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DETERMINATION OF THE EFFECT OF THICKNESS REDUCTION RATIO, DIE ANGLE, AND COEFFICIENT OF FRICTION ON RESIDUAL STRESSES IN IRONING PROCESS: AN ANALYSIS USING COMPUTER SIMULATION

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Ironing is a part of the group of metal forming processes, the process of reducing the thickness of the wall of a cup-shaped product. External load required to process metal forming, can cause residual stress. Residual stress can be beneficial or detrimental depending on the function of the product, the magnitude, and direction of the residual stress. Residual stress can act as an additional load on a given load. Residual stress can affect product quality, namely: dimensional accuracy, surface roughness, and mechanical properties. The speed of the ironing process is strongly influenced by the mechanical properties of the cup material, Thickness Reduction Ratio (TRR), and press tool design. The ironing process has a limited TRR value and if it is exceeded it results in product damage. Various studies on ironing were carried out to obtain an optimal process. In this research, stress analysis was carried out using the ANSYS software modeling simulation to obtain the occurring residual stress during the ironing process. The analysis was carried out by varying the TRR from 20 % to 30 %, the die angle from 25° to 30°, and the coefficient of friction from 0.05 to 0.15. Furthermore, processing and analysis of the stress analysis data are carried out to obtain the most dominant variables affecting the residual stress and the variable value that produces the lowest residual stress. Stress analysis was carried out on AA1100 aluminum cups with an outer diameter of 37 mm, a height of 20 mm, and a wall thickness of 2 mm. The results show that TRR and coefficient of friction are the most dominant variables affecting residual stress, while die angle has no significant effect. The lowest residual stress occurs at TRR 30 % and coefficient of friction 0.15

Keywords: thickness reduction ratio, die angle, coefficient of friction, residual stress

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1. Introduction

Bullet casings, pans, fire extinguishers, gas cylinders, and beverage cans are products of the metal forming process. This product belongs to the thin-walled cup product group. The manufacturing process starts from raw materials in the form of plates which are processed by blanking to produce blanks with a certain diameter and thickness. Then, through a process of deep drawing, the blank is formed into a cup. Furthermore, the wall thinning is carried out through an ironing process in order to obtain a uniform wall thickness. In the ironing process, the cup is placed on a die, and then in the middle pressed using a punch. The outer wall is compressed on the die which has a smaller diameter according to the die design, so as to reduce and uniform the wall thickness and increase the cup length [1].

During the ironing process, there is a tensile load on the cup wall. The amount of thinning or Thickness Reduction Ratio (TRR) is obtained based on the die design used. TRR has a limit and if it is exceeded, the tensile load that occurs is greater and generally results in damage to the base of the cup wall. The amount of TRR is influenced by several factors, including: the mechanical properties of the type of material being thinned, the design of the press tool used, the temperature conditions during the process. At low TRR, in order to achieve the desired thickness, the process must be repeated several times. On the other hand, at high TRR, a large punch force is required, so there is a high risk of product damage [2].

If the ironing process has been carried out, but the dimensions are not as desired, then the ironing process can be carried out in several stages until the appropriate diameter, wall thickness, and length are obtained. In designing a multistage ironing process, it is necessary to pay attention to changes in the characteristics of the material being processed. Based on this research, the material forming process, including ironing may cause residual stress or residual stress [3] and produce changes in the mechanical properties of the material, the tensile strength and hardness [4]. The amount of change in material characteristics is strongly influenced by the type of material, press tool design, and conditions during the process.

The properties of the material to be ironed must meet the requirements and depend on the characteristics of the desired product. Considering that ironing is a metal forming process, the main requirement that is dominant is the mechanical properties of the material. Various types of materials have been used in cup-shaped products, including bullet casings made of brass or aluminum, beverage cans made of aluminum alloy, pans made of stainless steel, gas cylinders and fire extinguishers made of mild steel.

Various studies have been carried out for a long time to get a high TRR in the ironing process. The ironing methods that have been developed include single stage ironing, multistage ironing, ironing with superimposed force, ironing in warm conditions, hydrostatic ironing, hydro ironing, and constrained ironing. Some of the ironing methods above can be compared as follows:

1. Single stage-ironing requires low punch force, but has a low TRR. If TRR increased, will increase the punch force and the risk of damage to the product. For this reason, if a large thickness reduction is required, it can be done through several ironing process.

2. Multistage ironing is an ironing process carried out in several stages [5]. This method can increase TRR, but strain hardening occurs at each stage, so it needs to be calculated carefully so as not to require annealing process at each stage.

3. Hydro-ironing is an ironing process that is supported by additional equipment to provide and control hydrostatic pressure [6]. This process can increase the TRR by up to 70 %.

4. Constrained ironing is an ironing process with improvised press tool design. This method can change the direction of the load, so that what was originally a tensile load becomes a compressive load. The method is able to produce high TRR at each stage up to 80 % [4].

However, in the existing research, most of the research objectives were used to select the ironing method that has a large TRR. Though variations TRR, die angle and coefficient of friction in the ironing process can result in residual stress. Residual stress can be beneficial or detrimental depending on the function of the product, the magnitude, and direction of the residual stress. Residual stress can act as an additional load on a given load. Residual stress can affect product quality, namely: dimensional accuracy, surface roughness, and mechanical properties. For this reason, it is very necessary to conduct research that discusses the effect of TRR, die angle, and coefficient of friction on the residual stress that occurs. In addition, it is also necessary to conduct an analysis to obtain the TRR value, die angle, and coefficient of friction that causes the lowest residual stress. The results of this research can then be used as a guide in the design press tool for ironing process.

