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# Simultaneous effects of temperature, holding time and thickness on bending springback of DP1000 steel: experiments and statistical analysis

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**The world is facing a critical global warming problem that requires a severe reduction in carbon emissions. Hence, reducing vehicle weight is crucial to lowering fuel use. Consequently, high-strength dual-phase steels, which produce lighter parts, are increasingly utilized in various industries. However, higher strength causes higher v-bending springback, which increases material waste. Therefore, various studies have been executed recently to minimize this complication. In these studies, the factors affecting springback were examined individually, which cannot reveal precise results because each factor affects another. This research aims to reveal a more realistic springback analysis by simultaneously examining the factors. In Design Expert, temperature, holding time and thickness factors were analyzed. ANOVA and Regression Analyses were executed. Each factor's influence was statistically compared for the first time. Based on experimental studies, an empirical formula was derived in which factors can vary simultaneously. The model's correlation coefficient was 0.99999, which indicated a perfect correlation between factors and springback. The temperature has the most significant influence, with the highest F-value, followed by holding time and thickness. For the first time, the interaction effects of the factors are statistically proven. Springback decreased by 94.75% compared to its initial value, which is remarkably promising.**

**Keywords** Springback, Dual-phase steel, Bending, Temperature, Holding time, Thickness

In the automobile industry, high-strength steels are extensively used to obtain lightweight components[1]. Lightweight components mean lighter vehicles[2]which leads to less fuel consumption and, therefore, fewer emissions[3]. Additionally, lighter vehicles have better acceleration rates[4] and safety performance[5]. On average, 560 kg of advanced high-strength steel was used in each of the approximately 92 million cars produced in 2019[6], and the global high-strength steel market is expected to reach $54.07 billion in 2027[7]. DP advanced high strength steels (AHSSs) play a crucial role in the automotive industry for the production of components such as door rings, B-pillars, and more[8]. Sheet metal forming, especially V-bending, plays an important role in numerous sectors; yet, issues like springback can impact both the quality and precision of the finished product[9]. Although the aforementioned information demonstrate the importance of high-strength steels, it should be noted that it is more challenging to form them because of higher springback[10]. Dual-phase steels are widely preferred[11] to procure the best of both worlds, as they are extremely strong and ductile simultaneously owing to their unique properties[12]. Despite all these unique properties, studies on springback in dual-phase materials are scarce. Springback represents a critical challenge in every sheet metal-forming process. This phenomenon is influenced by a variety of process variables[13]. This lack of literature has motivated the use DP1000 steel in this study, this is one of the details that distinguishes this study from other studies. This will be discussed in detail during the literature review.

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## Bending and springback

The bending operation is commonly used to mass-produce the desired shapes, especially in the automotive industry[14]. Although it is very prominent in producing goods used in everyday life, there might be significant caveats in the bending process. One of the most basic ones is the springback[15]which can be defined as an amount of returning to its initial shape after a bending operation because of elastic recovery[16]. As it may alter the final dimension of the part, it poses a significant defect risk for the final assembled product. The springback amount must be predictable to compensate for this drawback and get the correct dimensions within tolerances. If there is an incorrect dimension because of springback, improper assembly[17,18] and low quality[18] may be obtained, which lie behind a big waste of material. Thus, springback has indirect economic effects[19]. Several works were conducted to investigate eliminating or decreasing the springback in sheet metal bending, as reviewed in the previous studies section. However, there are still significant gaps in the literature upon closer investigation. For example, there is no helpful springback prediction formula available to support the industry, studies with the DP1000 material are almost nonexistent, and most importantly, the interaction effects are neglected in all studies. This issue of interaction effects will be discussed in more detail later.

*Temperature concerns*

The bending process can be categorized into three types, depending on the operating temperature: cold, warm, and hot. Warm bending, operated between room temperature and recrystallisation temperature[20]can be considered an intermediate process between cold and hot bending. It attempts to combine the advantages of both[21]. Warm bending has significant advantages over cold bending, such as lower springback and residual stresses; also, more complex shapes can be achieved[22]. Furthermore, the oxidation, energy cost, and process time are less when compared to hot bending. In addition, high-strength steels are more challenging to bend, especially at higher thickness and smaller bending angles; nevertheless, warm bending helps form that kind of product without cracking. Because the higher temperature provides better ductility and lower brittleness. Thus, crack-free bending surfaces can be achieved.

## Previous studies

Various researchers have studied factors affecting springback, such as material type, bending angle, thickness, punch radius, rolling direction, holding time, and so on. After a comprehensive literature survey, all these studies are summarized in Table 1. This table includes v-bending and other studies examining the effect of different processes on springback. The reason for this is to provide readers with a broader understanding of the literature and to present the overall context of springback better. Studies conducted in recent years have also shown that temperature may significantly affect springback. Since the temperature factor has not been investigated in DP1000 steel before, this research aims to be the first one. Previous studies on temperature are reviewed in a separate section below Table 1, as it is a significant factor both for the literature and this study. Studies are written in alphabetical order, not in reference order.

In the literature review, it was observed that the investigation of DP materials is rare. Thus, extra effort has been made to construct a general framework by considering the studies with other materials. In addition, not only bending but also other forming processes were examined in order to expand the number of studies. Mori et al.[27]Yanagimoto et al.[52] and Yanagimoto and Oyamada[42,53] investigated the springback behavior of different materials in various temperature ranges. In the warm temperature range, Ozturk et al.[32] studied different rolling

| Factors | Author & Year |
|---|---|
| Material Type | Béres et al., 2020; Garcia-Romeu et al., 2007; Hetz et al., 2020; Mori et al., 2007, 2005; Tekiner, 2004 [10,23-27] |
| Bending Angle | Garcia-Romeu et al., 2007; Şen and Taşdemir, 2021; Stachowicz et al., 2010; Tekaslan et al., 2008; Tekiner, 2004; Thipprakmas and Phanitwong, 2011 [21,23,24,28-30] |
| Thickness (t) | Béres et al., 2020; Garcia-Romeu et al., 2007; Kazan et al., 2009; Kılıç, 2009; Nakagawa et al., 2018b; Ozturk et al., 2009; Stachowicz et al., 2010; Tekaslan et al., 2008; Tekiner, 2004; Thipprakmas and Phanitwong, 2011; Xu et al., 2018[21,23,24,26,28,29,31-35] |
| Punch Radius | Fei and Hodgson, 2006; Gautam et al., 2012; Hetz et al., 2020; Kazan et al., 2009; Şen and Taşdemir, 2021; Thipprakmas and Phanitwong, 2011; Zong et al., 2015 [25,29,30,35-38] |
| Rolling Direction | Gautam et al., 2012; Hetz et al., 2020; Ozturk et al., 2009; Soualem and Hakimi, 2018 [25,32,37,39] |
| Holding Time | Hama et al., 2017; Mori et al., 2007; Nakagawa et al., 2018b; Saito et al., 2018, 2017; Şen and Taşdemir, 2021; Tekaslan et al., 2008; Tekiner, 2004; Zong et al., 2015 [10,22,23,28,30,31,38,40,41] |
| Die Width | Fei and Hodgson, 2006; Garcia-Romeu et al., 2007; Yanagimoto and Oyamada, 2007[24,36,42] |
| Specimen Width | Kılıç, 2009; Saito et al., 2017 [34,40] |
| Punch Velocity | Fei and Hodgson, 2006; Kılıç, 2009; Mori et al., 2007; Simões et al., 2019 [10,34,36,43] |
| Drawing Depth | Soualem and Hakimi, 2018 [39] |
| Localised Compression | Gautam et al., 2012; Mori et al., 2007 [10,37] |
| Grain Size | Ma et al., 2015; Xu et al., 2018 [33,44] |
| Counter Punch | Komgrit et al., 2016 [45] |
| Springback Prediction | Béres et al., 2020; Y. Li et al., 2019; Sumikawa et al., 2017; Yang et al., 2016 [26,46–48] |
| Electric Pulses | Orallo et al., 2020; Zhao et al., 2018 [49,50] |
| Discharge Parameters | Xiao et al., 2019 [51] |

