described.

- CWTs were measured according to the TTs for using CWT as a process parameter in WDD process. CWT showed quadratic behaviour mathematically.
- Temperatures obtained from index material were characterized by FTCs due to the non-isothermal conditions. These curves exhibited that there is serious differences between TTs and work-piece material temperatures.
- Forming temperatures accuracy was enhanced by using index material approach.

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