2. Literature review and problem statement

Since the discovery of the ironing process until now, many studies have been carried out to obtain the optimal ironing method. In the research on ironing force theoretically, the equation of ironing force is obtained which is the sum of the tensile force, frictional force, and shear force [7]. This study proves that the coefficient of friction has a direct influence on the magnitude of the ironing force. The ironing force or punch force is from the external load that must be required for the forming process, so that plastic deformation occurs. However, there has been no discussion about the effect of ironing style on the residual stress that occurs.

Research that aims to minimize residual stress in the deep-drawing process is carried out experiments and simulations. In this study, the parameters considered include the initial blank thickness, punch and die shoulder radii, blank-holder force, punch velocity, and coefficients of friction between die-blank, holder-blank, and punch-blank. Through the application of analysis of variance, the most important parameters can be determined, and the optimal value is obtained to minimize residual stress in the deep-drawing process [8]. Experiments on the effect of ironing on the residual stress and its distribution in the deep drawing cups were carried out. The results showed that ironing provides residual stress distribution along the cup wall. In the axial direction the maximum residual stress lies near the base of the cup and decreases along the wall to almost zero at the lip. Tangentially the residual stress is evenly distributed along the cup wall. Residual stress after deep drawing can be reduced by ironing. The number of ironing steps did not significantly affect the residual stress. Residual stress on steel material is higher than aluminum [3]. The focus of this research lies in the distribution of residual stress on the product resulting from the deep drawing process and the ironing process. Research to discuss the effect of TRR, die angle, and the coefficient of friction of the press tool design on the residual stress value that occurs, needs to be continued.

Research on the effect of TRR parameters, friction force, heat treatment, and material properties on the ironing process on aluminum cups was carried out experimentally. The purpose of this study was to obtain the magnitude of the punch force during the ironing process. The research was conducted on aluminum cups with 40 mm inner diameter, 1.5 mm wall thickness, 40 mm height, 17 % TRR, 5° die angle. The research was conducted by detecting the magnitude of the punch force along the ironing process. The results showed that the punch force was small at the beginning of the stroke and increased to a maximum at a step of 20 mm, then decreased to zero at a step of 40 mm [1]. In this study, what is discussed is the distribution of the punch force along the steps of the ironing process. The magnitude of the punch force is influenced by the tensile force, frictional force, and shear force [7]. This punch force is an external load required for the product formation process. For this reason, further research is needed to discuss the effect of variations in TRR, die angle, and coefficient of friction on the press tool design on the amount of residual stress that occurs.

The ironing process is a method that can also improve the surface quality and thickness precision of the cup of the drawn product. Besides being used to shape the outside of the cup, the ironing process can be used to improve the quality of the inner surface. The research was conducted through experiments to obtain the effect of punch design, TRR, and lubrication on the quality of the inner surface of the cup. The results show that the inner-ironing process is effective for improving the inner surface quality of the drawn cup, the optimal punch shape is 15° angle and a low viscosity lubricant produces a smooth surface, optimal surface roughness [9].

The type of lubricant affects the coefficient of friction between the punch and the cup and the cup and the die. Further research is needed to obtain the effect of the coefficient of friction on the amount of residual stress that occurs.

Conventional ironing processes generally have low thinning ratios and can be increased through the number of ironing steps, but this requires additional manufacturing time and costs. The ironing method was developed to overcome the problem of a low depletion ratio, namely the hydro ironing method. The research was carried out experimentally using a punch that was pushed to reduce the thickness of the cup wall and simultaneously exerted hydrostatic pressure on the inner surface of the cup. The results showed that the thickness reduction was higher, i.e., in one stage it reached about 70 %. Hydro ironing has 3 advantages compared to the previous method, namely higher thickness reduction, lower fluid pressure, and higher cup strength [6]. However, this study only focuses on increasing TRR, the effect on residual stress caused by further research needs to be done.

The development of conventional ironing methods continues, in order to increase the cup wall thickness reduction ratio. A new method of constrained ironing, which is an ironing method which previously was a thinning process in the form of tensile loads, through modification of the design of the press tool into compressive loads. This research was conducted experiments and was able to show high TRR results without additional processes such as multi-stage ironing and annealing between different stages. This method has a different punch and die design from conventional ironing. The thickness reduction process is carried out by pushing the constrained material, resulting in thinning of the outer surface of the cup by the die. The results showed that this method was able to produce a high thickness reduction ratio, about 80 % in one step, remove the annealing step, increase the tensile strength from 71 MPa to 204 MPa, and increase the hardness value from 25 HV to 85 HV [4]. The focus of this research is to produce a very high TRR value, which results in an increase in the tensile strength and hardness of the product material. For this reason, further research is needed that discusses the effect of a high TRR on the residual stress that occurs.

Research using numerical simulations and experiments was also carried out on the constrained ironing method. The experiment was carried out on aluminum cups with an outer diameter of 84 mm, height 10 mm, wall thickness 2.35 mm with a die angle varying from 5° to 30°, TRR varying from 60 % to 85 %, and coefficient of friction varying from 0.01 to 0.15. The purpose of this study was to investigate the effect of TRR parameters, die angle, and coefficient of friction in the constrained ironing process. The results of the study using FEM showed that the effect of increasing TRR from 60 % to 80 % of the punch force showed an increase, increasing the die angle resulted in a decrease in the punch force, the greater the coefficient of friction between the die and the cup and the cup and punch, the larger the punch force required [2]. The subject of this research is about the effect of TRR, die angle, and coefficient of friction on the punch force. Thus, further research is needed on its effect on the residual stress that occurs.

