Abstract

Tube Spinning is a near net metal forming process, used extensively in aerospace, automotive and defense industries. Parts produced using this process exhibit excellent strength and dimensional accuracy. With Maraging Steel 300 as material, Design of experiment (DOE) approach with the help of Taguchi method has been applied to study the influence of roller nose radius, roller relief angle, feed ratio and coolant concentration on surface roughness and circularity of the work piece. It has been concluded that roller geometry plays a vital role in controlling circularity and surface roughness of the finished product.

Keywords: *Flow Forming, Surface Roughness, Maraging Steel, Design of Experiments, Taguchi, Tube Spinning, ANOVA*

Contents

List of Figures

LIST OF TABLES:

CHAPTER 1: INTRODUCTION

1.1 Background

1.1.1 Flow Forming- An Introduction:

The Tube Spinning process, also known as Flow Forming process is a metal forming process which generates tubular products. It is done by deforming the blank over a revolving mandrel with the assistance of rollers, which displaces the metal axially over the mandrel, increasing the length at the expense of wall thickness while keeping the internal diameter constant. Modern CNC Flow Forming machines use two, three or six roller configurations depending on the initial internal diameter and percentage thickness reduction required to achieve the final product. The starting form of the blank can be pipe, sheet or a cup. Blanks are usually made by forging, drawing or spinning which are further machined to enhance the quality of the product. Flow Forming was introduced mainly in 1950's for commercial use. Most of the work since then have been reported by German and Japanese researchers. It finds a vast application in automotive, oil & gas, aerospace and defense industries.

Importance of Flow Forming or Tube Spinning is growing rapidly because:

- Components manufactured by flow forming have excellent dimensional accuracy and tolerance control.
- Wall thickness across the length of the product is very well controlled which helps into optimization of the overall process.
- Group of materials that can be flow formed is vast i.e., Steel and its alloys, aluminum alloys, Niobium, Hard-to-deform metals like Titanium alloys etc.
- Components have improved mechanical properties due to strain hardening effect because of cold working.
- In comparison to other metal forming process, components manufactured by Flow forming have good surface finish.
- Components after flow forming usually don't need any kind of machining or other surface operation.
- Material wastage is minimum as products are usually near net shaped, in comparison to forging, metal forming or machining processes.
- Due to hardening effect, heat treatments can also be skipped.

1.1.2 Process Details:

In tube spinning, as depicted by Figure 1, a finished blank is loaded onto a mandrel which gives it rotation. The blank is made to approach towards three or more rollers in axial direction. As contact is made between the two, the material deforms and stretches along the length of the mandrel, reducing thickness and increasing length of the work piece. According to research conducting by Gur et al (1982), the yielding of metal below the contact zone is composed of axial and circumferential components. If span of the circumferential contact is greater than the axial interaction between roller and the material by some factor, then the metal flow is axially dominated. In this case, the plastic deformation would be close to plane strain extrusion, giving an acceptable product. On contrary, if the axial contact span is greater than circumferential interaction between roller and material, then flow is largely in circumferential direction and bulging and waviness in the product is produced. Large thickness reduction of greater than 60% can be achieved in multiple passes. Reduction ratio is defined as

$$R_o = \frac{t_0 - t}{t_0} \qquad (1)$$

$$R_o = ln\frac{t_0}{t} \qquad (2)$$

Where $t_0$is the starting thickness of the preform and t is the concluding thickness of the preform

As per Kalpakcioglu (1961), reduction ratio gives us a crude way to analyze tube spinnablity of a material.

In table 1, terminologies and their definitions commonly used in industries and by researchers are summarized.

Table . I: Terminologies involved in Flow Forming

S.No.	Term	Definition
a)	**Conventional Spinning**	A metal forming process in which an axisymmetric product is formed from blank by keeping thickness constant and reducing diameter over the length of the die.
b)	**Shear Spinning**	A metal forming process in which an axisymmetric product is formed from a blank where its thickness and diameter are both changed to obtain desired final product.

c)	**Tube Spinning/ Flow Forming**	A forming process which produces axisymmetric metal products by reducing its thickness and increasing the length while internal diameter of the blank is kept constant generally.
d)	**Roller**	The tool which exerts force which results into yielding of the material hence metal forming.
e)	**Preform**	It's the initial work piece having dimensions and contour that is required in the final product. Preform is yielded into required product after spinning.
f)	**Starting Thickness** t_0	Thickness of the preform before tube spinning process.
g)	**Final Thickness** t	Thickness of the final required product.
h)	**Mandrel**	A die which is supported by chuck/spindle of the machine, having same contours as that required of the final product. Preform is deformed by the rollers over it.
i)	**Feed Rate**	Axial speed with which preform is deformed by the rollers. (Measured in mm/s)
j)	**Mandrel Speed**	Rotational speed with which preform is rotated for spinning purpose. (Measured in rev/s)
k)	**Feed Ratio**	Linear motion of roller relative to the mandrel for every revolution of it. (Measured in mm/rev)
l)	**Tangential, Circumferential & Axial Force**	Three components of force in polar co-ordinates. In flow forming, polar co-ordinates of forces are used to measure force exerted by the roller to deform the material over the mandrel.
m)	**Roller Nose Radius**	Radius on the roller which interacts with the material to exert force. It is found on the junction of two plane surfaces on the external region.
n)	**Roller Attack Angle**	The angle on the inclined roller surface and the mandrel. It is in front of the nose radius while metal deforming.
o)	**Roller Relief Angle**	The angle on the inclined roller surface and the mandrel, present on the backside of the nose radius.
p)	**Thickness Reduction**	Change in thickness after spinning (Measured in mm)

q)	**Axial Stagger**	The axial distance between the nose radius of the rollers (usually found in Multi roller Flow forming machines)
r)	**Radial Spacing**	Distance between roller nose radius and the mandrel.

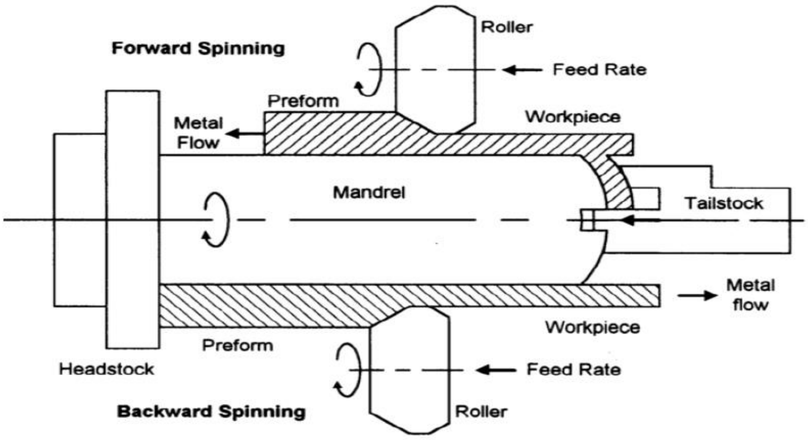

Figure 1: Variants of flow forming

As volume of the blank remains constant, length of the final product can be approximated by equating the volume before and after by using following equation

$$L_1 = L_0 \frac{S_0(d_i + S_0)}{S_1(d_i + S_i)} \qquad (3)$$

1.1.3 Methods of flow forming:

There are two methods by which tube spinning can be done, namely backward flow forming and forward flow forming. Based on the path of metal flow, the method is categorized into two categories.

a) Forward Flow Forming:

In this method, axial path of the material flow is identical to that of moving rollers. Mandrel along with the tail stock is used to clamp the material. Materials having a flange, cup or any closed configuration are usually flow formed with this method. Important thing about this method is that material of the blank that has not been formed moves ahead of the roller. Owing to superior dimensional quality produced by this method, it is extensively used in defense industry for the production of rocket motor casing, high pressure vessels and hydraulic cylinders. Productivity of forward flow forming is however lower than the backward flow forming as the rollers have to move over total elongated part of the tube.

b) Backward Flow Forming:

Blanks having both open ends are usually backward flow formed. In this method, blank is loaded on the mandrel and is coupled with the headstock with the help of a toothed part, that couples headstock and the blank. In this method, material flows under the rollers in the reverse path to clamped part of preform and towards the open end of the mandrel. Usually, backward flow forming is used in mass production and where ductility of the material is low. A common problem with backward flow forming is bell mouthing and distortion at the unsupported end.

Forwards flow forming is used whenever high precision is required while backward flow forming is preferred where productivity is the priority.

1.1.4 Maraging Steel:

Maraging steel is a high alloy steel, famous for its high strength. They have ability to give tensile strength as high as 2000 MPa when hardened. It's primary alloying constituents are Nickel (18%), Cobalt (7%) and traces of other valuable elements such as titanium. Whereas carbon concentration is less than 0.05% in it. A key benefit of Maraging steels is that it has excellent formability and machinability before hardening. Also, hardening treatment is at a relatively low temperature when distortion of machined parts is negligible. One of the disadvantage of this material is its high cost. Although it makes it up to it by delivering high strength and low machining costs.

Table 1: Chemical Composition of Maraging Steel 300 (Aircraft Materials, 2019)

Element	**C**	**Si**	**Mn**	**P**	**Ni**	**Mo**	**Co**	**Sulfur**
% Comp	0.03 max	0.10 max	0.10 max	0.010 max	18.0-19.0	4.6-5.2	8.0	0.010 max

1.2 Research Goal and Objectives:

The purpose of this report is to examine the impact of feed ratio, roller relief angle and coolant concentration on the average surface roughness and Ovality of the final product. The specific objectives set for this research report is as follows:

- To review critically the published literature with regards flow forming of Maraging steel 300 particularly influence of process factors on surface properties.