**Table 1**. Studies about springback excluding temperature effect.

directions of DP600, and Stachowicz[21] added numerical studies to the experimental work of stainless steel. Takata[54] continued by investigating the forming speed of aluminum alloy's deep drawing. There were other studies where the springback effect was studied in the hot temperature range. Lee et al.[55] studied numerically to clarify the punch corner radius effect, while Saito et al.[40] investigated the forming speed and stress relaxation through experiments. Nakagawa et al.[56] worked initially on thermal, mechanical, and transformation perspectives and then examined thick sheets' quench ability and deformation[31]. Saito et al.[22] claimed that lowering the flow stress through elevated temperature is the main reason for the springback reduction. Soualem and Hakimi[39] investigated isotropy and drawing depth through experiments. Löbbe and Tekkaya[57] worked on heat-assisted sheet forming. Q. Li et al.[58] and Choi et al.[59] investigated some heat treatment effects on the springback of different materials. Sajan et al.[60] claimed that the cooling rate has an important effect on springback in the hot stamping process and that springback can be decreased by controlling it. During the literature review, it was observed that the studies on warm bending intensified again after a break. Simões et al.[43] conducted cylindrical cup forming between 22 °C and 200 °C. Park et al.[61] investigated the springback of Mn steel depending on bending temperature, time, Mn content, and austenitizing temperature in stamping. Mauduit and Maillard[62] stated that heating both the die and the material can be more helpful in reducing springback. They also added that warm bending reduces the risk of cracking. YU and Lee[63] investigated the holding time and temperature effect on springback separately in the warm V-bending process. Sun et al.[64] investigated the high amplitude current and single-pulse effect on the springback of aluminum alloy sheets, and also analyzed the mechanical properties and microstructure after this phenomenon. Atxaga et al.[65] studied the hot forming of AA2198 aluminum-lithium alloy on complex shapes. Sharma et al.[66] investigated the bending radius effect on the springback of the SS304/Al1050/SS304 clad sheet. Sharma et al. (2023)[67] reported that sheet setting and punch radius parameters have a great impact on springback, and observed a noticeable agreement between the experimental results and the simulations. Mulidran et al.[68] studied the friction and blank holder force effect on the springback of dual-phase steel. Xu et al.[69] obtained a new springback model that is more accurate than the conventional one. Huang et al.[70] established an analytical springback model and investigated the stamping speed and blank holder force effects on springback. Sharma et al. (2025)[71] used experimental and numerical methods to determine the springback of an AA1050-Fly ash green composite during V-bending and to analyze the residual stresses.

The aforementioned studies are consistent in their findings regarding the significant effects of temperature on springback. Therefore, the temperature was chosen as the primary variable in this study as well. However, all of these studies investigated the factors individiually. In contrast, this study investigates the temperature effect in conjunction with material thickness and holding time effects. Investigating the effects separately only gives an idea about each factor itself. However, it does not tell anything about the combined effects among them. The reason for this will be explained deeply in Sect. "Evaluation of previous studies". As indicated in Table 1, the most studied factors in the literature are thickness and holding time. Since it was seen in previous studies that these factors reduce springback, it was thought that combining the effects of them with temperature would reveal significant results and developments. In addition, it became possible to statistically compare which of these most studied factors has the most significant effect. Moreover, this approach enabled a statistical comparison of which of these major parameters exerts the strongest influence.

*Evaluation of previous studies*

The research carried out to date paints a consistent overall picture of the direction in which each factor impacts springback. For instance, many studies have confirmed that springback decreases with higher thickness or temperature. This kind of information exists for most of the factors. Therefore, instead of saying which factor reduces or increases springback, it is necessary to go further. It should be investigated how strongly a factor can affect springback. Thus, the following question can be asked: both thickness and temperature can reduce springback, but which one does it more? Which factor matters more? However, it is impossible to answer this question by examining the factors individually, because to comment on the power of a factor, it is necessary to compare it with the power of another one. In other words, in order to measure the power of the temperature effect, it is necessary to compare it with other factors' effects, such as thickness and bending angle. Therefore, the factors should be examined together, not separately. As the antithesis to this, one might say: 'One study examined thickness alone and found that it reduced springback by 40%, while another study found that temperature reduced it by 30%. In this case, it can be said that the effect of thickness is greater without the need for a common examination.' This study categorically rejects this claim. This is where the most important claim of this study comes into play: one factor modifies the effects of another factor. Therefore, examining a factor alone cannot give a precise result, and the outcomes obtained in this way cannot be used in factor comparison. This claim is important because this issue has not been mentioned in the literature before. Here is an example to better explain what is meant.

Let us say that a 1 mm thick specimen is bent to 90° at room temperature, with 10° of springback. When the sample changes to 2 mm, assume the springback is approximately 6°. In this case, it can be said that the thickness factor has an effect of 40% or 4°. Nevertheless, in the first case, if the thickness was kept as 1 mm and the temperature was increased to 400 °C, the springback would be about 2°. Now, let the thickness factor be tested again under these last conditions. When the thickness is increased from 1 mm to 2 mm at 400 °C, the springback will decrease from approximately 2° to 1.6°. In this case, the thickness has an effect of 0.4° and 20%. So which one is correct? Neither of them is wrong according to their own measurement conditions. However, one researcher working in the first conditions may say that the thickness has a 40% reduction effect on the springback, while another researcher working in the second conditions may claim that it has a 20% reduction effect. However, mathematics is not relative. Moreover, the fact that one factor has changed altered the effect of another factor. Thickness has a relatively high effect at room temperature but less at 400 °C. Judging by the example given, increasing the thickness decreased the springback in both conditions. So it can be said that the

direction of influence of a factor is independent of other factors. However, when examining how strongly a factor affects springback, changes in other factors should also be considered.

In other words, if factors are to be compared or the magnitude of their effects is to be measured, those factors should be analyzed within the same pool. Only in this way is it possible to make a statistical comparison. This approach, which was determined in this study and tried to be proved statistically by conducting experiments and analyses, is called the Combined Effect Approach in Springback (CEFAS). This is the most fundamental detail that distinguishes this study from other studies. This effect is also discussed in the later parts of the study, based on experimental results and statistics.

In addition, when previous studies are examined, there is no mathematical equation that consists of various factors explaining springback as a guide for the bending operators and die producers. There are just a few springback formulas obtained from the resultant graphs without any regression analysis. Besides, these formulas contain only one variable factor at a time. For instance, if the variable is holding time, it will be a different springback vs. holding time formula just for a thickness of 1 mm, and another formula for a thickness of 2 mm. For any other thickness, there is no formula for it. To our knowledge, an empirical three-variable formula for the simultaneous effects of temperature, thickness and holding time (or any other variable) is not yet available in the literature.

The ANOVA analysis conducted in this study confirmed the interaction effects and showed the shortcomings in the literature. Applying a single factor curve-fitted formula to industrial products is far away from catching desired tolerances for the industrial products. However, sensitivity can be increased if several essential factors and interactions are examined together. This higher sensitivity leads to better dimensions and tolerances, hence better productivity.

### Objective of the study

In order to increase the contribution of these scientific studies to the industry, the data should be processed in an industry-appropriate manner. The main objective of this study is to examine the basic effects on the springback of DP steels in a combined form and to formulate these results empirically by making detailed statistical analyses after precise laboratory work. Thus, for those who want to use it in industry, a novel springback formula that simultaneously incorporates multiple factors and their interactions can be offered.

## Experimental work

### Material

The springback behavior of high-strength-dual-phase Docol 1000DP steel that contains ferrite and martensite[72] was examined in this study. This material, one of the six categories of the high-strength steel group[73]was developed mainly for car safety applications, focusing on high strength and formability characteristics. The complex parts of vehicles, like seat constructions, door, sill, and bumper reinforcements[74] are manufactured from DP steels using sheet metal forming processes. The specific mechanical properties of the material ( Docol CR700Y 1000T-DP) used in the experimental work are given in Table 2[75].

Specimens with dimensions of 25 mm × 50 mm were selected in the experiments as the width and length with 1 mm and 2 mm thicknesses. Thicknesses less than 1 mm are not preferred in part production because they are very thin and weak. Also, DP1000 steel sheets thicker than 2.1 mm are not yet available in the market[75].