Research using simulation modeling on ironing is carried out on cups with varying TRR and die angles, in order to obtain the stresses that occur on the cup walls. The modeling was carried out using software on a cup diameter of 37 mm, a height of 20 mm, and a wall thickness of 2.5 mm with a TRR of 10 %, 20 %, 30 %, and die angles of 5°, 10°, 15°, 20°, 25°, 30°. The results show that at the same TRR and varying die angle, the stresses that occur in the cup vary. At the higher TRR, the higher the voltage [10]. Based on the results of this study, further research is needed on the effect of TRR and die angle on residual stress.

3. The aim and objectives of the study

The aim of this study is to obtain the variables of TRR, die angel, and coefficient of friction that have the biggest influence on the occurrence of residual stress.

To achieve this aim, the following objectives are accomplished:

– analyze the maximum stress using equivalent or von-Mises stress remaining in the cup after passing through the die at various variations of TRR, die angle, and coefficient of friction;

– analyze the stress analysis result to get the variables that affect the residual stress;

– interpret the results of the analysis to obtain the value of the influential variables that are generating the lowest possible residual stress.

4. Material and method of analysis

The research was conducted on aluminum cups made from Aluminum sheet AA1100 as a raw material in the form of a 2.0 mm thick plate which was processed by blanking and deep drawing. The shape and dimensions of the cup as shown in Fig. 1. Aluminum sheet AA1100 has initial yield strength of 130 MPa, hardening constant: 299 MPa, hardening exponent: 0.23, strain rate: 0.001 [11].

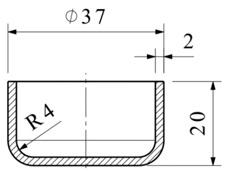


Fig. 1. Cup dimensions (in mm)

Simulations were carried out using ANSYS 2020 R2 licensed software through the Explicit Dynamics sub-program. Explicit Dynamics is a sub-program of ANSYS analysis systems that functions to study transient explicit dynamics analysis that can display variation simulations in engineering fields, including the nonlinear dynamic modeling behavior of solids, fluids, gases, and their related interactions. The ANSYS explicit dynamics sub-program can help to perform physical visualization in a short period of time on the model or product that has been made and has high nonlinear cases and dynamic transient forces so that it can maximize the design or product that has been made.

The composition of the equipment used in the ironing process simulation as shown in Fig. 2. D_0 is the initial diameter of the cup, D_1 is the final diameter of the cup, Δt is the amount of reduction in cup wall thickness, and a is the die angle. The zone in the die, which has a diameter of D_1 is called die land. TRR is $\Delta t/(0.5(D_1-D_0))\cdot 100$ %. Zone 0-0 is the beginning of the thinning process and zone 1-1 is the end of the process.

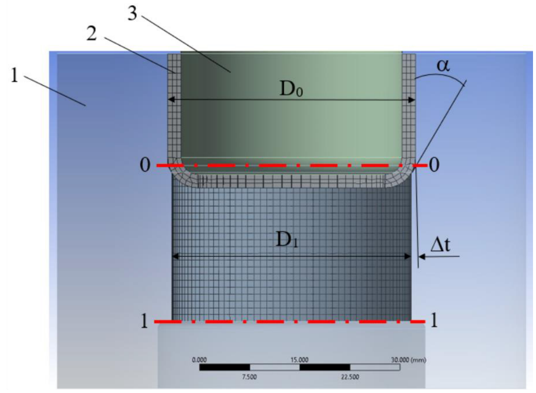


Fig. 2. Composition of the equipment:
1 — Die; 2 — Cup; 3 — Punch

The ironing process simulation using ANSYS software begins with the selection of an explicit dynamics sub-program. In this simulation, three main components are used, namely die, cup, and punch.

In general, the stress analysis steps in the ironing process using ANSYS software can be divided into three, namely:

– preprocessing.

Geometry modeling is carried out to create the design of the components used: die, cup, and punch. To vary the TRR and die angle, the die is designed on the design modeler menu with varying geometric shapes Δ*t* and α. After that, it is continued by defining the stiffness behavior of the die and cup as a rigid model, while the cup is a flexible model.

Filling in the material data used via the engineering data sources menu. The cup material data is AA1100, while the die and punch materials are structural steel. Next is meshing on the die, cup, and punch. Meshing on the cup is done by selecting Method: Multizone; Mesh Type: Hexa; Mesh Method: Uniform; and Element Order: Linear. Meanwhile, the meshing of the die and the punch is used Method: Quadrilateral Dominant; Mesh Type: Quad/Tri; Mesh Method: Uniform; and Element Order: Linear. To vary the coefficient of friction μ, set in the menu model – connections – contacts – frictional;

– solution.

In this step, the definition of physical type: structural, analysis type explicit dynamics, and target solver: AUTODYN is carried out. Analysis setting is defined with number of steps: 7, load step type: explicit time integration. At the constraint condition, the die is defined as a fixed support and the load is applied to the punch with type: velocity. The data on the calculated solution is the stress intensity. After everything is ready, the calculation process is carried out;

– general postprocessing.

The result of this simulation calculation is the stress intensity that occurs during the thinning process until it is finished. During the thinning process from zone 0-0 to zone 1-1, there is stress on the cup wall due to the punch and thinning of the die. However, after passing through zone 1-1 the thinning process is complete, there is no more punch force acting on the cup. In this condition, In this condition, as shown in Fig. 3, what remains is residual stress. These residual stress data are then documented as in Table 1. Residual stress in the tangential direction is evenly distributed at the bottom of the cup, but in the axial direction the maximum value is located near the bottom of the cup and decreases along the wall to almost zero at the cup rim;

– equivalent stress – von Mises stress.