- To summarize the established facts and identifying the knowledge gaps with respect to flow forming of Maraging steel 300 based on literature review.
- To examine the influence of combination of altered process parameters and conditions that can affect flow forming of Maraging Steel 300 in terms of work piece surface roughness and ovality by using Taguchi Approach.
- To examine the dominance of key flow forming variables on average surface roughness and ovality in flow forming of Maraging steel 300.

CHAPTER 2: LITERATURE REVIEW

First work on tube spinning is reported by Hayama et al (1979). In his work, the mechanism of deformation was discussed using experimental technique. Double roller configuration was setup on a lathe machine which held mandrel in its chuck and rollers in tool holders. Mild steel was used for these experiments. Volume of material that is built up in front of the roller, maximum reduction of the roller and elongation of the material under the roller was investigated, and an analytical model was presented to understand the complex concept of metal flow under the roller. Forces applied on the roller were calculated by measuring deflection of the shank of roller, in terms of Axial, Tangential and Radial Force. Some of the key observations made are:

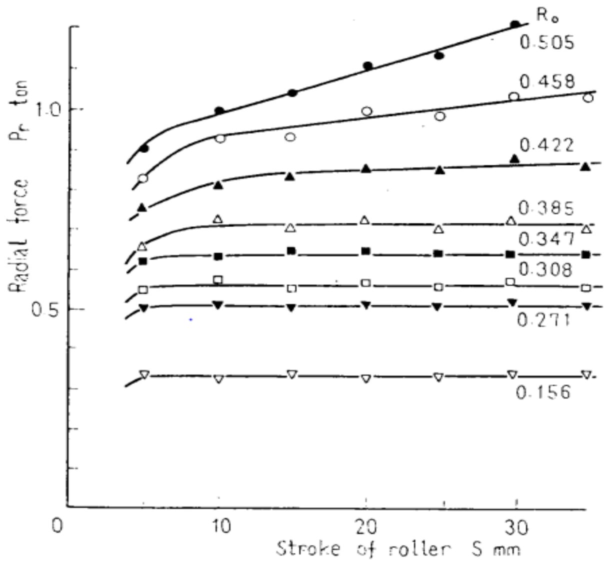

Figure 2: Association between radial force Pr and stroke of the roller with variable wall thickness reduction

Gur et al. (1982) came forward with analytical analysis using Upper Bound theorem to understand the stability in the flow forming process. According to their studies, if the circumferential span of contact between roller and work piece is larger than axial length of contact, then material will tend to move in axial path. In this situation, circularity of the tube would be better. On contrary, if the circumferential span is lower than the axial span than the tube would tend to flow in circumferential direction and will cause instability. According to their study, instability can be evaded by a larger reduction ratio, decreasing the axial feed and lowering angle of attack of the roller.

R.P. Singhal (1987) conducted a study on different materials to relate flow forming properties with the mechanical features of the spun parts. He concluded that tensile strength of the formed parts increased up to 75% wall thickness reduction. Around 80%, it was observed to decrease. It was because of generation of micro cracks in the material. Lubrication played an important role in decreasing the friction between work piece and material. However, the type of lubrication is not very vital. He concluded that on given materials, thickness reduction up to 70% can be obtained by annealing the material beforehand and reducing them in passes.

Song Zong-hua et al (1992) developed an electronic system, detecting defects during the flow forming process using forming forces against time. In their studies, they were successful in finding defects like micro cracks, material breakage, wavy surface, thinning of the work piece during the flow and unequal force distribution on forming rollers.

Xue Kemin et al (1997) studied the process parameter in staggered flow forming process and concluded that radial spacing, speed and geometry of the roller have the highest influence on the dimensional accuracy. In the study, diametric growth decreases with increase in wall thickness reduction, increase in feed rate. Thickness variation along the length increased with increase in thickness reduction and remain unchanged when feed rate was increased. The study concluded that spring back shows a vital role in geometric accurateness of the spun part. In another study, the researchers used ADINA FEM program to simulate the stagger flow forming process. In this study, they highlighted problems faced during simulation and their disposal. The results were then checked using experimental setup.

Nawi et al (1998) conducted a theoretical study on the hydrodynamic lubrication during tube spinning process. As discussed by the researchers, thickness of the lubrication film was analyzed at different zones. It was shown that high lubrication film was obtained under certain condition. Angle of attack of the roller, mandrel rotation and feed ratio influence the thickness of the film formed. Larger the attack angle, smaller is the thickness of the lubrication film. Increasing federate and rpm increases the thickness of the lubrication film.

Jahazi et al. (2000) inspected the effect of tube spinning factors on the dimensional accuracy of the finished part. Microstructure studies were carried out to find consequence of heat treatment to get finest blend of strength and toughness. In the study, as feed rate is decreased, the diameter of the work piece started increasing. On contrary, when high feed rate was employed, thickness variation in the spun parts were observed. They concluded that plastic flow under the roller is influenced by the attack angle of the roller and penetration of roller in the work piece i.e. percentage reduction. This phenomenon was related with S/L ratio during flow forming, when attack angle is increased, the S/L ratio will increase and metal will incline to move in the axial direction. If the S/L ratio becomes too large, the material will flow in wavy structure and thickness variation in the spun part will increase. In the end, it was concluded that by controlling the heat treatment parameters, desired values of strength and toughness can be achieved.

S.I. Hong et al (1998) studied the neck in process of thin walled tube using flow forming process. Experimental and finite element method was applied to get the desired shape and dimension of the product. The study concluded that neck in process is difficult to manage in backward flow forming process, as this variant has less dimensional accuracy. Neck in process can be achieved using forward flow forming process. Neck in process is critical as the thickness is small which can fracture at the tapered region of the mandrel.

X. Song et al (2014) studied the increase in the diameter and residual stresses generated after forward flow forming process. Finite Element results were validated using experiments. The study suggested that using rigid plastic material model for FEM simulations yields inaccurate results as it suppresses the elastic strain, which is responsible for spring back in the material. In comparison, elasto-plastic model yields better results as phenomena of diametric growth and spring back is covered by residual elastic strain. Simulation for diametric growth was done without using strain rate dependent model. As the simulation results of diametric growth very quiet accurate by comparing them with experimental results, it was concluded in the study that diametric growth is dependent of strain. Diametric growth in SS 304L and AA 6061 increased with increase in feed rate. The result of friction on the diametric increment was also studied and it was concluded that as friction between work piece and mandrel reaches zero, diametric growth because minimum. As a conclusion, the effect of lubrication is not negligible on diametric growth, as suggested by earlier work. In the end, researchers proposed an empirical model to understand diametric growth during the process.

Qinxiang et al. (2014) proposed multi-pass staggered flow forming to be the best suited method to produce long tubes with nano grain structure. In their study, work was also done on the heat treatment of such tubes to find out best suited combination to obtain a tube having high strength and a fine grain structure.

Vriens BC et al (2014) studied the process of splined mandrel flow forming to examine the consequence of roller stagger and geometry on the service life of the mandrel. Due to the presence of splines in SPFF, the mandrel is prone to fatigue failure. Researchers found that most critical factor that effects forming force on the roller is the stagger between the rollers. An optimum condition involving inlet angle, inter roller distance was calculated using Taguchi technique and was validated by comparing number of tubes produced before mandrel failure.

Razani et al (2014) investigated the outcome of tube spinning parameters on the hardness of the tube after the process. SS 321 was selected for experimentation. Mandrel rotation speed, feed of the rollers and thickness reduction was selected as critical parameters to analyze the effect. An optimum condition was obtained in which hardness was found to be maximum i.e. 153 HRB. Researchers concluded that hardness of the flow formed part increases with increase in rpm of mandrel and percentage thickness reduction.

L.Y. Sun et al (2014) worked extensively on Laser assisted flow forming process in which a beam of laser light is used in conjunction with conventional flow forming process. According to researchers, laser beam can assist hard to deform material to undergo flow forming. Formability of the laser effected region increases directly with increase in laser power and decreasing the beam spot radius. A comparison was done in which tube was heated entirely and deviation in the internal diameter was calculate. Same experiment was conducted using laser assisted heating and result showed that geometric accuracy increased by using Laser assisted flow forming.

Zhen Cao et al. (2015) used hot tube spinning process to study properties of tube spinning parameters on AZ80 magnesium alloy. Mechanical attributes and microstructure of the final product were analyzed. An optimized value of temperature range, spindle speed and feed ratio was obtained by the researchers. It was concluded that spindle speed has vital role in dictating formability and mechanical properties of the final part. Feed ratio also plays an important role in mechanical properties but its role on microstructure is minimal. It was also observed that the grain structure is different than that obtained by rolling or extrusion.

D.Tsivoulas et al. (2015) investigated the effect of residual stress on Cr-Mo-V steel tubes with the help of XRD and neutron diffraction technique.. Researchers concluded that residual stress has direct relation with these parameters i.e. low hardness, low percentage thickness reduction, low contact angle of the roller generate lower level of residual stress.

S.Ekinovic et al. (2015) used design of experiment approach to study the surface topography of aluminum products obtained by flow forming process. Feed, percentage thickness reduction and spindle speed were varied to find an optimum value of surface waviness of the tube.

D. Woźniak et al. (2016) used FEM to compare the results of deep drawing and flow forming using Hastelloy C-276 alloy. Results of numerical simulation was then compared with experimental results and was concluded to be in conformity.