Although both sheets are made from the same material grade, the 1 mm and 2 mm sheets were produced in different batches, and the manufacturer's certificates indicate a strength difference of approximately 2% between them. There are studies in the literature on the relationship between strength differences and their effect on springback. For example, in the study by Béres et al. (2020)[26]between DP600 and DP800, strength increased by 28.3%, while springback increased by 21.4%; between DP800 and DP1000, strength increased by 33.2%, while springback increased by 35.3%. Similarly, in the study by Leu and Zhuang (2016)[76]a 34% increase in strength was observed in SPFC 440 and SPFC 590 steels, which have yield strengths of 265 MPa and 355 MPa, respectively, according to the JIS G3135 standard, while a 23% increase in springback was observed. Therefore, since it was evaluated that a difference in strength of around 2% would cause a change of around 1% on springback and that this would be negligible in the face of the 65% springback differences caused by the thickness change, no additional tensile test was performed before the experiment. The experimental results, which revealed approximately 65% difference in springback between the two thicknesses, further confirmed this assessment.

### Experimental setup

Special dies were designed for experimental requirements. Hot work tool material DIN 1.2367 was selected because of its high-temperature levels. In previous studies, most experiments were conducted with a die angle of 90°. Thus, a 90° die angle was chosen to make a point-by-point comparison with the literature. The punch radius (R) and die width (W) were defined by the technical data sheet of SSAB, which is a producer of DP steel[77]. It is suggested in the datasheet, R/t should be a minimum of 2, and W/t should be a minimum of 10 to prevent bending cracks. That indicates R should be a minimum of 4 and W should be a minimum of 20 since the largest

| Yield Strength $R_{p,02}\ N/mm^2$ | | Tensile Strength $R_m\ N/mm^2$ | | Elongation | Min bending radius for 90° |
|---|---|---|---|---|---|
| Min | Max | Min | Max | Min | |
| 700 | 950 | 1000 | 1200 | 7 | 2 x t |

**Table 2**. Mechanical properties of DP1000[75].

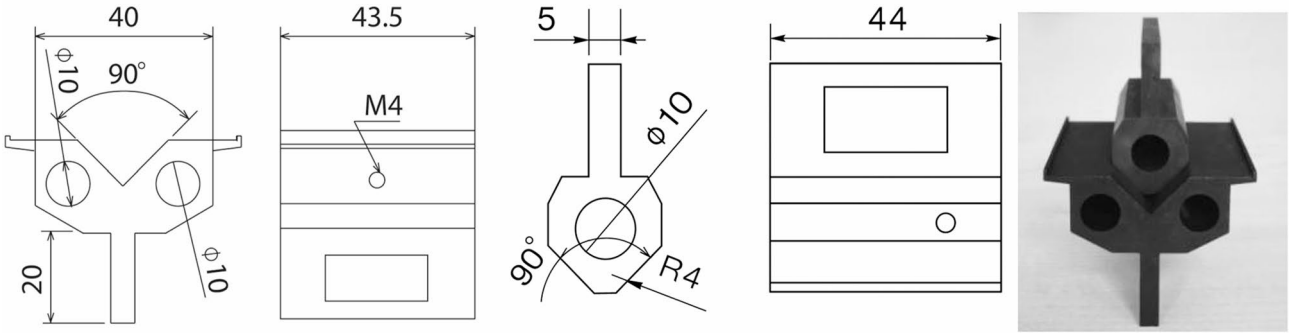



**Fig. 1**. Upper and lower dies (90°).

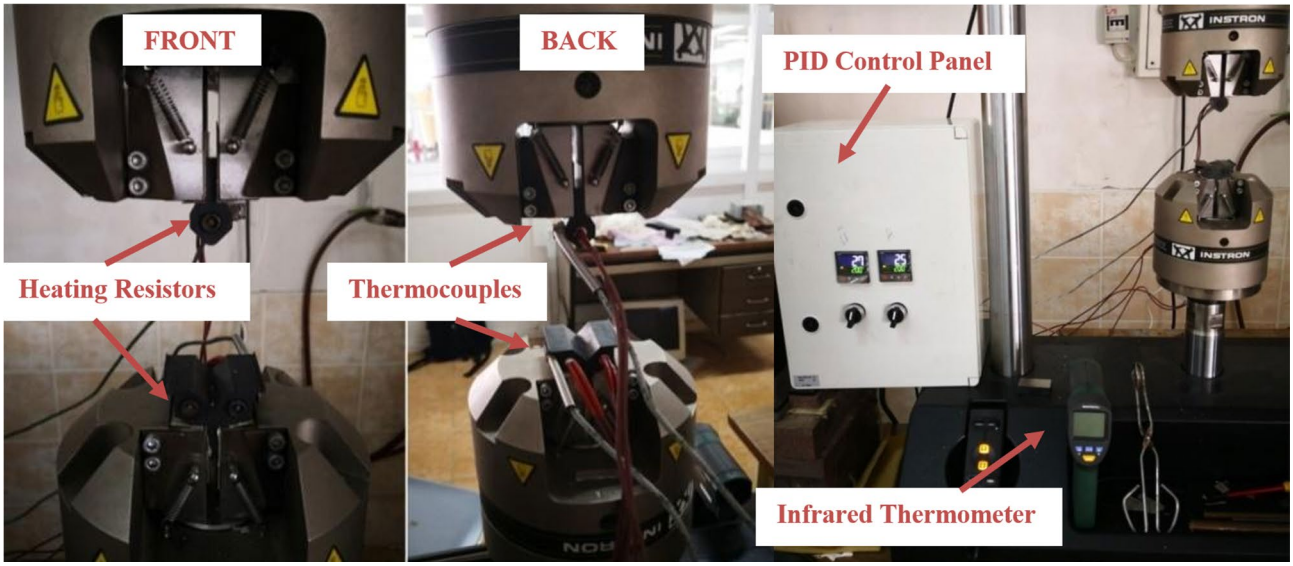



**Fig. 2**. Experimental setup.

specimen thickness is 2 mm. Upper-lower dies are given in Fig. 1, including their technical drawings. After the dies were delivered, the quality controls were carried out through the Coordinate Measuring Machine (CMM).

The specimens were cut by a laser cutting machine. Cartridge Heating Resistors with 200-Watt power, 10 mm diameter, and 45 mm length were utilized to heat the dies and the specimens. Two resistors were used for the lower die, whereas a single one was utilized for the upper die. The PID control system was specially designed to control the temperature accurately. Heating resistors and thermocouples were connected between the dies and the control panel. The temperature level was configured on LED screens placed on the control panel's front cover. An infrared thermometer was used to ensure the temperature of the specimens. After all the preliminary work, the PID control panel was placed near the testing machine. The experimental setup is given in Fig. 2.

## Confirming temperature and other factors' levels during bending

This study examines the effect of temperature, holding time and thickness on springback. Unlike other studies, it has examined the combined effects of each factor and aims to prove that they interact with each other. The measurements had to be extremely sensitive to get the most accurate results. Incorrect measurement of any factor level could affect the result of the entire study. Therefore, double checks were made on all factor levels to prevent this phenomenon. The thickness measurement was the easiest, which can be determined clearly through a caliper and did not change over time. The holding time was also easily measured with a stopwatch. The counting started with the bending process and ended with punch release.

Nevertheless, to be sure of the temperature, a system was needed. Here, a two-stage mechanism was established to control it. The first one includes already setting the temperature to the correct temperature level. As mentioned before, cartridge resistors and thermocouples were placed in both upper and lower dies and connected to the PID control system. The PID control system was able to adjust the temperature of the dies to precisely the right degree of Celsius utilizing these two instruments. However, the temperature of the sample was crucial for experimental results. The samples were placed on the lower die before bending it. With a basic knowledge of thermodynamics, it was known that the die, with a much greater mass than the sample, would

bring the sample to the same temperature as itself in a short time. All that was needed was to wait some time and regularly check the temperature.

It should be noted that the waiting time mentioned here has nothing to do with the holding time, which is one of the factors affecting springback. This can be confused from time to time by some readers. Holding time is when the upper die continues to apply force to the sample after the bending process occurs. This period ends when the upper die goes up, and the load is discharged. It is irrelevant to how long it takes to reach the required temperature. Holding time is the time during the bending operation, and waiting time, which is necessary to heat the specimen up to the same temperature as the die, occurs before the bending operation.

After a particular time, the temperature remains constant and does not change in the method used in this study. In many other studies, only the sample was heated and bent between cold dies. However, that method has two significant disadvantages. One of them is that the dies are cold, which will change the temperature of the specimen during bending. The second one is that if only the sample is heated, there would be heat loss during the transport of the sample, making it impossible to adjust the specimen's temperature precisely. Therefore, both the die and the sample were heated in this study. As a result, the temperature was assured, but the experiments took relatively longer because heating the sample without heating the dies was a much quicker and simpler solution.