In the ironing process which belongs to the category of metal forming, the stress that occurs in the material being formed must exceed the yield stress in order to cause plastic deformation. Plastic deformation is a permanent change in the shape of the material even though the load is removed, so that it forms the desired material. Yield criteria are standards that determine whether yielding or initial deformation has occurred in a material subjected to stress. The yield criteria are used to predict when the yield will occur. Yield criteria under uniaxial loading occur when the stress exceeds the yield stress ($\sigma > \sigma_{yield}$). But in fact, in the process of metal forming, the stress that occurs is three-axis stress (σ_1, σ_2, σ_3). No matter how complex the loading system, through stress analysis, stress conditions can be obtained which are expressed as principal stresses. Through various possible principal stress combinations, yield criteria are used to assess the occurrence of plastic deformation;

– Tresca's yield criteria.

Based on the Tresca yield criteria, yield conditions will occur when the maximum shear stress reaches a critical value, *k* (shear yield limit). Therefore, the Tresca yield criterion is also called the maximum shear stress yield criterion: $\tau_{max} = k$.

At uniaxial loading, the yield criterion of Tresca reaches a critical value:

$$\sigma_1 = \frac{F}{A}; \ \sigma_2 = \sigma_3 = 0.$$

Plastic deformation occurs if the stress (σ_1) reaches the yield strength of the material (σ_y):

$$\sigma_1 = \frac{F}{A} = \sigma_{yield}.$$

So, the shear stress is:

$$\tau_{\max} = \frac{(\sigma_1 - \sigma_3)}{2} = \frac{\sigma_1}{2}.$$

So that plastic deformation will start if:

$$\tau_{\max} = \tau_{yield} = \frac{\sigma_y}{2} \text{ and } \tau_{yield} = \frac{\sigma_y}{2}.$$

Tresca's yield criteria can be written as: $\sigma_1 - \sigma_3 = \sigma_y$.

In other words, the maximum shear stress that occurs is equal to half of the difference between the largest and the smallest principal stresses;

– von Mises' yield criteria.

The yield criterion of von Mises, which is the theory of maximum distortion, states: a material will be plastically deformed when the maximum distortion energy due to loading reaches its critical value. In the metal forming process, the plastic area is represented by the flow stress (σ_0) on the stress-strain curve (σ–ε). Von Mises' yield criteria are stated as:

$$\sigma_0 = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{2}},$$

where σ_1, σ_2, σ_3 are the principal stresses and σ_0 is the flow stress, i.e., the stress required to produce deformation. In the Von Misses criterion the role of the principal stress σ_2 is clearly visible. Therefore, Taylor and Quenney stated that the Von Misses criteria were better than the Tresca criteria (the results were close to the actual).

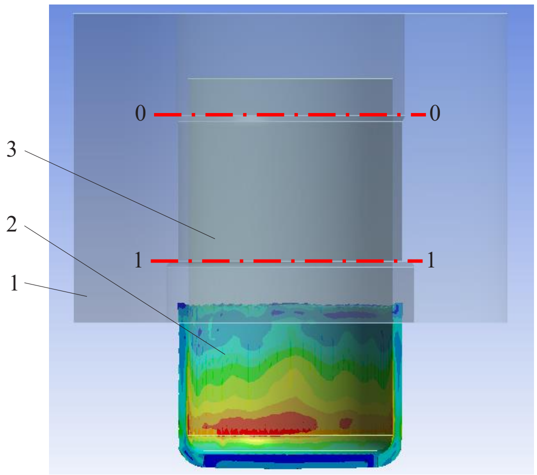


Fig. 3. Composition of the equipment after passing zone 1-1: 1 – Die; 2 – Ironed Cup; 3 – Punch

The data from the ANSYS simulation were then analyzed statistically using «multiple linear regression». This analysis method is used to measure the effects of independent variables on the dependent variable. Like other parametric tests, linear regression has conditions that must be fulfilled. This condition must be met so that the prediction model produced is a best linear unbiased estimation.

Tests that need to be performed on multiple linear regression include: residual normality, multicollinearity, heteroscedasticity. Furthermore, multiple regression tests can be carried out through: hypothesis testing, coefficient of determination, regression equations. Tests that need to be performed on multiple linear regression include: residual normality, multicollinearity, heteroscedasticity. Furthermore, multiple regression tests can be carried out through: hypothesis testing, coefficient of determination, regression equations. The residual normality test was conducted to check the distribution of the response data, namely the residual stress obtained had a difference or not when compared to the theoretical normal distribution. Multicollinearity test was conducted to check on the independent variables, namely TRR, die angle, and friction coefficient, whether multicollinearity occurred or not. Heteroscedasticity test was conducted to check the independent variables, namely TRR, die angle, and friction coefficient, whether heteroscedasticity occurred or not. Hypothesis testing was conducted to examine the independent variables, namely TRR, die angle, and coefficient of friction has an effect or not, either partially or simultaneously on the residual stress. The coefficient of determination is used to predict how much influence the independent variables, namely TRR, die angle, and friction coefficient have on the residual stress. The regression equation is the result of the regression analysis/test. This regression equation is a predictive function of the residual stress value which is influenced by TRR, die angle, and coefficient of friction.

5. Results of the study of the dominant factors that influence the residual stress

5. 1. Analysis of the stress to get residual stress

The results of stress analysis are residual stresses that occur in ironing products with variations in TRR, die angle, and coefficient of friction as follows:

Residual stress that occurs in the product resulting from the ironing process with a TRR of 20 %, die angle of 25°, coefficient of friction 0.05 based on the simulation results of ANSYS software through explicit dynamics, can be seen in Fig. 4.