Bylya (2017) investigated important elasto plastic material properties which play an significant part in defining the flow formability of a material. In his study, he showed how complex deformations and stress state is during flow forming. This complexity makes it difficult to understand using generalized tests and their data. According to him, resilience, tensile area reduction and strain hardening are important parameters that are obtained from uni-axial tensile testing.

Rajan et al. (2001) highlighted some key defects that are experienced in flow forming technology by experimenting on SAE 4130 material. Few defects that he highlighted in research are fish scaling, diametric growth (ovality), micro and macro cracks and bursting of tube. He concluded that machine, process and material parameters play important in determining type of defect during tube spinning.

Nahrekhalaji et al. (2010) investigating the impact of different control variables on thickness variation and process timing of flow forming of Aluminum alloy 2024 using Design of Experiments (DOE). Five input factors selected for alteration were initial thickness of preform, time of aging, mandrel rpm, thickness reduction % and feed rate, having two levels. It was decided that low starting thickness, low thickness reduction percentage, low mandrel speed and high feed rate yields low thickness variation results.

Srinivasulu et al. (2012) examined the effect of flow forming parameters on ovality of AA6082 alloy. Feed rate, thickness reduction percentage and roller radius were selected as input parameter and ovality as response. In another study conducted with DOE approach, the author used ANOVA, regression statistics and RSM to find contribution of input factors on mean dimeter of flow formed part.

Wang et al. (2012) studied the impact of process parameter during shear spinning using Design of Experiment approach. A tool compensation method was also proposed to improve the tool path during shear spinning. Impact of material and feed ratio was analyzed on dimensional accuracy of the product.

Table 2 summarizes research on flow forming using Design of Experiment Approach along with techniques used to analyze results, number of factors and orthogonal array.

Table 2: List of research papers with DoE approach in the field of Flow Forming

S.No.		(Davidson et al. ,2008)	(Nahrekhalaji et al. , 2010)	(Srinivasulu et al.,2012)	(Aghchai et al. 2012)	(L. Wang et al,2013)
a)	DoE Methodology	Taguchi (L9)	Fractional Factorial	Box-Benknen Design	Taguchi (L4)	Box-Benknen Design
b)	Factors	Radial Spacing, Mandrel RPM, Roller Feed rate	Percentage Reduction, Mandrel RPM, Roller Feed rate, solution time and aging, Nose radius	Nose Radius, Mandrel RPM, Roller Feed rate	Material, Mandrel RPM, Roller Feed rate	Percentage Reduction, Mandrel RPM, Roller Feed rate
c)	Levels	Three	Two	Two	Two	Three
d)	Selected Output	Reduction Ratio	External Diameter	Internal Diameter	Internal Diameter, Thickness	Ovality
e)	Analysis	ANOVA	ANOVA, Regression method	ANOVA, Regression method, RSM	ANOVA	ANOVA, RSM

Although DoE approach has been used to find relationship of different process or machine parameters on dimensional or surface properties, many factors are still not accounted for. In this research, two of such factors, namely Coolant Concentration and Roller Relief Angle are studied along with federate to analyze the impact on surface (Surface Roughness) and dimensional (Ovality) property of formed tube. Similarly, no literature was found regarding flow forming of Maraging Steel 300.

CHAPTER 3: EXPERIMENTATION DETAILS & ANALYSIS PROCEDURE

3.1 Equipment:

3.1.1 Grinding Machine:

As mentioned in Chapter 2, roller relief angle is one of the three geometrical parameters of roller. Material of the roller being used was AISI D2 with the hardness of 63 HRC. In order to prepare different level of roller relief angle, a manual Universal grinding machine (John & Shipman 1300) was used. Angles was measured with the help of templates which were manufactured on high precision CNC machines.

Figure 3: Manual Universal Grinding machine

3.1.2 Flow Forming Machine:

A 5-axis Flow Forming machine having CNC controller (Siemens 840D) was used to perform experiments. Machine has three rollers, which are at 120° to each other.

3.1.3 Coolant Oil:

Solcut Oil by Pakistan State Oil was used as a coolant oil during flow forming process. It is a general purpose oil which is mixed with water to form a milky emulsion. Mixing ratio of Solcut Oil with water was altered to get desired level of Coolant concentration. which was checked using Brix Refractometer, as shown in figure 5. Key features of the oil are mentioned in Table 4.

Table 3: Properties of Solcut Oil (PSOpk,2019)

S.No.	Properties	Values
1.	Kinematic Viscosity @40°C,(cSt)	20.7
2.	Viscosity Index	110
3.	Flash Point, (C0C),°C	92
4.	Emulsion Stability,24-hrs 5% in water	Stable
5.	pH	5.5
6.	Copper Corrosion 3-hrs at 110°C	1a

Figure 4: Siemens 840D Control

Figure 5: Brix Refractometer

3.1.4 Surface Roughness Tester:

Surface roughness of the flow formed part was inspected using Moore & Wright Surfscan 200 surface roughness tester, as show in Figure 6.

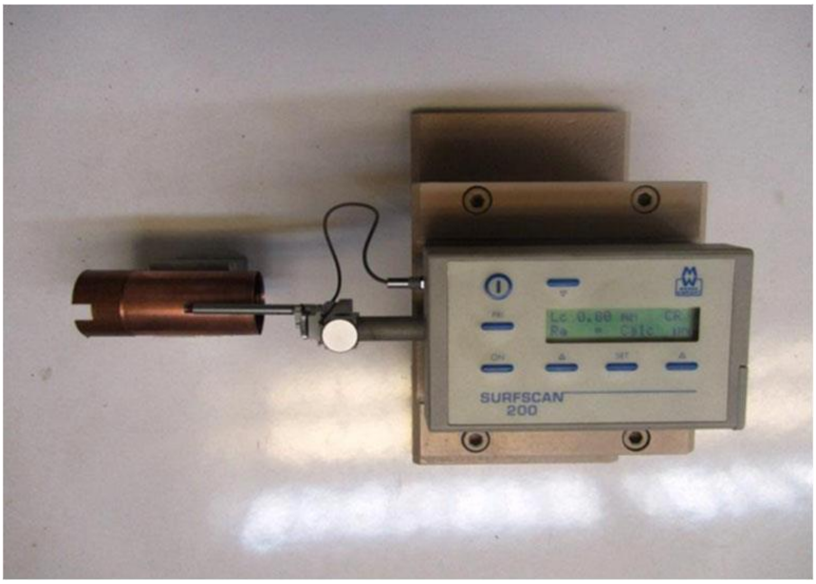

Figure 6: Digital Surface Tester

A cutoff length of 2mm was selected with an evaluation length of 6mm from head stock side of the tube. Complete specification of the tester is mentioned in table 5.

Table 4: Specification of Digital Roughness Tester

S.No.	Specification	Description
1.	Resolution	0.01 µm
2.	Traverse speed	1 mm/s
3.	Cut off values	0.25, 0.8, 2.0 mm
4.	Standard traverse lengths	3 selected cut-off values

3.1.5 Mahr Dial Indicator:

Mahr Dial Indicator, having measuring span of 1mm and graduation value of 0.001mm was used to check circularity of the tube from the middle, as shown in figure 7

Figure 7: Dial Indicator

3.2 Experimental Setup:

3.2.1 Tube Spinning Conditions:

In tube spinning, the roller which is axially staggered at the very back is usually responsible for the surface finish of the tube. So, relief angle of 3rd roller is altered for experimentation purpose as shown in figure 8. Axial Stagger between rollers, Radial distance between roller and the mandrel, Nose radius of the rollers, thickness reduction of the material and coolant flow rate were kept constant during the experimentation.

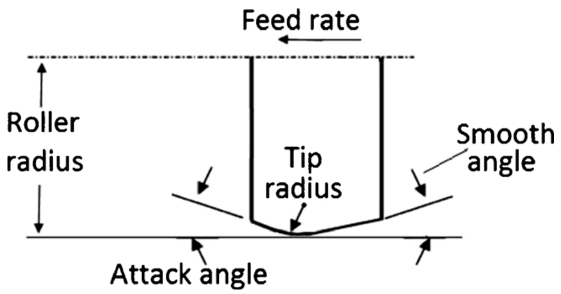

Figure 8: Different features of Roller Geometry

3.2.2 Preform Design:

Preform specification are shown in figure 9.

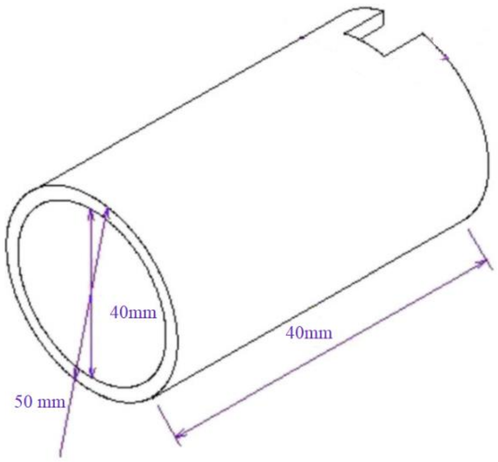

Figure 9: Preform Dimensions in mm

3.2.3 Measurement of Surface Roughness:

Surface roughness is generally the only quantitative measure of the quality of surface texture present. Surface roughness plays a significant role in determining friction and adhesion of particles on the work piece. It is also important for visual aesthetics of the product.

Roughness is measured by different parameters, with Ra being the most commonly used factor. In our experiments, Ra was chosen to be the parameter of roughness indicator.