Since the temperature effect was also examined in the experiments, thermal stresses should also be discussed. Thermal stresses generally occur when a material's tendency to expand or contract is mechanically restricted. In other words, if the entire material is heated but cannot expand freely because it is physically fixed, or if only one region of the material is heated while the other regions remain cooler, the hotter region will want to expand while the cooler regions resist this expansion, resulting in thermal stresses.

However, the conditions described above were not present in this study because the heating and cooling processes were applied while the sample was free, allowing for free expansion and contraction without physical impediments. Additionally, the die and sample were brought to the same temperature, and the bending process was conducted under uniform temperature conditions. Consequently, the formation of thermal gradients and stresses resulting from temperature differences is assumed to be negligible under these conditions.

Although it is known that the sample will have the same temperature as the die when enough time has passed, extra temperature control has been made by not being content with this. Additionally, the temperature of the sample was also checked with a laser thermometer. This double-check has been carried out to prevent an error in the PID control system. The bending process was carried out just after the laser thermometer confirmed the correct temperature. The PID control system ensured this temperature remained the same throughout the process. Mastech MS6540B was used as a laser thermometer here. It can measure temperatures from −32 °C to +1050 °C with an accuracy of ±0.5% and a resolution of 0.1 °C. Confirmation measurement with the laser thermometer on the test sample is shown in Fig. 3.



**Fig. 3**. Temperature measurement with Laser Thermometer.




**Fig. 4**. Coordinate measuring machine.

| | | | |
|---|---|---|---|
| Measuring Range | 1.2 mm | Maximum permissible length measurement error | 0.025 mm |
| Single point repeatability | 0.014 mm | Maximum permissible probing size error | 0.012 mm |
| Volumetric accuracy | ± 0.025 mm | Maximum permissible probing location error | 0.035 mm |
| Arm Weight | 10.2 kg | Maximum permissible probing form error | 0.025 mm |

**Table 3**. Technical details of CMM[79,80].

## Bending tests and springback measurements

The bending tests were conducted on an Instron 8801 Servo Hydraulic Fatigue Testing System[78] by placing the dies on the upper and lower grips of the machine. The machine has a force capacity of up to 100 kN with speed control. The punch velocity was fixed in all experiments to get consistent results. During the bending process, the upper die position was continuously monitored via the digital control panel. The moment when the upper sheet reached the final bending position between the upper and lower dies was carefully monitored both via the control panel and through manual observation. At this point, the upper die was retracted in a controlled manner by operator intervention, and the die stroke was precisely adjusted.

The CMM, with a Hexagon Metrology Romer Absolute Arm RA-7312 [79], shown in Fig. 4, was used to measure the springback. It is a coordinate measuring system, including an absolute arm to take measurements and a computer with its goal-oriented software. Its working principle is taking various points from an existing surface to define it as a model in a 3D coordinate system. The point-taking is made by using its absolute arm. The surface model is identified automatically with these marked points through its software. In our study, to satisfy the high precision and reliability of the measurement, at least nine points were randomly taken from both inside surfaces of bent parts. This process was repeated three times for every part to achieve the most reliable results by minimizing possible errors due to surface quality or similar effects. Additionally, upper and lower dies were checked five times to ensure their dimensions that may affect the experiments' sensitivity.

There is a specially designed table forCMM and a powerful magnet circle on it. First, the specimen was fixed with the help of this magnet. Then, the points were defined using the probe of the absolute arm. After surface definitions were made, the exact angle between them can be calculated by the software and displayed through the monitor. Thus, the exact angle between the surfaces was determined accurately, and so was the springback. Technical details of the CMM are given in Table 3.

Furthermore, since the rolling direction is one of the parameters affecting the springback, all specimens were cut in the same rolling direction; thus, the effect of this parameter was eliminated to obtain healthier results.

## Design and analysis of experiments

In this study, experiments investigated the effect of temperature, holding time, and thickness on springback, and the results were analyzed. In total, 40 experiments were conducted and analyzed. Under test conditions without a holding period, each experiment was repeated three times. However, under conditions involving elevated temperatures with prolonged holding times, samples tended to adhere to the die, which could have led to die surface deformation. To preserve die surface integrity and prevent thermal damage to the test system, the number of repeats under these conditions was limited to two.

To ensure consistency in statistical analysis, and because the number of repeats should not vary across conditions, the three repeats performed under conditions without a holding time were also reduced to two repeats, and the third measurement was excluded from the analysis, standardizing all conditions to two replicates.

Regarding the factor levels, these two thickness levels were selected because the most common thicknesses of DP1000 steel sheets on the market are 1 mm and 2 mm. For the temperature parameter, 400 °C was set as the maximum temperature, thus remaining below the warm forming limit. To better observe the effect of temperature, a temperature level was tested every 100 °C. For the holding time, a suitable range was selected to prevent deformation of the die under high temperature and load, while also providing stress relaxation. Therefore, a holding time of 40 s was chosen.

The punch velocity was 7.5 mm/sec and constant for all replicates. Each bending operation was performed as soon as the parts reached the correct temperature. The springback of every part was measured, and analysis was performed with Design Expert® software, version 11 (Stat-Ease Inc.), using a Factorial Design. The current version of the software and detailed information are available at: https://www.statease.com/software/design-expert/.

Since there are multiple levels in factors, a Multi-level Categoric Design that allows analyzing the interaction and individual effects of different independent variables[81] was selected. The factors and their levels are shown in Table 4:

The measured bending results were input into the statistical software. ANOVA (Analysis of Variance) was performed to clarify the effect of each factor and their interactions. A numerical model was selected, and the 3FI (three factor interaction) process was conducted. F-values and p-values were calculated to determine statistically significant factors and quantify their effects. As a next step, regression analysis, a statistical method to calculate the correlation between variables[82]was carried out. Utilizing this analysis, the correlation, which is employed to identify the degree of relation[83] between springback and all factors, was calculated, and the springback equation was constructed and presented. The fit statistics were obtained. When the correlation coefficient is positive, the correlation is in the same direction. If it is one, the correlation is perfectly strong, and when it is 0, it can be said that there is no relation at all[84]. Additionally, all required plots were generated to clearly observe each factor's effects. After all, the results were compared with previous studies.

## Results & discussion

The effects of temperature, holding time, thickness, and their interactions among each other were investigated simultaneously. The specimens were tested with two replicates at each level combination. The punch was retracted immediately after the bending in half of the experiments. In the other half, the punch was held on the specimen. The force was applied constantly for 40 s to investigate the holding time effect. The results of the experiments are presented in Table 5.

The average springback angles obtained under different test conditions, along with their standard deviations, are presented in bar chart format in Fig. 5 to visually demonstrate the consistency of the results.

ANOVA (Analysis of Variance) analysis was performed with these results, and the statistical power of each factor was clarified. The results of the ANOVA are given in Table 6.

A p-value lower than 0.05 indicates that the outcomes are statistically significant[86,87]. Table 6 clearly demonstrates that every factor and their interactions have a statistically highly significant effect on springback as the p-value of the model, factors, and interactions are smaller than 0.0001[88].

The F-value indicates the factor which has a more significant effect on the model[89]. If the F-value of a factor is greater than the other one, this factor's effect is more significant[89]. The results showed that temperature has the highest F-value and, therefore, the most significant effect on springback among these three factors. After the temperature, holding time and thickness come, respectively. However, it should be noted that F-values are very close between thickness and holding time. The interaction effect of thickness and holding time is the most significant among the interaction effects. Despite having less effect than the main parameters on springback, it should be considered. Other interactions only affected it marginally.