Residual stress that occurs in the product resulting from the ironing process with a TRR of 20 %, die angle of 25°, coefficient of friction 0.10 based on the simulation results of ANSYS software through explicit dynamics, can be seen in Fig. 5.

Residual stress that occurs in the product resulting from the ironing process with a TRR of 20 %, die angle of 25°, coefficient of friction 0.15 based on the simulation results of ANSYS software through explicit dynamics, can be seen in Fig. 6.

Data residual stress that occurs at TRR 25 % to 30 %, die angle 25° to 30°, and the coefficient of friction 0.05 to 0.15 as shown in Table 1.

In Table 1 the residual stress that occurs is the result of stress analysis using ANSYS software through an explicit dynamics sub program. The data has three independent variables, namely TRR, die angle, and coefficient of friction, and the results of data analysis are residual stresses.

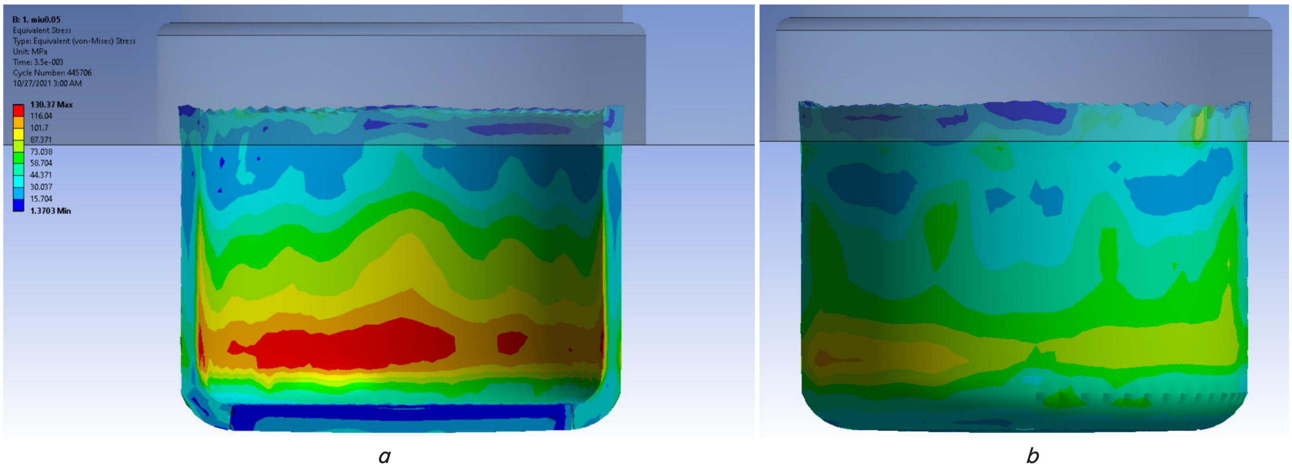
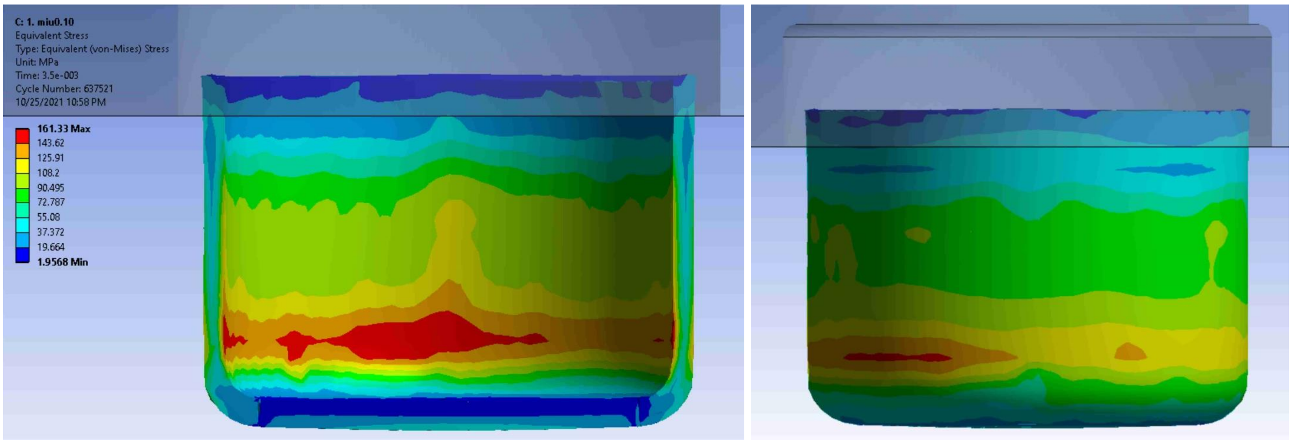
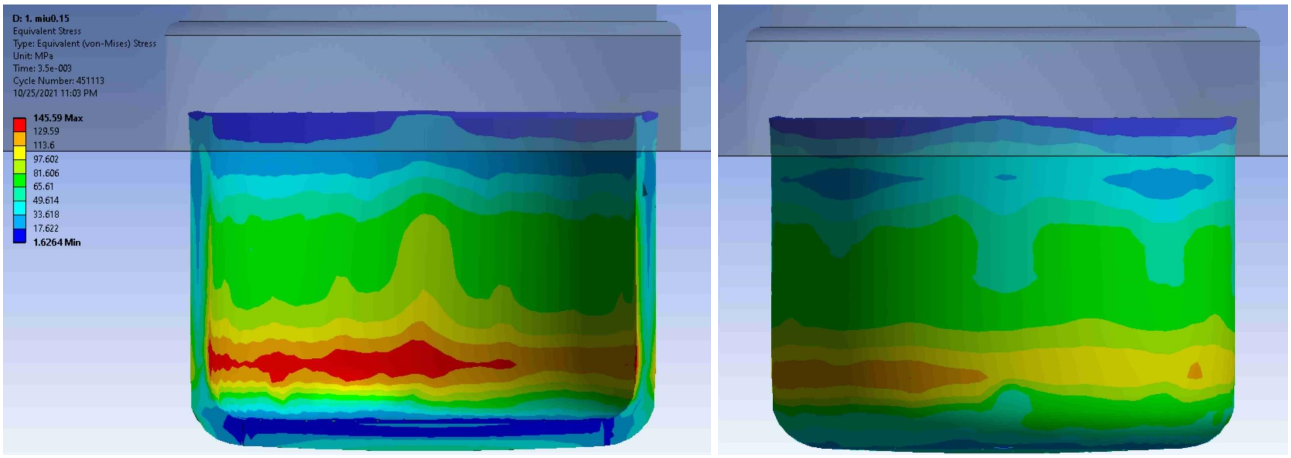