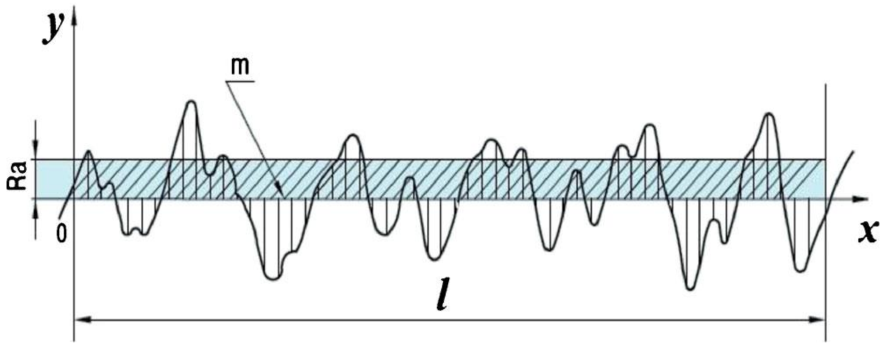

Figure 10: Representation of Ra value as per DIN 4768

The arithmetic mean roughness parameter shows arithmetic mean of absolutes values of all variances in the roughness profile over the given area, as shown by equation 4 (Degarma EP et al.,2008)

$$R_a = \frac{1}{l} \int_0^l |f\ (x)|\ dx \qquad (4)$$

3.3 Design of Experiments and Analysis Procedure:

3.3.1 Taguchi Method, Factors and Levels

Taguchi method was selected to obtain the dominant factors on surface roughness and circularity of the formed part. By using this method, time required to study the individual effects as well as combined effects can be significantly reduced. In this research, three input parameters were chosen i.e. Roller Relief Angle, Feed Ratio, Coolant Concentration. Three levels of each parameter were selected, as shown in Table 6.

Table 5: Input factors and levels

S. No.	Factors	Level 1	Level 2	Level 3
1.	Roller Relief Angle (°)	2.5	2.75	3
2.	Feed Ratio (mm/rev)	0.5	0.667	0.75
3.	Coolant Concentration	1%	3%	5.5%

L9 Orthogonal Array was designated based on input factors and their levels. A total of 9 experiments were conducted in first stage in order to find the best combination of process and machine factors with respect to lowest Ra value and ovality. The taguchi array selected is revealed in table 7.

Table 6: L9 Taguchi OA

Experiment No.	Roller Relief Angle (°)	Feed Ratio (mm/rev)	Coolant Percentage (%)
1.	2.50	0.500	1
2.	2.50	0.667	3
3.	2.50	0.750	5.5
4.	2.75	0.500	5.5
5.	2.75	0.667	1
6.	2.75	0.750	3
7.	3	0.500	3
8.	3	0.667	5.5
9.	3	0.750	1

Outcomes or responses which were to be measured after flow forming each preform were:

1. Surface Roughness of the formed tube (Ra value)
2. Circularity of the tube from the middle (mm)

3.3.2 Analysis Procedure:

To investigate and analyze the experimental results of tube spinning, two analysis techniques were utilized a) S/N (Signal to Noise) Ratio b) Analysis of Variance (ANOVA). On the basis of these two analysis, optimum process and machine parameters were obtained regarding surface roughness and circularity.

a) Signal to Noise (S/N) Ratio

The application of S/N ratio concept is generally used to improve the quality through reducing variability. In Taguchi method, 'signal' means the required value whereas the 'noise' signifies unwanted value. Both of them are obtained for a certain response characteristic. There are three categories of Signal to Noise ratio concept:

S/N ratio - Nominal the best: This type of S/N is used when a specific value is desirable which can be obtained using the formula as under:

$$\frac{S}{N}\text{ratio} = -10\log\frac{\bar{y}}{s_y^2}$$

S/N ratio - Smaller the better: When target is to achieve a minimum value of certain response then this type of S/N ratio becomes useful and is calculated as under

$$\frac{S}{N}\text{ratio} = -10\log 1/n\sum y^2$$

S/N ratio - Larger the better: When aim is to achieve a maximum value of certain response then this category of S/N ratio is utilized which can be calculated using following formula.

$$\frac{S}{N}\text{ratio} = -10\log 1/n\sum 1/y^2$$

In above three equations $\bar{y}$ is the mean of measured data, s_y^2 is the discrepancy of y, n *is* the total number of measurements and y is the response data. Disregarding the type of the S/N ratio concept, a large S/N ratio represents better quality features. Therefore, the ideal level of the process inputs is the level with the highest S/N ratio. Since objective of this research work was to lessen both surface roughness and ovality, so S/N ratio smaller the better mentioned above was suitable for this target.

b) Analysis of Variance (ANOVA)

The optimization of performance was achieved using analysis of variance (ANOVA) technique. It is helpful to perform a arithmetical analysis to see which process inputs are statistically important. This was accomplished by measuring Summation of square, Average of squares and F-ratio. The biggest value of variance (F-ratio) gave the most influential process parameter on surface roughness. This investigation was performed at five percent significance level and a ninety five percent confidence level. The importance of control factors in ANOVA was obtained by relating the F values of each input parameter. The sum of squared deviations (SS) total sum of squared deviations (SS_T) and percentage contributions were calculated by using the following equations (W.H.Yang, 1998) :

$$SS = \sum_{j=1}^{2} (\eta_{ij} - \eta)^2$$

$$SS_T = \sum_{i=1}^{n} (\eta_i - \eta)^2$$

$$Contribution\ (\%) = \frac{sum\ of\ squared\ deviations\ (SS)}{total\ sum\ of\ squared\ deviations\ (SS_T)} * 100$$

In above three equations η_{ij} is average S/N ratio of ith parameter of jth level, η is the overall mean S/N ratio and is the S/N ratio for ith parameter. Calculations of these equations for both of the above mentioned analysis were done on Microsoft Excel. Furthermore, Minitab 17 ® was used to verify the analysis performed by Microsoft Excel calculations.

3.3.3 Step by Step Experimental Procedure:

- Three different roller having desired relief angle were grinded and measured using templates.
- After mounting the specific roller on the machine, A CNC program having desired process parameters were written. Feed ratio was altered as desired in this step.
- Before flow forming, QC of the preform was done, as dimensional accuracy of the product is heavily reliant on on the preform quality.
- Coolant mixture from the emulsion tank was constantly checked using refractometer. According to the requirement of the experiment, the coolant ratio was altered by mixing desired water or coolant oil in the tank.
- After the flow forming, product was cleaned inside and outside using Acetone.
- Moore & Wright Surfscan 200 surface roughness tester was applied to measure the Ra values. Three measurements were taken for each machining trial in order to minimize any measurement error occurred.

- The final product was then checked for circularity by supporting the tube from both ends with the help of bearings. Mahr Dial indicator was setup in the middle of the tube. Tube was rotated slowly and reading on the dial indicator was noted for one complete rotation.
- After predicting the optimum cutting conditions using Taguchi method in respect of surface roughness and tool wear, further experiments were performed to verify/confirm these predicted optimum results.

CHAPTER 4: RESULTS AND DISCUSSION

5.1 Results and Analysis of Surface Roughness

The results of average Ra values for each experiment with respect to the input variables is summarized in Table 8.

Table 7: Results of Surface Roughness with respect to experiments

Experiment No.	Inputs			Response
	Roller Relief Angle (°)	Feed Ratio (mm/rev)	Coolant Percentage (%)	Average Surface Roughness Ra (μm)
1.	2.50	0.500	1	0.58
2.	2.50	0.667	3	0.65
3.	2.50	0.750	5.5	0.79
4.	2.75	0.500	5.5	0.44
5.	2.75	0.667	1	0.55
6.	2.75	0.750	3	0.80
7.	3	0.500	3	0.69
8.	3	0.667	5.5	0.74
9.	3	0.750	1	1.10

4.1.1 Signal to Noise ratio (S/N) for Surface Roughness

Irrespective of Signal/Noise ratio category, statistically it is known that the larger is the ratio, the lesser is the alteration of surface roughness around the wanted value. Since lowest surface roughness is the most desirable value therefore "Smallest-the-better" equation was selected while calculating S/N ratio for surface roughness.

Table 8: Response Table of S/N ratio for Surface Roughness

Experiment No.	Inputs			Response	
	Roller Relief Angle (°)	Feed Ratio (mm/rev)	Coolant Percentage (%)	Average Surface Roughness Ra (μm)	S/N Ratio
1.	2.50	0.500	1	0.58	4.73144
2.	2.50	0.667	3	0.65	3.74173
3.	2.50	0.750	5.5	0.79	2.04746
4.	2.75	0.500	5.5	0.44	7.13095
5.	2.75	0.667	1	0.55	5.19275
6.	2.75	0.750	3	0.80	1.93820
7.	3	0.500	3	0.69	3.22302
8.	3	0.667	5.5	0.74	2.61537
9.	3	0.750	1	1.10	-0.827854

Table 10 demonstrates the response table for signal to noise ratio whereas Table 11 displays response table for means.