Here, it should be noted that to compare the effects of two or more factors on springback, it is necessary to investigate them simultaneously in the same model. The comparison should be carried out based on statistical

| Temperature (°C) | RT | 100 | 200 | 300 | 400 |
|---|---|---|---|---|---|
| Thickness (mm) | 1 | 2 | | | |
| Holding Time (sec) | 0 | 40 | | | |

**Table 4**. Experimental factors and their levels.

| TRIALS | 1 mm Thickness | | | | 2 mm Thickness | | | |
|---|---|---|---|---|---|---|---|---|
| Temperature | No Holding Time | | 40 s. of Holding | | No Holding Time | | 40 s. of Holding | |
| RT | 7.434˚ | 7.463˚ | 5.306˚ | 5.323˚ | 4.563˚ | 4.548˚ | 4.083˚ | 4.088˚ |
| 100˚C | 6.794˚ | 6.775˚ | 4.879˚ | 4.82˚ | 4.297˚ | 4.28˚ | 3.681˚ | 3.628˚ |
| 200˚C | 6.358˚ | 6.317˚ | 3.476˚ | 3.499˚ | 4.001˚ | 3.986˚ | 2.744˚ | 2.732˚ |
| 300˚C | 3.988˚ | 4.00˚ | 1.56˚ | 1.602˚ | 2.297˚ | 2.257˚ | 1.403˚ | 1.422˚ |
| 400˚C | 1.536˚ | 1.525˚ | 0.444˚ | 0.466˚ | 1.105˚ | 1.093˚ | 0.222˚ | 0.207˚ |

**Table 5**. Springback angle (°) measurements. Note: The springback values at room temperature with no holding time for 1 mm and 2 mm thicknesses (only 4 out of 40 data points) were published in our earlier study[85].

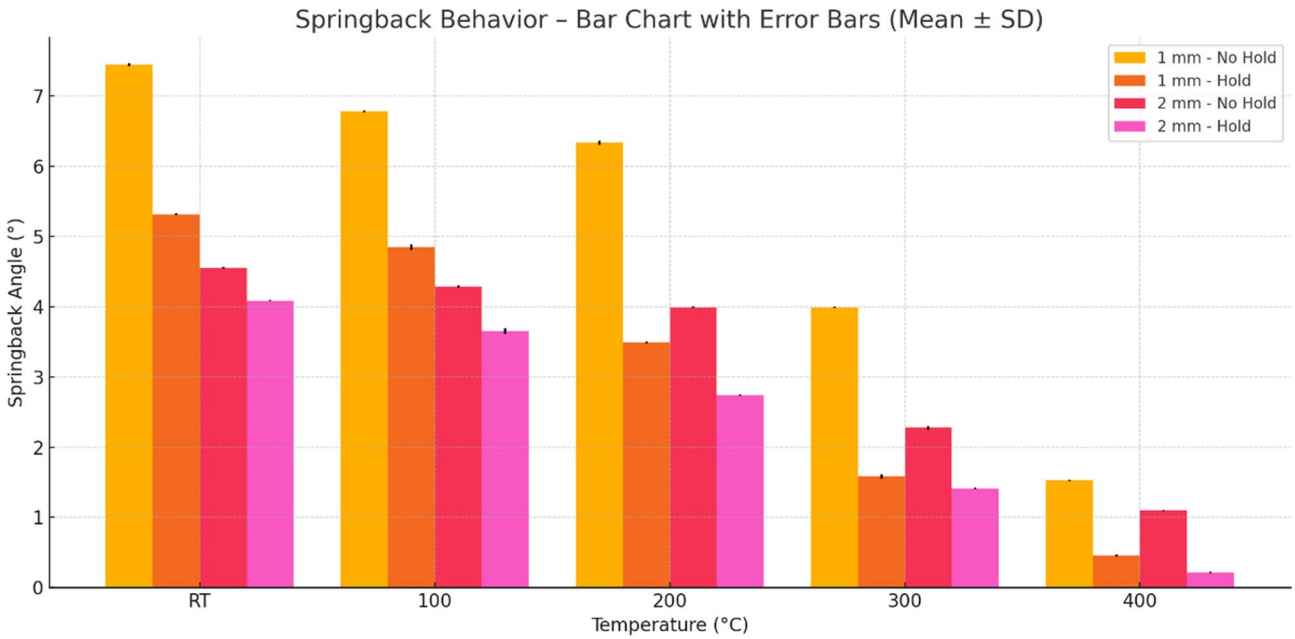



**Fig. 5**. Average springback results with error bars.

| Source | Sum of Squares | Df | Mean Square | F-value | *p*-value | |
|---|---|---|---|---|---|---|
| **Model** | 163.41 | 19 | 8.60 | 20773.23 | < 0.0001 | significant |
| a- Temperature | 114.59 | 4 | 28.65 | 69190.66 | < 0.0001 | |
| B- Holding Time | 20.94 | 1 | 20.94 | 50570.88 | < 0.0001 | |
| c- Thickness | 18.01 | 1 | 18.01 | 43489.20 | < 0.0001 | |
| aB | 1.28 | 4 | 0.3211 | 775.64 | < 0.0001 | |
| Ac | 3.95 | 4 | 0.9875 | 2385.16 | < 0.0001 | |
| Bc | 3.91 | 1 | 3.91 | 9445.39 | < 0.0001 | |
| aBc | 0.7370 | 4 | 0.1842 | 445.02 | < 0.0001 | |
| Pure Error | 0.0083 | 20 | 0.0004 | | | |
| Cor Total | 163.42 | 39 | | | | |

**Table 6**. ANOVA results for the 3FI process for springback.

results with F-values of the same model. It should also be noted that conclusions from these comparisons can only be drawn and are valid within the model. Comparing 1000 s of holding time at a 250 °C temperature level and 10 s of holding time at a 500 °C temperature level can give totally different ideas about the factors' effects. Here, the levels should be chosen considering the facts of manufacturing. For instance, holding time can be chosen as 50–100 s but not 500 s, because the production will be ten times slower than that of the other

producers. Hence, the labor cost will be ten times more, which will cause losing the related project to another company.

Moreover, the temperature level should be chosen as the minimum level that affects springback significantly. In this study, it was found that this is around 300 °C. Otherwise, comparing the temperature effect with other factors will be meaningless, because temperature affects springback after some level, and the effect is very limited before that level. In the study of YU and Lee[63]a non-statistical based claim was made that the holding time has a more significant effect than temperature. They compared 1000 s of holding time with the temperature effect at 250 °C. Their claim can only be valid for these levels, and no generalizations can be made from that point about the holding time effect more powerful than that of temperature.

Regression analysis was performed to predict the relationship among process parameters. The standard deviation, mean, correlation coefficient, and other statistical results of fit statistics are found as given in Table 7.

Adequate (Adeq) Precision implies a ratio between signal and noise. Generally, if it is more than 4, that indicates adequate model distinction[90]. The adeq precision of 502.78 shows that there is an adequate signal here. $R^2$ indicates if the data points fit a curve or not. If $R^2$ is one, that means the data points entirely fit a line or a curve. Adjusted $R^2$ also shows the same, but this coefficient is found after adjusting for the number of data points[91].

The calculated correlation coefficient of 0.9999 indicates an extremely strong correlation between the factors and springback. As seen in Table 7, the $R^2$ and the predicted $R^2$ are almost the same. The higher the predicted $R^2$ represents the higher proximity between the actual values and the predicted values of this model. The springback equation, which is obtained by the statistical analysis, is given in Eq. (1) in terms of coded factors. In this equation, a is temperature, B is holding time and c is thickness.

$$\begin{aligned} &Springback\ Angle\ Equation\ (^\circ) = 3,50 + 1,85 * a + 1,39 * a^2 + 0,625 * a^3 - 1,19 * a^4 - 0,7235 * B - 0,6709 * c \\ &+0,0725 * a * B + 0,0812 * a^2 * B - 0,2915 * a^3 * B - 0,0958 * a^4 * B - 0,3596 * a * c - 0,2518 * a^2 * c - 0,0911 * a^3 * c \\ &+0,1996 * a^4 * c + 0,3127 * B * c + 0,1033 * a * B * c + 0,0126 * a^2 * B * c + 0,0746 * a^3 * B * c + 0,0744 * a^4 * B * c \end{aligned} \quad (1)$$

The following comparison graphs given in Fig. 6 were prepared to demonstrate the compatibility between the obtained regression equation and the experimental data.

The normal plot of residuals, which was established to compare the experimental results with the normal distribution[92] is given in Fig. 7. As is seen from the graph, experimental data were gathered around the normal distribution line. The results are close to linear, indicating that the experimental results are consistent.

The residuals vs. run plot in Fig. 8 is used to check whether the experiment was done randomly. Here, it can be seen that all the experiments were randomly executed. It is also possible to confirm if the results are consistent from this graph by checking if the outcomes fall within the range +/-3 sigma confidence levels.

After the statistical plots, the graphs of the factors were constructed to see their effect on the springback behavior. Springback against temperature depending on holding time for 1 mm and 2 mm thicknesses is given in Figs. 9 and 10, respectively.