Fig. 4. Residual stress at 20 % thickness reduction ratio, 25° die angle, and 0.05 coefficient of friction: *a* – Inner cup; *b* – Outer cup



a *b*

Fig. 5. Residual stress at 20 % thickness reduction ratio, 25° die angle, and 0.10 coefficient of friction:
a — inner cup; *b* — outer cup



a *b*

Fig. 6. Residual stress at 20 % thickness reduction ratio, 25° die angle, and 0.15 coefficient of friction:
a — Inner cup; *b* — Outer cup

Table 1

Residual stress that occurs in the variation of TRR, die angle, and coefficient of friction (Initial diameter $Do = 37.0$ mm, Wall thickness $t = 2.0$ mm)

TRR (%)	Thickness Reduction (mm)	D_1 (mm)	α (°)	μ	$\sigma_{residual}$ (MPa)
1	2	3	4	5	6
20	0.40	36.2	25	0.05	130.37
20	0.40	36.2	25	0.10	162.33
20	0.40	36.2	25	0.15	145.59
25	0.50	36.0	25	0.05	154.87
25	0.50	36.0	25	0.10	137.28
25	0.50	36.0	25	0.15	136.60
30	0.60	35.8	25	0.05	162.84
30	0.60	35.8	25	0.10	128.94
30	0.60	35.8	25	0.15	127.43
20	0.40	36.2	27.5	0.05	158.84
20	0.40	36.2	27.5	0.10	160.40
20	0.40	36.2	27.5	0.15	146.87
25	0.50	36.0	27.5	0.05	157.08
25	0.50	36.0	27.5	0.10	151.50
25	0.50	36.0	27.5	0.15	139.02
30	0.60	35.8	27.5	0.05	148.66
30	0.60	35.8	27.5	0.10	124.56
30	0.60	35.8	27.5	0.15	119.11
20	0.40	36.2	30	0.05	161.30
20	0.40	36.2	30	0.10	163.33
20	0.40	36.2	30	0.15	154.55
25	0.50	36.0	30	0.05	138.49
25	0.50	36.0	30	0.10	133.49
25	0.50	36.0	30	0.15	121.86
30	0.60	35.8	30	0.05	127.43
30	0.60	35.8	30	0.10	139.78
30	0.60	35.8	30	0.15	121.07

For this reason, the data were then analyzed using the statistical method of regression analysis in order to find out which variables had a significant effect on the residual stresses that occurred. In addition, this statistical method is used to determine the optimum value of each of these influential independent variables in order to produce the lowest residual stress value.

5. 2. Analysis of the variables that affect the residual stress

Determination of the effect of independent variables, or a combination of more than one independent variable, is carried out through analysis using the statistical method of regression analysis on the data resulting from stress analysis in Table 1. It aims to find out which variables have a significant effect and how much influence each variable has. Besides that, it is also used to determine the optimum value of each influential variable to produce the lowest residual stress.

Residual normality test on residual stress data in Table 1, obtained a probability plot as shown in Fig. 7. The normality test criterion is P-Value>0.05, so the distribution of the data, namely the residual stress, is not different from the theoretical normal distribution. If the P-Value<0.05, then the distribution of residual stress data is different from the theoretical normal distribution.

Fig. 7 shows that the P-Value>0.05, so the distribution of residual stress data is the same as the theoretical normal distribution.

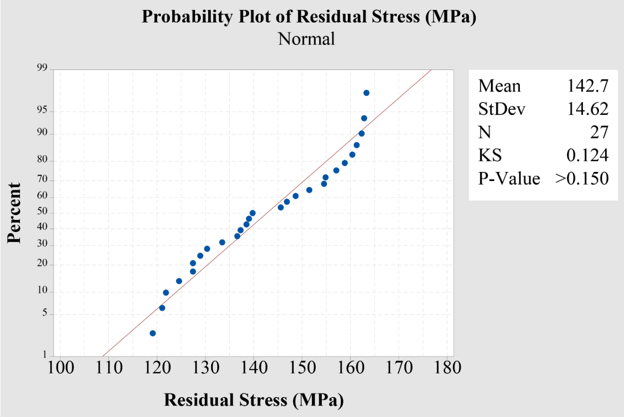


Fig. 7. Probability Plot of Residual Stress (MPa)

The criteria for testing for multicollinearity are VIF-Value>10, then multicollinearity occurs, while at VIF-Value<10, multicollinearity does not occur.

The results of the regression analysis of the data from Table 1 produce the coefficients as shown in Table 2.

In Table 2, it can be seen that the VIF-Value is at TRR=1.00, Die Angle=1.00, and Coefficient of Friction=1.00, which means that multicollinearity does not occur.