Table 9: Response Table for Signal to Noise Ratios (Surface Roughness)

Level	Roller Relief Angle	Feed Ratio	Coolant Percentage
1	3.507	**5.028**	3.032
2	**4.754**	3.850	2.968
3	1.670	1.053	**3.931**
Delta	3.084	3.976	0.964
Rank	2	1	3

Table 10: Response table for means of surface roughness

Level	Roller Relief Angle	Feed Ratio	Coolant Percentage
1	0.6733	**0.5700**	0.7433
2	**0.5967**	0.6467	0.7133
3	0.8433	0.8967	**0.6567**
Delta	0.2467	0.3267	0.0867
Rank	2	1	3

Table 8 and Table 9 show that surface roughness is minimum when Roller relief angle is at level 2 (2.7°), Feed is at level 1 (0.50 mm/rev) and Coolant Percentage is at level 3 (5.5%). This demonstrates that low feed rate and high concentration of coolant oil produces minimum surface roughness on the product whereas roller relief angle has minimum and maximum critical value in which it produces optimum results. The graphical representation of main effects plot for means and S/N ratio for surface roughness are shown in Figure 11 and Figure 12 respectively which were obtained by Minitab 17 Statistical Software.

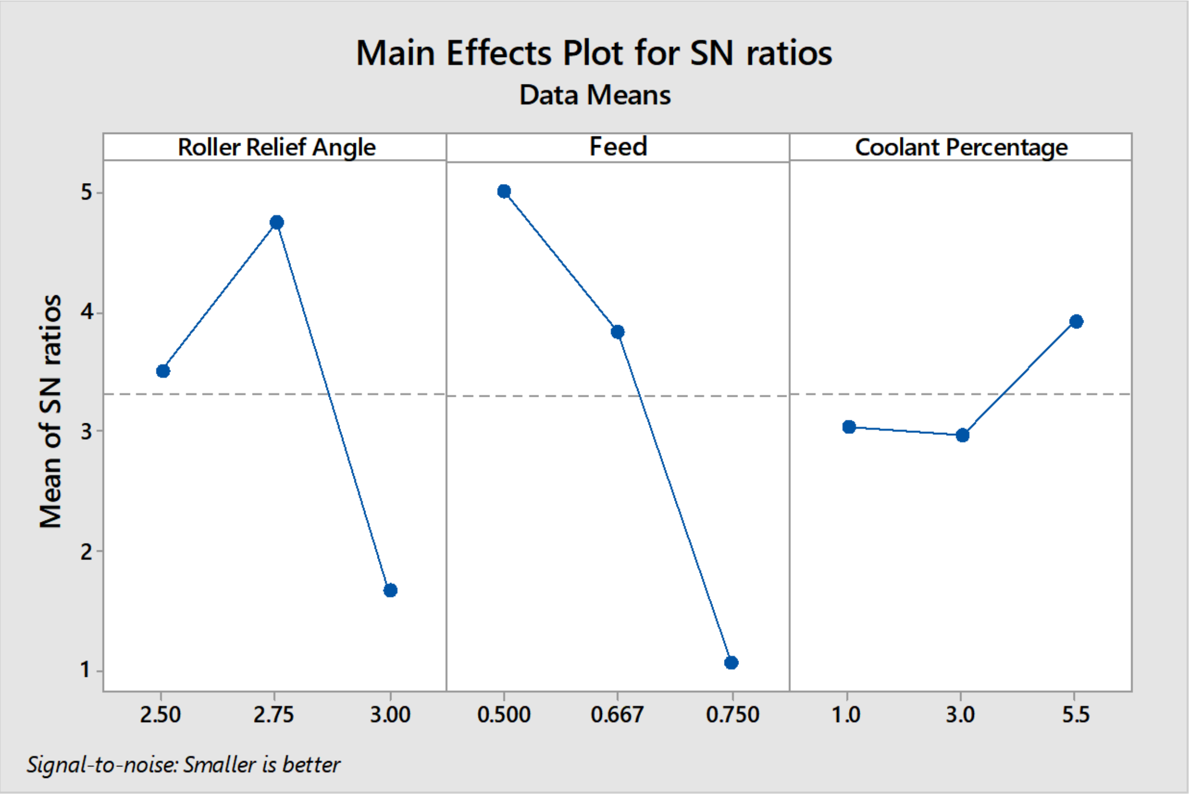

Figure 11: Main Effects Plots for Signal to Noise Ratio for Surface Roughness

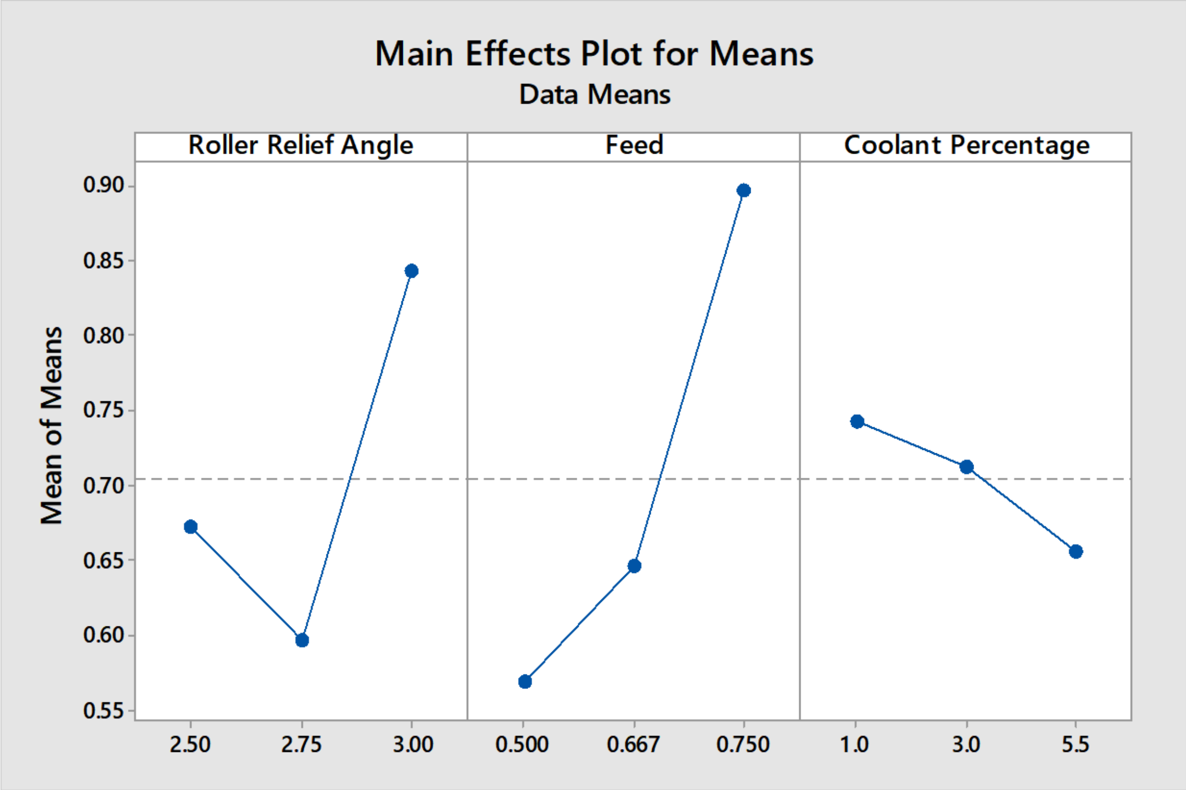

Figure 12: Main Effects Plots for Means for Surface Roughness

4.1.2 Analysis of Variance (ANOVA) for Surface Roughness

On the basis of flow forming results with regards to surface roughness Analysis of Variance (ANOVA) was completed in order to conduct the numerical analysis of factor dominance to understand the implication of each input factors on surface roughness. In this analysis, the comparative significance between the three input variables on the surface roughness will be calculated. F-ratio matching to 95% confidence level in assessment of input factors was considered to be significant. Table 12 shows the contribution percentage, F-Value and P-value of process parameters on Ra value whereas Figure 13 is graphical representation of contribution of input factors on surface roughness.

Table 11: Analysis of Variance for Transformed Response

Source	Degree of Freedom	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Roller Relief Angle	2	0.191378	**34.84%**	0.191378	0.095689	**60.71**	**0.016**
Feed Ratio	2	0.331655	**60.38%**	0.331655	0.165827	**105.20**	**0.009**
Coolant Percentage	2	0.023079	**4.20%**	0.023079	0.011539	**7.32**	**0.120**
Error	2	0.003153	0.57%	0.003153	0.001576		
Total	8	0.549264	100.00%				