As the temperature increases, the springback decreases, as shown in Fig. 9. The dots on the lines are the results under the relevant test condition. If these dots are looked at carefully, it will be seen that there are two overlapping points. That is, the lines were merged over both replicates of the experiments. In the figure, the red line is formed by connecting the dots showing the springback results for each temperature condition without a holding time effect. Afterward, the holding time effect was applied to each experiment, and the green line depicts the results. Analyzing the holding time effect for each temperature condition together is easier with these lines. For instance, at 200 °C, the springback difference can be clearly seen from the red and green points aligned with the temperature. The lines are steeper between 200 °C and 400 °C. In that range, the dominant effect of temperature on springback can be observed. Between RT-100 °C, the decrease caused by the temperature increase is slight. Between 100 °C and 200 °C, the combined effects of temperature and holding time are significant, although the impact of temperature without holding time is weak. The holding time effect is significant at every temperature, as is seen from the vertical distance between each point of the two lines. Nevertheless, it is less pronounced at 400 °C. The interaction effect of temperature and holding time was not clearly observed between RT − 100 °C and between 200 and 300 °C because the lines are almost parallel.

The effect of both temperature and holding time on springback for 2 mm thickness is shown in Fig. 10. The difference between the holding and no holding conditions results is clearly observed at 200 °C.

Figure 10 was constructed using the same logic as Fig. 9, but this time for 2 mm thickness. Therefore, the holding time effect can be analyzed with the same mentality. The temperature continues its decreasing effect for 2 mm thickness. However, both temperature and holding time effects on springback are less when compared to 1 mm sheet because of the lower springback obtained at thicker sheets as expected. From RT to 200 °C, the temperature effect is negligible if there is no holding time. The holding time effect is still noticeable at 200 °C.

| | | | |
|---|---|---|---|
| Std. Dev. | 0.0203 | $R^2$ | 0.9999 |
| Mean | 3.5 | Adjusted $R^2$ | 0.9999 |
| C.V % | 0.5809 | Predicted $R^2$ | 0.9998 |
| | | Adeq Precision | 502.7826 |

**Table 7**. Fit statistics of the 3FI process of springback.

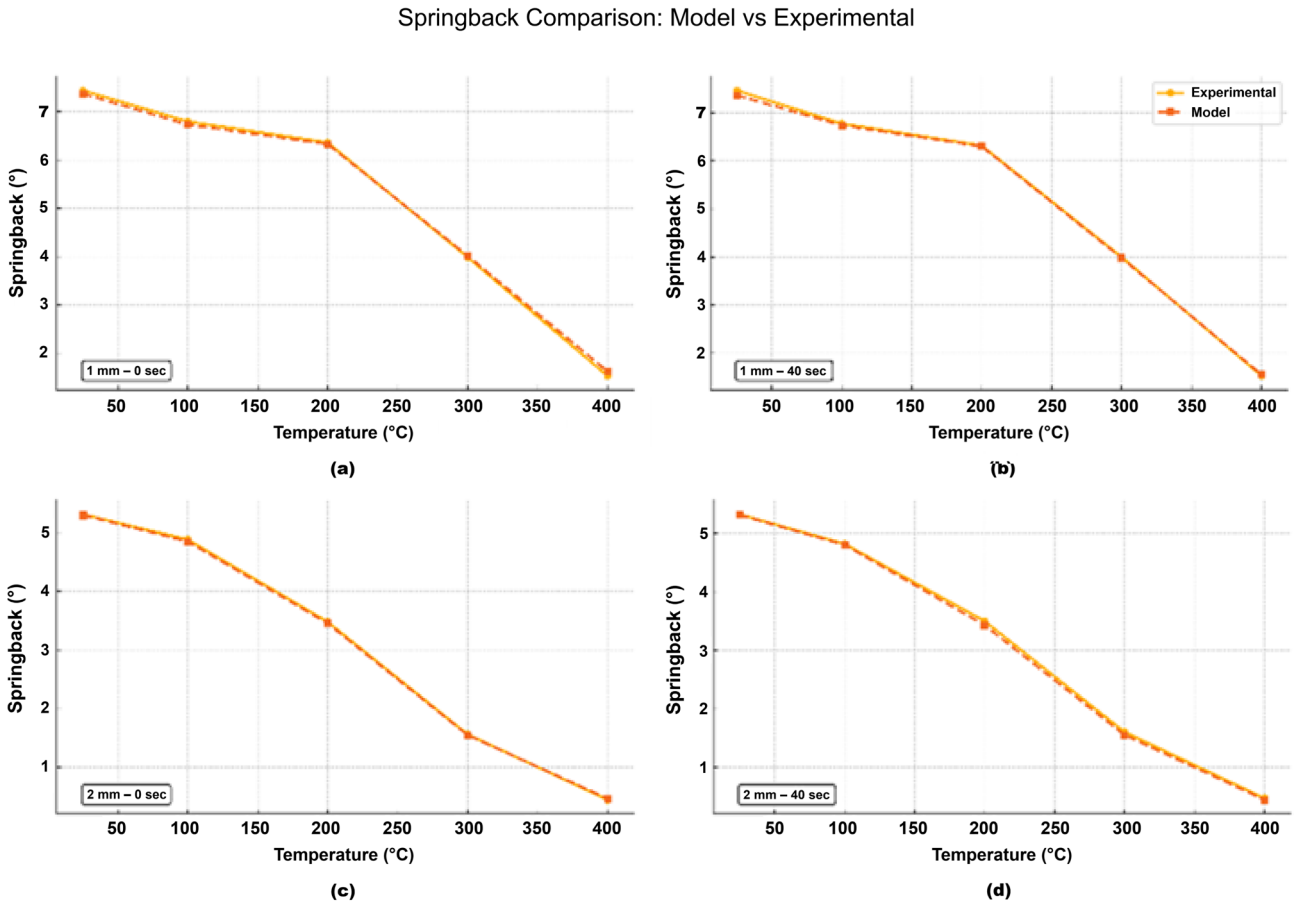



**Fig. 6**. Comparison of experimental and predicted springback angle results.

It was observed that springback is almost zero for 2 mm thickness, at 400 °C, with 40 s of holding time. Therefore, holding time is crucial at 400 °C to eliminate springback. If the aim is not to eliminate springback but to decrease it, the optimum value can be determined by adjusting temperature and holding time levels according to customer needs, tolerances, energy costs, time limits, and machine capacities.

The effect of holding time on springback was plotted for two different thicknesses in Fig. 11. Average values of temperature were used to generate this graph. The effect of increasing holding time and thickness on the reduction of springback is apparent. However, the restrictions between the two effects can also be observed. The thickness effect becomes minor at a higher holding time, and the holding time effect becomes smaller when the thickness increases. This also proves that the effect of factors mostly depends on each other. Hence, the interaction effect cannot be ignored.

Table 8 presents the quantitative change in the amount of springback for 1 mm and 2 mm thicknesses at different temperatures, with and without holding times. The first four columns show the test results using the 1 mm sample, while the next four columns contain the data obtained for the 2 mm thickness.

The statistical results in Table 8 show that temperature has the most significant effect on springback compared to other factors. Table 8 also exhibits that the effect of temperature becomes even more significant at higher values. Between RT and 400 °C, the temperature effect on its own resulted in 79% and 75% decreases in springback in 1 and 2 mm sheet thicknesses, respectively, while it decreased the springback 91% and 95% with holding time. The thicker material resulted in lower springback under all conditions than thinner ones.

In experiments without holding time, as the temperature increases from RT to 200 °C, springback decreases by approximately 14.9% for the 1 mm and 12.3% for the 2 mm samples; in the 200–400 °C range, this reduction reaches 75.9% for the 1 mm and 72.5% for the 2 mm. When holding time is applied, the reduction between RT and 200 °C is 34.4% for the 1 mm and 33.0% for the 2 mm samples; and 87.0% and 92.2%, respectively, in the 200–400 °C range. From these results, it is clearly seen that springback decreases much more significantly in the 200–400 °C range compared to the decrease between room temperature and 200 °C.

The flow stress level, which does not vary from room temperature to 200 °C, decreases significantly from 300 °C to 500 °C. Ultra-high-strength martensiti c steels generally exhibit thermal softening because phase transformation and partition begin at higher temperatures[93](Kim et al., 2022). The aforementioned substantial reduction in springback beyond 200 °C can be attributed to this thermal softening.