Table 2

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	223.2	31.6	7.07	0.000	–
TRR (%)	–2.042	0.514	–3.97	0.001	1.00
Die Angle (°)	–0.55	1.03	–0.54	0.595	1.00
Coefficient of Friction	–142.0	51.4	–2.76	0.011	1.00

Heteroscedasticity testing is done by checking the spread of the points. If the points are spread irregularly, then there is no arousal. The results of the regression analysis of the data from Table 1, obtained as shown in Fig. 8. Fig. 8 shows the distribution of the points that are not irregular, so there is no heteroscedasticity.

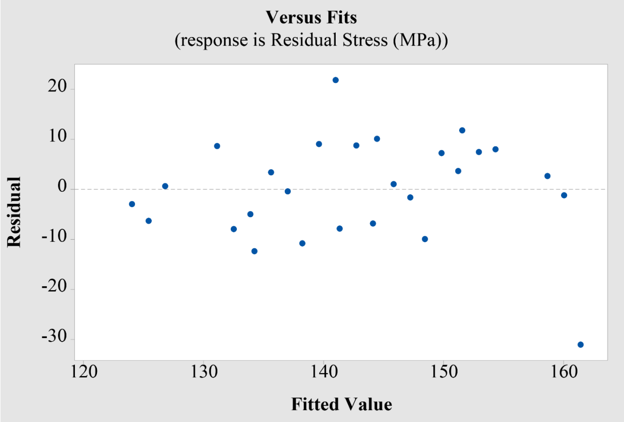


Fig. 8. Versus Fits

Multiple Regression Test is carried out by comparing the P-Value in Table 3. If the P-Value value is <0.05, then there is a partial effect and if the P-Value value is >0.05, then there is no partial effect.

The results of the regression analysis of the data from Table 1 produce the analysis of variance as shown in Table 3.

Table 3

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	5819.7	1939.91	9.74	0.000
TRR (%)	1	2791.3	2791.29	14.01	0.001
Die Angle (°)	1	1.0	0.97	0.00	0.945
Coefficient of Friction	1	3027.5	3027.46	15.20	0.001
Error	23	4580.8	199.17	–	–
Total	26	10400.5	–	–	–

Based on the data in Table 3, the TRR variable has a P-Value of 0.001 or 0.1 %, a friction coefficient of 0.001 or 0.1 %, and a die angel variable of 0.945 or 94.5 %. This indicates that TRR and coefficient of friction are variables that have a dominant influence on the residual stress that arises, while die angel has no significant effect.

Furthermore, to get the value of the independent variable that influences the residual stress value, it can be done by looking at the relationship between these variables through a contour plot. Fig. 9 to 11, show the contour plot of the results of the regression analysis from the data in Table 1.

The regression equation obtained from the results of regression analysis is:

$$\text{Residual Stress (MPa)} = 253.3 - 2.491\,\text{TRR (\%)} - 0.09\,\text{Die Angle } (^\circ) - 259.4\,\text{Coefficient of Friction}.$$

Fig. 9 shows the effect of the TRR variable, the die angle variable, and the combination of the two on the residual stress that occurs. The plot can be seen in dark green to light green. The color of the contour represents the residual stress that occurs. Dark green shows the largest residual stress value and light green shows the smallest residual stress value. The contour plot shows the lowest residual stress between < 135 MPa, occurring at a TRR of 30 % with a die angle of 30°.

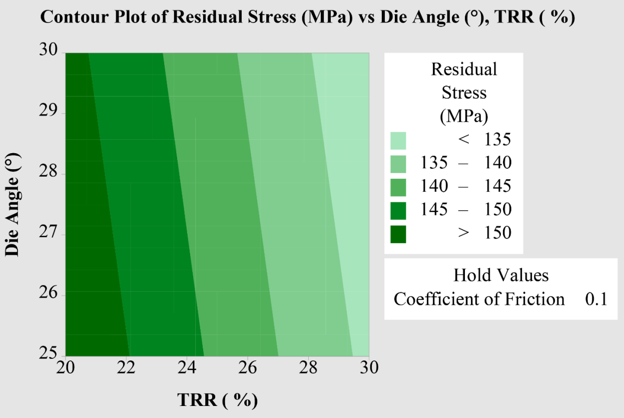


Fig. 9. The contour plot of residual stress vs dies angle (°); TRR (%)

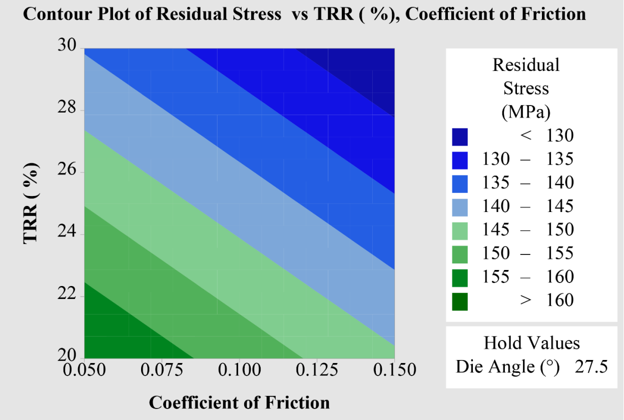


Fig. 10. Contour plot of residual stress vs coefficient of friction; TRR (%)

Fig. 10 shows the effect of the TRR variable, the coefficient of friction variable, and the combination of the two on the residual stress that occurs. The plot can be seen in dark green to light green and light blue to dark blue. The color of the contour represents the residual stress that occurs. Dark green shows the largest residual stress value and dark blue shows the smallest residual stress value. The contour plot shows the lowest residual stress under 130 MPa, occurring at a TRR of 28 % to 30 % with a combination of coefficient of friction 0.125 to 0.15.