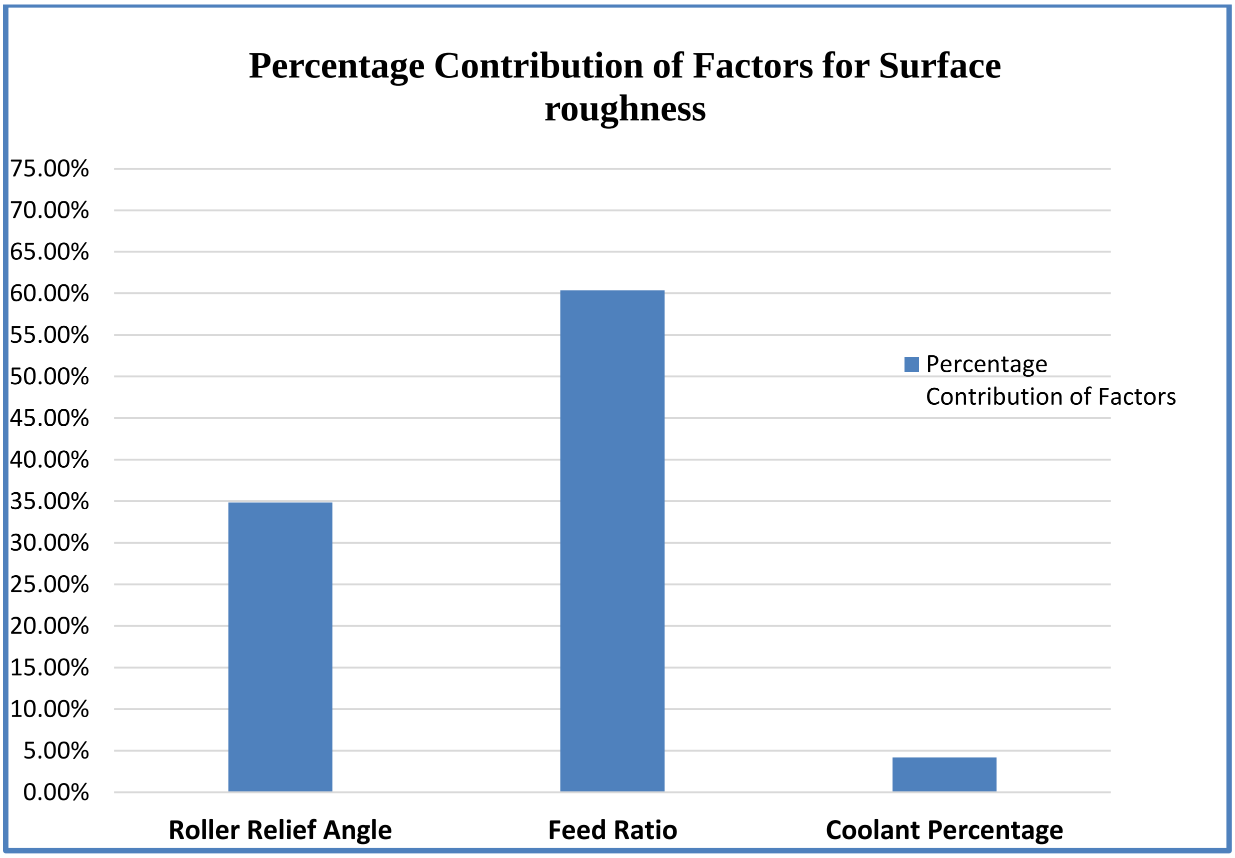

Figure 13: Percentage Contribution of Factors

5.2 Results and Analysis of Circularity (Ovality)

The results of ovality of the tube spinning products for each experiment are summarized in table 8.

Table 12: Ovality of finished product with respect to experiments

Experiment No.	Inputs			Response
	Roller Relief Angle (°)	Feed Ratio (mm/rev)	Coolant Percentage (%)	Ovality
1.	2.50	0.500	1	1.15
2.	2.50	0.667	3	1.10
3.	2.50	0.750	5.5	0.80
4.	2.75	0.500	5.5	1
5.	2.75	0.667	1	0.75
6.	2.75	0.750	3	0.65
7.	3	0.500	3	0.90
8.	3	0.667	5.5	0.85
9.	3	0.750	1	0.55

4.2.1 Signal to Noise ratio (S/N) for Ovality

Since lowest ovality in the flow formed tube is the most desirable value therefore “Smallest-the-better” equation was selected while calculating S / N ratio for ovality. The calculated S/N ratios for every experiment is tabulated in Table 14.

Table 13: Signal to Noise ratio of experiments for Ovality

Experiment No.	Inputs			Response	
	Roller Relief Angle (°)	Feed Ratio (mm/rev)	Coolant Percentage (%)	Ovality	S/N Ratio
1.	2.50	0.500	1	0.58	-1.21396
2.	2.50	0.667	3	0.65	-0.827854
3.	2.50	0.750	5.5	0.79	1.93820
4.	2.75	0.500	5.5	0.44	0
5.	2.75	0.667	1	0.55	2.49877
6.	2.75	0.750	3	0.80	3.74173
7.	3	0.500	3	0.69	0.915150
8.	3	0.667	5.5	0.74	1.41162
9.	3	0.750	1	1.10	5.19275

Table 15 displays the response table for S / N ratio whereas Table 16 displays response table for means.

Table 14: Response Table for Signal to Noise Ratios (Ovality)

Level	Roller Relief Angle	Feed Ratio	Coolant Percentage
1	-0.03454	-0.09960	2.15919
2	2.08017	1.02751	1.27634
3	2.50651	3.62423	1.11661
Delta	2.54104	3.72383	1.04258
Rank	2	1	3

Table 15: Response table for means for Ovality

Level	Roller Relief Angle	Feed Ratio	Coolant Percentage
1	1.0167	1.0167	**0.8167**
2	0.8000	0.9000	0.8833
3	**0.7667**	**0.6667**	0.8833
Delta	0.2500	0.3500	0.0667
Rank	2	1	3

Table 15 and Table 16 show that ovality is minimum when Roller relief angle is at level 3 (3°), Feed is at level 3 (0.75 mm/rev) and Coolant Percentage is at level 1 (1%). This demonstrates that high feed ratio and larger roller relief angle generates minimum ovality on the product whereas Coolant concentration percentage has no effect on it. The graphical representation of main effects plot for means and S/N ratio for ovality are shown in Figure 14 and Figure 15 respectively which were obtained by Minitab 17 Statistical Software.