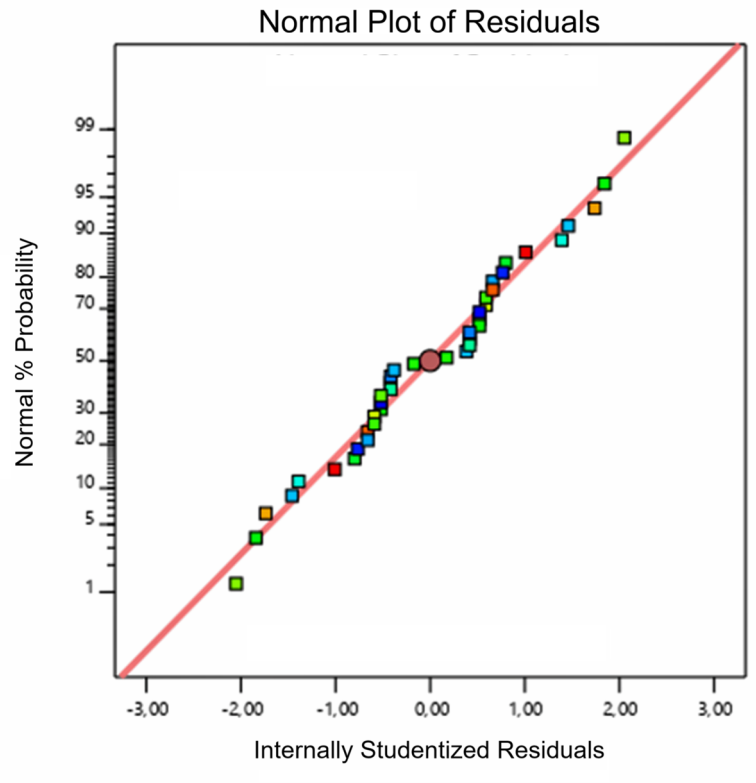



**Fig. 7**. Normal Plot of Residuals the 3FI process of springback.

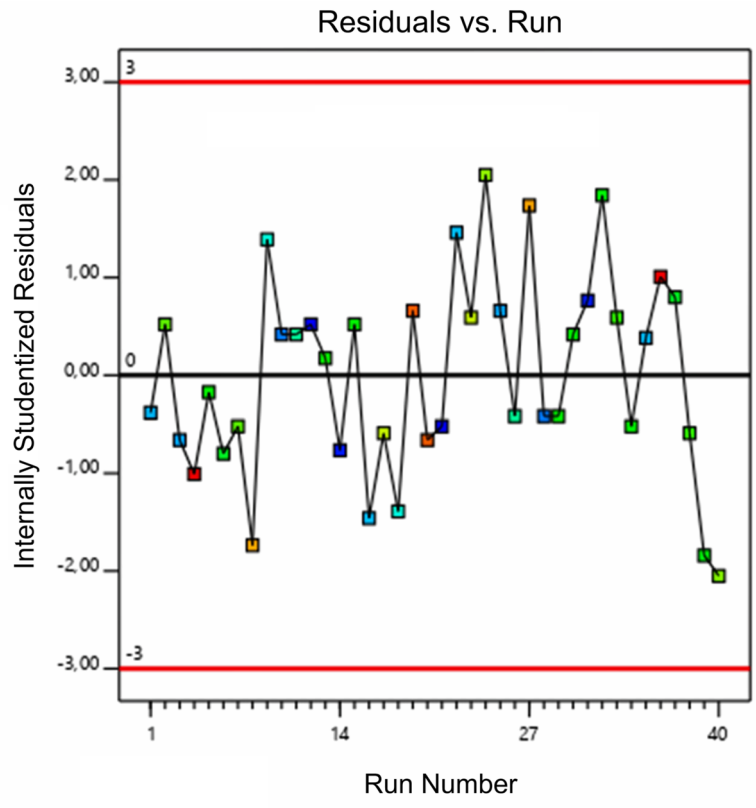



**Fig. 8**. Residuals vs. Run plot of the 3FI process of springback.

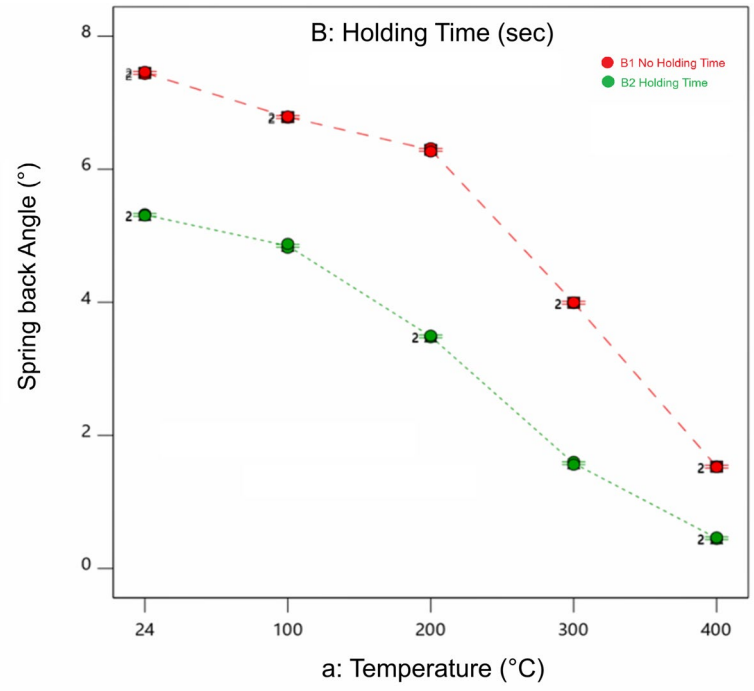



**Fig. 9**. The relationship between temperature, holding time and springback for 1 mm thickness.

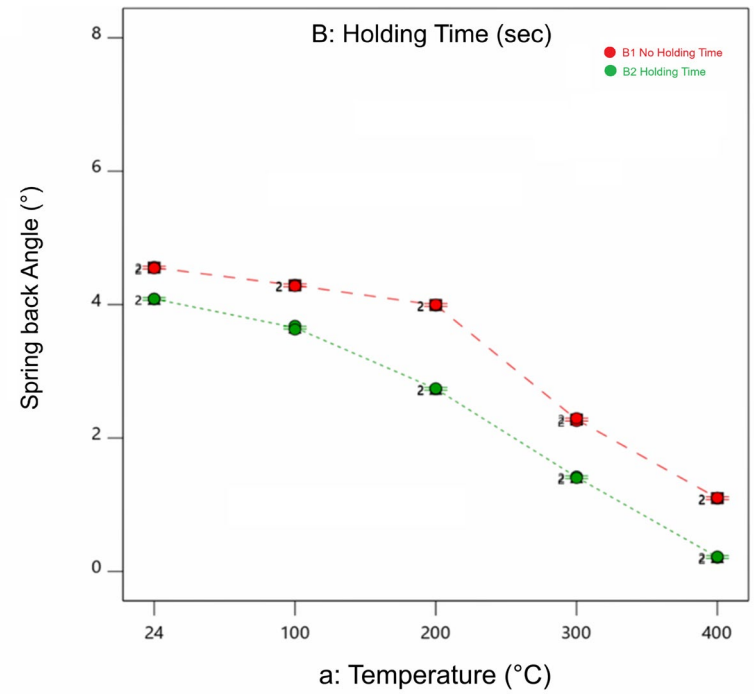



**Fig. 10**. The relationship between temperature, holding time and springback for 2 mm thickness.

This reduction in springback with temperature was also reported in previous studies carried out by Mori et al.[27] Yanagimoto and Oyamada[53] Ozturk et al.[32] Stachowitz et al.[21] Takata[54] Lee et al.[55] Saito et al.[22,40] and Soualem and Hakimi[39].

The percentage decreases with holding time at each temperature for both thicknesses are given in Table 9.