Fig. 11 shows the effect of the die angle variable, the coefficient of friction variable, and the combination of the two on the residual stress that occurs. The plot can be seen in dark green to light green and light blue. The color of the contour represents the value of the residual stress that occurs. Dark green shows the largest residual stress value and dark blue shows the smallest residual stress value. The contour plot shows the lowest residual stress between 140 MPa to 150 MPa occurs at a friction coefficient of 0.14 to 0.15. Meanwhile, at a die angle of 25° to 30°, the difference in the amount of residual stress that occurs is almost the same or not significant.

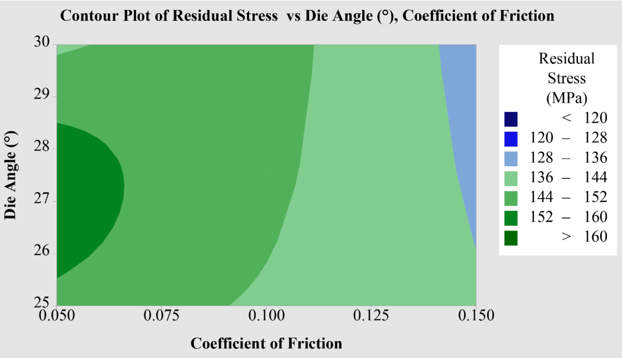


Fig. 11. Contour plot residual stress vs die angle (°); coefficient of friction

5. 3. Interpretation of the value of variables that result in the lowest residual stress

Based on the results of the regression analysis of the residual stress data that occurs, as shown in Table 1 shows that:

– the TRR variable and the coefficient of friction variable μ are very dominant variables affecting the residual stress that occurs, while the die angle variable does not have a significant effect.

– the combination of TRR variable and die angle variable α that can reach the lowest residual stress value 135 MPa, occurs at 30 % TRR with a 30° die angle.

– the combination of the TRR variable and the coefficient of friction variable μ that can reach the lowest residual stress value below 130 MPa, occurs at a TRR of 28 % to 30 % with a combination of coefficient of friction 0.125 to 0.15.

– the combination of the coefficient of friction variable and die angle variable α that can reach the lowest residual stress value between 140 MPa to 150 MPa occurs at the coefficient of friction 0.14 to 0.15. Meanwhile, at a die angle of 25° to 30°, the difference in the amount of residual stress that occurs is almost the same or not significant.

6. Discussion of the results of the study of the dominant factors that influence the residual stress

The aims of this study are to find out or investigate which parameters are dominantly influential, among TRR, die angle, and coefficient of friction, on the residual stress that occurs in the ironing process product. The residual stress on the cup resulting from the ironing process is the stress that is locked in the cup material when the external load from the punch force is removed. The investigation was carried out using explicit dynamic simulation modeling on ANSYS with varying TRR values, die angles, and coefficients of friction. The results of the ANSYS simulation are the residual stress values in the cup resulting from the ironing process, as shown in Fig. 4–6. The overall results are shown in Table 1. The location of the largest residual is on the inner side of the lower wall near the base of the cup. At this location, when the punch force is removed, there is a locked internal stress. The magnitude of this stress is in the axial direction, the higher towards the lip of the cup the smaller the stress value is, the closer to zero. However, on the lip of the cup there is a difference in the diameter of the cup, so that the outer diameter of the lip of the cup is larger than the diameter of the bottom. In order to get which variables, have a significant effect on the residuals, an analysis is carried out using multiple regression tests. The results of the analysis of the residual stress data obtained the P-Value value as shown in Table 3. Based on the result in Table 3, the TRR variable has a P-Value of 0.001 or 0.1 %, a friction coefficient of 0.001 or 0.1 %, and die angel variable of 0.945 or 94.5 %. This indicates that TRR and coefficient of friction are variables that have a dominant influence on the residual stress that arises, while die angel has no significant effect.

Based on the research objective is to find out/investigate which parameter dominantly affects the residual stress that occurs, then in the process of ironing a cup, it is expected that the residual stress that occurs in the cup product is very small. Thus, the benefit of the results of this study is that it can be used as a consideration in designing the press tool in the ironing process, especially in the design of die dimensions.

The limitation of this research which is the weakness of this research is that the investigation is only carried out using the ANSYS software simulation. The limits of the TRR values used are 20 %, 25 %, and 30 %, the die angles used are 25°, 27.5°, and 30°, and the coefficients of friction used are 0.05, 0.10, and 0.15.

For this reason, this research can be followed up and developed in further research with wider values of TRR and die angle variables or by including other variables that may affect the residual stress value. In addition, it is also necessary to verify or justify using residual stress measurements through experiments or the like.

7. Conclusion

1. The results of the stress analysis are residual stresses that occur in the ironed cup. The amount of residual stress that occurs is influenced by parameters on the die, namely TRR, die angle, and coefficient of friction. The residual stress is distributed along the cup wall. Axially maximum residual voltage is located near the base of the cup and drops along the walls, to near zero at the lip of the cup.

2. The results of the analysis of the data obtained, show that the TRR parameter and the coefficient of friction have a p-value of 0.001, while the die angle has a p-value of 0.945. This shows that the TRR parameter and the coefficient of friction have a dominant influence on the magnitude of the residual stress that occurs, while the effect of the die angle is not significant.

3. Based on the simulation results using ANSYS with a TRR value of 25 % to 30 %, a die angle of 25° to 30°, and a friction coefficient of 0.05 to 0.15, the lowest residual stress occurs at 30 % TRR and a coefficient of friction of 0.15.

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