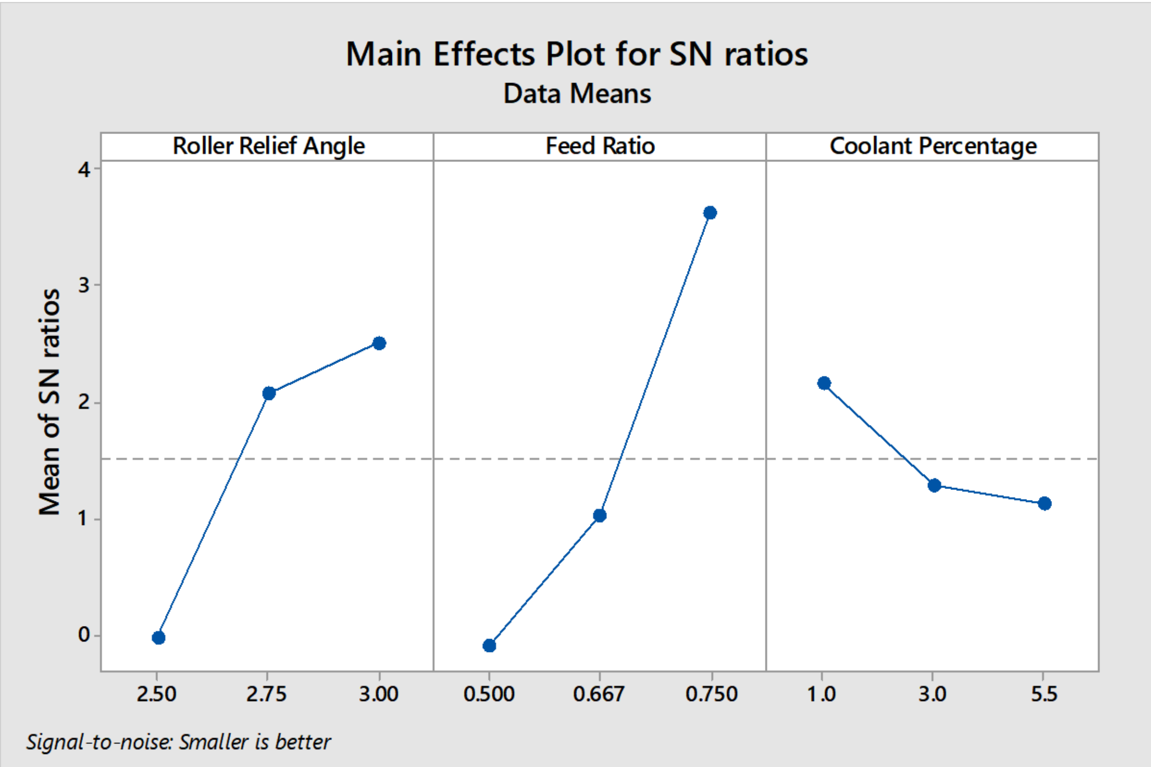

Figure 14: Main Effects Plots for S / N ratio for Ovality

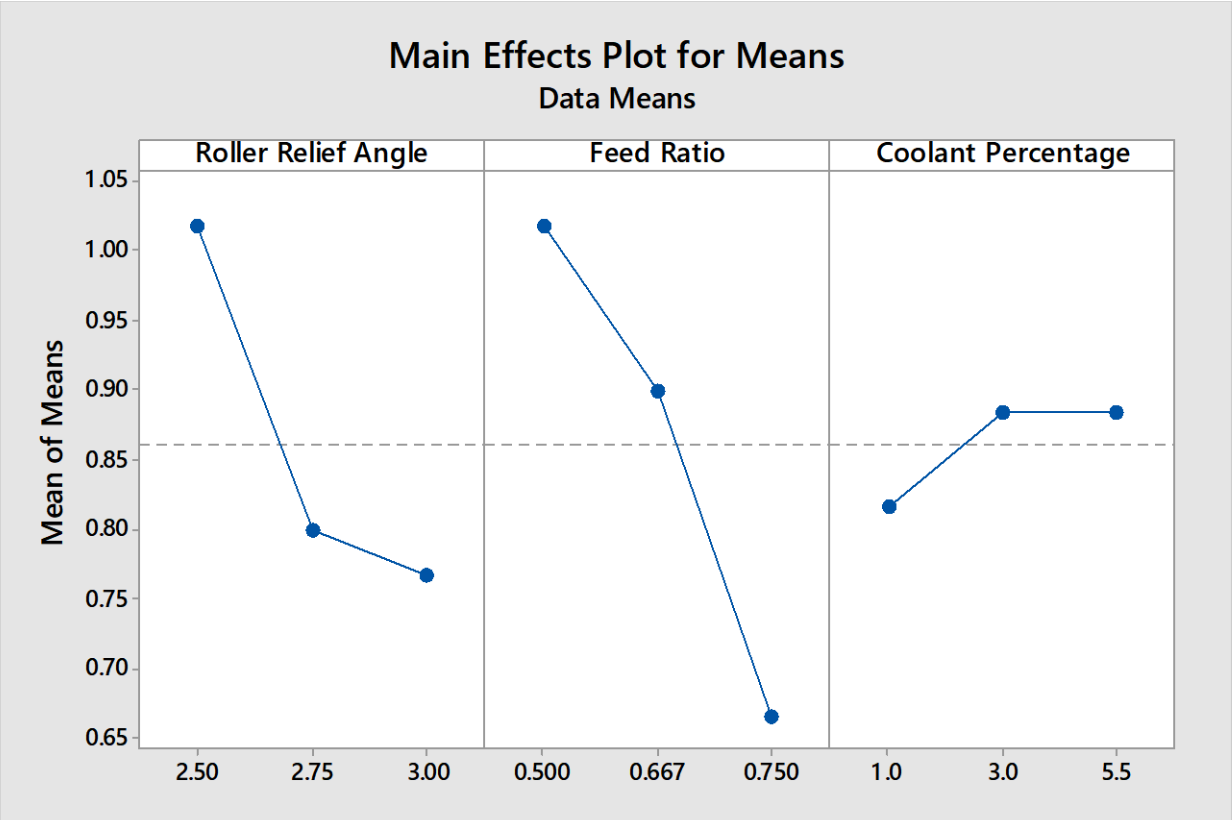

Figure 15: Main Effects Plots for Means for Ovality

4.2.2 Analysis of Variance (ANOVA) for Ovality

On the basis of flow forming results with regards to ovality of the tube, Analysis of Variance (ANOVA) was completed in order to conduct the numerical analysis of factor dominance to understand the importance of each input variable. In this analysis, the relative importance between the three input variables on the ovality will be calculated. F-ratio relating to Ni confidence level in assessment of input factors was considered to be significant. Table 17 shows the contribution percentage, F-Value and P-value of input factors on ovality whereas Figure 16 is graphical representation of contribution of input factors on ovality.

Table 16: Analysis of Variance for Transformed Response (Ovality)

Source	Degree of Freedom	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Roller Relief Angle	2	0.213976	28.36%	0.213976	0.106988	**57.40**	**0.017**
Feed Ratio	2	0.471839	**62.53%**	0.471839	0.235919	**126.57**	**0.009**
Coolant Percentage	2	0.064985	**8.61%**	0.064985	0.032493	17.43	0.054
Error	2	0.003728	0.49%	0.003728	0.001864		
Total	8	0.754528	100.00%				

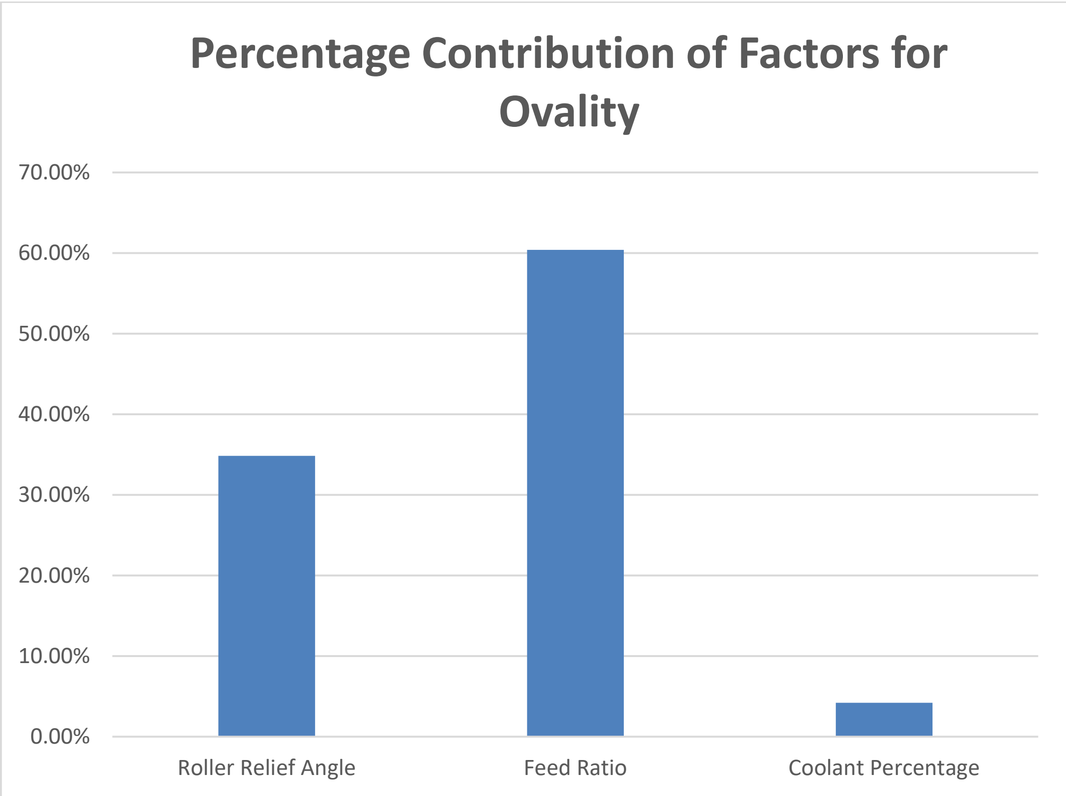

Figure 16: Percentage Contribution of Factors for Ovality

Chapter 5: Conclusions

After finding the optimum input conditions for surface roughness and ovality by Taguchi method further tests were performed for conformation of the analysis. The ideal settings for lowest surface roughness and lowest ovality has already been performed as Experiment No. 4 and Experiment 9 respectively, so there was no need to repeat the experiment. Table 18 shows the optimum conditions for both objective function along with surface roughness and ovality values.

Objective Function	**Optimum Input Parameters**			**Response**	
	Roller Relief Angle (°)	**Feed Ratio (mm/rev)**	**Coolant Percentage (%)**	Surface Roughness	Ovality
Minimize Surface Roughness	2.75	0.5	5.5	0.44	1.00
Minimize Ovality	3	0.75	1	1.10	0.55

CHAPTER 5: CONCLUSIONS

5.1 Surface Roughness

- Surface roughness of the tube spinning products increase with an increase of feed ratio.
- The effect of coolant mixture with water starts to impact as its concentration increases from 3%. Before that, impact of coolant concentration is negligible on surface roughness.
- As Gur et al. (1982) pointed out, ratio of circumferential contact span to axial contact span play an important role in flow forming process. By changing the roller relief angle, axial contact length of the roller has been changed which produced better surface roughness of the product. However, as researchers pointed out, if this ratio exceeds a critical limit, it tends to create bulging and instability in the metal flow. By using Taguchi, it has been we have successfully found the limit of that range by altering roller relief angle while keeping other process parameters constant.

5.2 Ovality

- Ovality of the tube spinning products decreases with an increase of feed ratio.
- The effect of coolant mixture with water is negligible at all levels.
- Ovality of the finished products decreases as relief angle is increased.

5.3 Future Recommendations

New factors, relating to the roller geometry can be added along with roller relief angle to find the impact on surface roughness and ovality as responses. These observations about roller relief angle can be verified by taking some other material.

References:

1. Masujiro Hayama, Hiroaki Kudo, “Experimental Study of Tube Spinning”, The Japan Society of Mechanical Engineers, 1979 Volume 22 Issue 167 Pages 769-775 https://doi.org/10.1299/jsme1958.22.769
2. Masujiro Hayama, Hiroaki Kudo, “Analysis of Diametral Growth and Working Forces in Tube Spinning”, The Japan Society of Mechanical Engineers, 1979 Volume 22 Issue 167 Pages 776-784, https://doi.org/10.1299/jsme1958.22.776
3. Masujiro Hayama, “Theoretical Study of Shear Spinning”, The Japan Society of Mechanical Engineers, 1965 Volume 8 Issue 31 Pages 460-467, https://doi.org/10.1299/jsme1958.8.460
4. Masujiro Hayama, Hiroaki Kudo, “Experimental Study of Shear Spinning”, The Japan Society of Mechanical Engineers, 1965 Volume 8 Issue 31 Pages 453-460 https://doi.org/10.1299/jsme1958.8.453
5. Micha Gur, Jehuda Tirosh, “Plastic Flow Instability Under Compressive Loading During Shear Spinning Process”, 1982, Journal of Engineering for Industry 104(1), 17-22 (Feb 01, 1982), https://doi.org/10.1115/1.3185791
6. R.P.Singhal, S.R.Das, Rajnish Prakash, “ Some experimental observations in the shear spinning of long tubes”, 1987, Journal of Mechanical Working Technology Volume 14, Issue 2, March 1987, Pages 149-157 , https://doi.org/10.1016/0378-3804(87)90057-X
7. Song Zong-hua, Le Wei-min, Chen Shao-chun, Gu Wen-bin, QianXin-miao, “ Real-time defects detection in flow-forming process”, 1992, Journal of Materials Processing Technology, Volume 32, Issues 1–2, July 1992, Pages 365-370, https://doi.org/10.1016/0924-0136(92)90193-V
8. Rajnish Prakash, R.P.Singhal , “Shear spinning technology for manufacture of long thin wall tubes of small bore”, 1995, Journal of Materials Processing Technology Volume 54, Issues 1–4, October 1995, Pages 186-192, https://doi.org/10.1016/0924-0136(95)01940-5
9. Xue Kemin, Lu Yan, Zhao Xianming , “A study of the rational matching relationships amongst technical parameters in stagger spinning”, 1997, Journal of Materials Processing Technology Volume 69, Issues 1–3, September 1997, Pages 167-171 , https://doi.org/10.1016/S0924-0136(97)00012-5
10. Xue Kemin, Lu Yan, Zhao Xianming, “The disposal of key problems in the FEM analysis of tube stagger spinning”, 1997, Journal of Materials Processing Technology Volume 69,