It is observed that the effect of holding time alone is significantly important but not as much as the temperature. However, the effect of holding time is found to be greater at higher temperatures. Thus, it can be said that temperature and holding time have a powerful impact together. For the first time, this is statistically

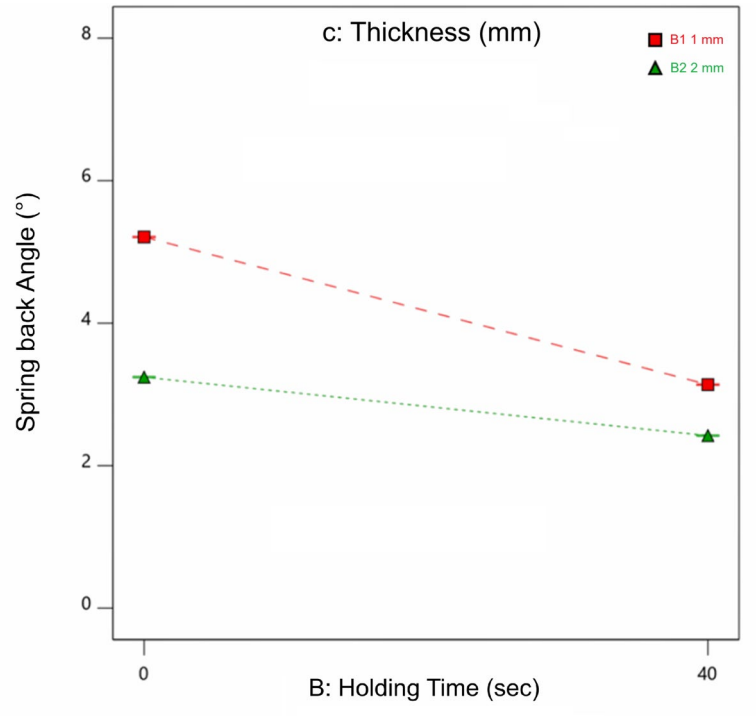



**Fig. 11**. Springback against holding time depending on thickness taking the average temperature.

| Temperature | No Holding Time(°) | Decrease (%) | With Holding Time(°) | Decrease (%) | No Holding Time(°) | Decrease (%) | With Holding Time(°) | Decrease (%) |
|---|---|---|---|---|---|---|---|---|
| RT-100 °C | 7.45 to 6.78 | 8.9145 | 5.31 to 4.85 | 8.750 | 4.55 to 4.29 | 5.861 | 4.08 to 3.65 | 10.550 |
| 100–200 °C | 6.78 to 6.34 | 6.5885 | 4.85 to 3.49 | 28.085 | 4.29 to 3.99 | 6.879 | 3.65 to 2.74 | 25.079 |
| 200–300 °C | 6.34 to 3.99 | 36.9796 | 3.49 to 1.58 | 28.085 | 3.99 to 2.28 | 42.987 | 2.74 to 1.41 | 48.411 |
| 300–400 °C | 3.99 to 1.53 | 61.6813 | 1.58 to 0.45 | 71.221 | 2,28 to 1.1 | 51.739 | 1.41 to 0.21 | 84.814 |
| RT to 400 °C | 7.45 to1.53 | 79.4534 | 5.31 to 0.45 | 91.439 | 4.55 to 1.1 | 75.879 | 4.08 to 0.21 | 94.750 |

**Table 8**. The percentage decreases of springback angle with temperature.

| | 1 mm Thickness | | | | | 2 mm Thickness | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | RT | 100 °C | 200 °C | 300 °C | 400 °C | RT | 100 °C | 200 °C | 300 °C | 400 °C |
| % | 28.725 | 28.466 | 44.953 | 60.401 | 71.046 | 10.33 | 14.918 | 31.328 | 38.158 | 81.081 |

**Table 9**. The percentage decreases of springback with and without holding time.

proven. In the literature, Tekiner[23] and Tekaslan et al.[28] also reported that springback decreases with increasing holding time. Saito et al.[40] found that holding time decreased the springback until the 5th second; then, there was no effect until the 20th second. Mori[10] claimed that the holding time effect is minimal. In our results, its effect is significant in almost any condition, especially when combined with temperature. Throughout the holding time, the specimen is restricted between the punch and the lower die, and it allows the workpiece time for stress relaxation. At this time, the internal stresses are decreased. It is thought that the reason for the springback decrease is this stress relaxation[40]. This decrease in internal stresses causes smaller elastic strain and greater plastic strain. It is well known that springback happens because of elastic recovery. Hence, when the elastic strain decreases, springback decreases, too[38].

From Tables 8 and 9, it can be seen clearly that springback decreases by increasing the thickness in every condition. In the literature, most of the results mentioned the same tendency. Tekiner[23]Garcia-Romeu et al.[24]Kılıç[34]Stachowitz et al.[21]Thipprakmas and Phanitwong[29] found that the springback decreases with increasing the thickness. However, Tekaslan et al.[28] claimed that the springback has increased by increasing the thickness. Thus, the results are compatible with most of the previous studies. It was also observed that the result is consistent with the widely used springback formula[94]which is given as Eq. (2). The springback and thickness are inversely

proportional in this formula and our results. In Eq. (2), T is thickness, Y is yield stress, E is elastic modulus, $R_i$ is initial and $R_f$ is the final radius. This formula clearly shows the relation between thickness and springback; however, it should be noted that the temperature effect is not included here.

$$\frac{R_i}{R_f} = 4\left(\frac{R_i Y}{ET}\right)^3 - 3\left(\frac{R_i Y}{ET}\right) + 1. \tag{2}$$

## Conclusions

The findings of this study contributed to the literature by filling a crucial gap: effects were examined simultaneously, while previous studies examined them individually. It has been proven that analyzing a factor alone can lead to misleading results about its impact. Univariate graphical formulas were obtained in previous studies. After the regression analysis, the springback formula, which consists of three variables that can be changed simultaneously, was proposed for the first time in the literature based on multivariate regression analysis. If the findings of scientific investigations do not meet the needs of industry, they cannot positively contribute to production. This formula, which will be accessible to the die-makers, will let them know a part's approximate springback amount before being produced. In this way, designers can make the die with a suitable angle on the first production attempt; thus, the desired results will be directly achieved on the final part by overbending, without excessive metal waste. A deeper investigation was executed on temperature, holding time, and thickness factors. Each factor and its interactions were statistically analyzed. The results were compared with previous studies.

The following conclusions can be summarized after the study:

- The study addresses a significant gap in the literature by considering both high-temperature heating and holding times simultaneously. The combined effect of these two factors is quite strong; holding time allows the targeted reduction in springback to be achieved at lower temperatures, thereby preventing damage that very high temperatures can cause to the material, die, and bending equipment.
- The research adds new and valuable information to the literature regarding the springback behavior of DP1000 steels, whose use has rapidly increased in recent years due to their high strength and light weight.
- Springback formula with three variables that can be simultaneously changed was derived by regression analysis for the first time.
- The correlation coefficient was 0.9999. This very challenging-to-achieve result indicates a near-perfect relationship between the factors and the springback in our model.
- The effects of parameters were investigated along with their interactions for the first time. The p-values of the interaction effects, which are well below 0.05, proved that all interaction effects are significant, including the interaction of all three factors.
- The significance of the factors was statistically compared with each other for the first time. According to statistical results, the temperature has the most significant effect with the F-value of 69190.66, holding time (50570.88), and thickness (43489.20) are the next ones, respectively.
- It was proven that the relationship between springback and these three factors is inversely proportional. Because with the increase of these factors, the springback decreased.
- Temperature and holding time have potent effects together. Usage of holding time with less temperature can decrease energy costs remarkably. A "less energy - less springback" model can be executed with the addition of holding time effect to the correct temperature level.
- It can be said that the bending operations should be carried out between 200 °C and 400 °C to significantly reduce springback with lower energy cost, up to springback necessities.
- Without benefiting from the effect of temperature and holding time, the springback, which was 7.463˚ at 1 mm sheet metal, decreased to 0.207˚ with the holding time effect at 400 °C for 2 mm thickness. The effect of the established model of the study is clearly observable. From these results, it can be said that springback is almost eliminated with the model used.

### Future studies

- For DP steels, the holding time parameter can be examined in more detail to determine whether its effect on springback is linear or becomes more pronounced after a certain threshold value. This would allow for the identification of critical holding time values for process optimization.
- The microstructural changes underlying the decrease in springback due to temperature can be characterized in detail.
- By using the experimental data obtained in this study and, if necessary, by adding additional experiments, validated finite element (FEM) models can be developed. These numerical models can provide a powerful tool for springback prediction in industrial applications.
- By integrating the obtained findings into real-world production processes, practical applications for springback control under different die geometries and processing conditions can be developed.

## Data availability

All relevant data are included in the study.

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## Competing interests
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