Issues 1–3, September 1997, Pages 176-179 https://doi.org/10.1016/S0924-0136(97)00014-9

11. Xue Kemin, Wang Zhen, Lu Yan, Li Kezhi, " Elasto-plastic FEM analysis and experimental study of diametral growth in tube spinning", 1997, Journal of Materials Processing Technology Volume 69, Issues 1–3, September 1997, Pages 172-175 https://doi.org/10.1016/S0924-0136(97)00013-7
12. Ismail Nawi, S.M. Mahdavian , "Hydrodynamic lubrication analysis for tube spinning process", 1998, Wear, Volume 220, Issue 2, October 1998, Pages 145-153 https://doi.org/10.1016/S0043-1648(98)00248-8
13. S. I. Hong, S. H. Rhee, S. J. Yun, "A Study on the Neck-in Process by Flow-forming", 1998, Metals and Materials, August 1998, Volume 4, Issue 4, pp 895–898 https://doi.org/10.1007/BF03026419
14. M. Jahazi, G. Ebrahimi , "The influence of flow-forming parameters and microstructure on the quality of a D6ac steel", 2000, Journal of Materials Processing Technology Volume 103, Issue 3, 17 July 2000, Pages 362-366, https://doi.org/10.1016/S0924-0136(00)00508-2
15. Eamonn Quigley, John Monaghan, "Metal forming: an analysis of spinning processes", 2000, Journal of Materials Processing Technology Volume 103, Issue 1, 1 June 2000, Pages 114-119 https://doi.org/10.1016/S0924-0136(00)00394-0
16. K.S Lee, L Lu, " A study on the flow forming of cylindrical tubes", 2001, Journal of Materials Processing Technology Volume 113, Issues 1–3, 15 June 2001, Pages 739-742 https://doi.org/10.1016/S0924-0136(01)00585-4
17. X. Song, K. S. Fong, S. R. Oon, W. R. Tiong, P. F. Li, Alexander M. Korsunsky, A. Danno "Diametrical growth in the forward flow forming process: simulation, validation, and prediction", 2014, The International Journal of Advanced Manufacturing Technology, March 2014, Volume 71, Issue 1–4, pp 207–217 https://doi.org/10.1007/s00170-013-5492-x
18. Amin Abedini, Samrand Rash Ahmadi, Ali Doniavi, "Roughness optimization of flow-formed tubes using the Taguchi method", The International Journal of Advanced Manufacturing Technology, May 2014, Volume 72, Issue 5–8, pp 1009–1019 https://doi.org/10.1007/s00170-014-5732-8
19. Qinxiang Xia, Gangfeng Xiao, Hui Long, Xiuquan Cheng, Baojian Yang, "A study of manufacturing tubes with nano/ultrafine grain structure by stagger spinning, 2014,

Materials & Design Volume 59, July 2014, Pages 516-523 https://doi.org/10.1016/j.matdes.2014.03.012

20. Vriens BC, et al. Investigation of the effect of roller inclination angle on the forming forces during a splined mandrel flow forming operation. J Manuf Process (2014), https://dx.doi.org/10.1016/j.jmapro.2014.07.003
21. N. A. Razani, Abdolhossein Jalali Aghchai, Bijan Mollaei Dariani, "Flow-forming optimization based on hardness of flow-formed AISI321 tube using response surface method", The International Journal of Advanced Manufacturing Technology February 2014, Volume 70, Issue 5–8, pp 1463–1471 https://doi.org/10.1007/s00170-013-5377-z
22. L. Y. Sun and C. Yang, "Numerical Investigation on Laser-Assisted Flow Forming Process", Key Engineering Materials, Vol. 620, pp. 29-34, 2014 https://doi.org/10.4028/www.scientific.net/KEM.620.29
23. Zhen Cao, Fenghua Wang, Qu Wan, Zhenyan Zhang, Li Jin, Jie Dong, "Microstructure and mechanical properties of AZ80 magnesium alloy tube fabricated by hot flow forming", (2015) Materials & Design Volume 67, 15 February 2015, Pages 64-71 https://doi.org/10.1016/j.matdes.2014.11.016
24. D.Tsivoulas, J.Quinta da Fonseca, M.Tuffs, M.Preuss, " Effects of flow forming parameters on the development of residual stresses in Cr–Mo–V steel tubes", (2015) Materials Science and Engineering: A, Volume 624, 29 January 2015, Pages 193-202 https://doi.org/10.1016/j.msea.2014.11.068
25. S.Ekinovic, H.Đukic, I.Plancic, E.Begovic, "Assessment of the Surface Topography of Al 99.5% Tubular Products Formed by Cold Flow Forming Technology", (2015) Procedia Engineering Volume 132, 2015, Pages 389-396 https://doi.org/10.1016/j.proeng.2015.12.510
26. D. Woźniak, M. Hojny, T. Gądek, M. Głowacki, "Numerical and Experimental Forming of Axisymmetric Products Using Methods of Deep Drawing and Flow Forming", (2016), Archives of Metallurgy and Materials Volume 60: Issue 4, https://doi.org/10.1515/amm-2015-0453
27. Olga I.Bylya, Timur Khismatullin, Paul Blackwell, Rudolf A.Vasin, "The Effect of Elasto-Plastic Properties of Materials on their Formability by Flow Forming", 2018, Journal of Materials Processing Technology, Volume 252, February 2018, Pages 34-44. https://doi.org/10.1016/j.jmatprotec.2017.09.007
28. M. Runge, Spinning and Flow forming, (D.H. Pollitt, Trans) Leifield GmbH, Werkzeugmaschinenbau/Verlag Moderne Industrie AG, D-86895, Landsberg/Lech, 1994.

29. Chang, S C., Huang, C a., Yu, S Y., Chang, Y, Han, W C., Shieh, T S., Chung, H C.,Yao , H T. ,Shyu , G D. , Hou , H Y., Wang , C C., Wang , W S.. "Tube spinnability of AA 2024 and 7075 aluminum alloys". J Mater Process Technol 1998; 80-81: 676–682. https://doi.org/10.1016/S0924-0136(98)00174-5
30. K. M. Rajan, K. Narasimhan , " An investigation of the development of defects during flow forming of high strength thin wall steel tubes", 2001 , Practical Failure Analysis, October 2001, Volume 1, Issue 5, pp 69–76 https://doi.org/10.1007/BF02715366
31. Ahmad reza Fazeli Nahrekhalaji, Majid Ghoreishi, Ebrahim Sharifi Tashnizi, "Modeling and Investigation of the Wall Thickness Changes and Process Time in Thermo-Mechanical Tube Spinning Process Using Design of Experiments", 2010, Engineering, 2010, 2, 141-148, https://doi.org/10.4236/eng.2010.23020
32. M. Srinivasulu, M. Komaraiah and C. S. Krishna Prasada Rao, "Experimental studies on the characteristics of AA6082 flow formed tubes", Journal of Mechanical Engineering Research Vol. 4(6), pp. 192-198, October 2012. https://doi.org/10.5897/JMER11.063
33. M. Srinivasulu, M. Komaraiah and C. S. Krishna Prasada Rao, "Experimental investigations to predict mean diameter of AA6082 tube in flow forming process – A DOE approach", 2012, IOSR Journal of Engineering (IOSRJEN), ISSN: 2250-3021 Volume 2, Issue 6 (June 2012), PP 52-60
34. Abdolhossein Jalali Aghchai, Nabi Allah Razani and Bijan Mollaei Dariani, "Flow forming optimization based on diametral growth using finite element method and response surface methodology", 2012, Proc IMechE Part B: J Engineering Manufacture 226(12) https://doi.org/10.1177/0954405412461328
35. Lin Wang, Hui Long, "Roller path design by tool compensation in multi-pass conventional spinning", Materials and Design 46 (2013) 645–653 https://doi.org/10.1016/j.matdes.2012.10.048
36. Air Craft Materials, 2019, Maraging Steel 300/ C300, viewed on 1st August 2019, https://www.aircraftmaterials.com/data/nickel/C300.html
37. DeGarmo, E.P., Black, J.T. and Kohser, R.A. (2003) Materials and Processes in Manufacturing. 9th Edition, John Wiley & Sons Ltd., Chichester.
38. PSO Solcut Oil, 2019, Solcut Oil, viewed on 1st August 2019 https://psopk.com/en/product-and-services/lubricants/pso-industrial-lubricants-greases/metal-working-fluids/solcut-oil
39. W.H.Yang, Y.S.Tarng, "Design optimization of cutting parameters for turning operations based on the Taguchi method", 1998, Journal of Materials Processing Technology

Volume 84, Issues 1–3, 1 December 1998, Pages 122-129 https://doi.org/10.1016/S0924-0136(98)00079-X