International Journal of Technical Innovation in Modern Engineering & Science (IJTIMES)
Impact Factor: 5.22 (SJIF-2017), e-ISSN: 2455-2585
Volume 4, Issue 9, September-2018

A REVIEW: FACTOR AFFECTING WIRE QUALITY IN WIRE DRAWING PROCESS

MOHAN NARAYAN GUPTA[1], SUKHDEEP S. DHAMI[2]

[1,2]MECHANICAL ENGINEERING DEPARTMENT & NATIONAL INSTITUTE OF TECHNICAL TEACHER TRAINING & RESEARCH CHANDIGARH, INDIA

ABSTRACT- Wire drawing is widely used forming process in which diameter of wire is reduced by using converging die. It has several advantages like good surface finish, dimensional accuracy and better mechanical properties. Wire drawing process is complex problem because plastic deformation is non-linear in nature. It becomes highly important to increase the efficiency of the process and the quality of the desired product as the competition in the market continuously increases. In this paper wire drawing process, its mechanism, how to simulate the process with the help of FEM, process parameters and the monitoring of the process have been reviewed. This paper also reviews the new technique of lubrication like axial and radial ultrasonic vibration. This paper emphasises mainly on the new technique which improves the process and optimized the consumption of available resources.

Keywords- Wire drawing, Reduction ratio, Approach angle, Drawing speed, FEM

INTRODUCTION

There are several processes which comes under the forming process. Wire drawing is one of them, in which the cross section of the wire is reduced by applying pulling force with the help of a drawing die. This process is performed at room temperature. There are two main factors which govern or control the process, one is the drawing die geometry and the other one is process parameters of the wire drawing viz. reduction ratio, drawing velocity, coefficient of friction etc. Drawing die is usually made of tungsten carbide and diamond and it is divided into 4 regions - entry, approach, bearing and relief regions. Process parameters control the mechanical properties of the wire.

LITERATURE REVIEW

Literature review revels different aspects of wire drawing process such as effects of process parameters, techniques used for improving the quality of drawn wire, approaches used for monitoring the wire drawing process and the numerical/ simulation tools used for optimizing the wire drawing process.

Process parameters of wire drawing process

Cetinarslan and Guzey [1] analyzed the effect of the process parameters like drawing velocity and reduction ratio on the tensile property of various low carbon steel wire, four type of wire SAE1006, SAE1008, SAE1015, SAE10B22 is used in this study. The result of this study shows the percentage of C and Mn influence the tensile property of wire and it also shows that as the value of reduction ratio and drawing velocity increases, yield strength and ultimate tensile strength increases and elongation at rupture decreases, reduction ratio has larger influence as compare to drawing velocity on tensile property of wire.

Vega et al. [2] optimized the die design and investigated the effect of process parameter like approach angle, friction coefficient and bearing length. The case study presented show that friction has the dominant role in wire drawing process, the value of drawing force can be limited by controlling the die angle, friction coefficient and bearing length. The result show that the value of drawing force and maximum equivalent strain increases, as the value of die angle increases, it also shows increment of a maximum equivalent strain makes the deformation more inhomogeneous over the cross section.

Cetinarslan et al. [3] studied the effect of parameter (reduction ratio and drawing velocity) on cold drawing of ferrous wires. In this study C45, C63, C65 and C70 material is used and do the process for different reduction ratio and drawing velocity. Main aim of this study to achieve high tensile and torsion strength of wire by changing these parameters. The result of this study shows drawing speed, reduction ratio and C content effects the tensile and torsional strength of steel wire.

Tittel et al. [4]discussed the effect of the drawing angle size of a die on the wire. In this study a comparison is made between two dies which has different die angles, one has $2\alpha=13$ and another one has $2\alpha=13$ and do the experiment or performing the wire drawing process on these dies and calculate scrap, workability and tensile strength of wire. This study shows the consumption of die is influenced by the quality and accuracy of die geometry, die pressure also varies with die geometry.

Abbas et al. [5] optimized the die life and wire tensile strength, which are the larger- the- better quality characteristics (QCH) types, on SUS 304 wire drawing process with the help of grey relational analysis utilizing Taguchi method. In this paper Grey relational analysis and ANOVA were conducted for S/N ratio. There are three factor reduction ratio, lubricant temperature and drawing speed, and their levels are also three, are studied by $L_9(3^4)$ orthogonal array.

Suliga et al. [6] analyzed the effect of drawing speed on the properties of TRIP Transformation induced Plasticity steel wire. For achieving TRIP type structure it is required to do heat treatment of steel containing C = 0.09%, Mn = 1.57% and silicon = 0.9%, TRIP steel wire is used for production of connecting element. In this research wire is drawn at various drawing velocity at their tensile test is carried out. The result of the study shows that as the drawing speed increases, non-dialation strain, internal stresses and temperature also increases, as the drawing speed increases yield strength and tensile strength also increases approximately 9-10% and the last one is as the drawing speed increases, plasticity properties decreases.

Lee et al.[7] analyzed the effect of high temperature on the mechanical properties of wire like torsional properties, in this research high carbon steel wire is used at room temperature where reduction can take place by more than one passes, due to this temperature increases which produces delamination. For preventing the delamination of wire, a new thermal pass schedule is used. The result of this study shows that the temperature of 7^{th} pass, when delamination starts, has the maximum temperature. It also shows that by knowing the heat generated due to plastic deformation, a method can be established by which we can find out the temperature of wire, delamination is not present there in any passes after redesigning, the temperature of wire in redesigning process is about 170c in all the passes and the result are also improved.

Effect of different techniques on process wire drawing process

Mcallen et al.[8] described the effect of central burst on ductile fracture in drawn 2011 Aluminium wire. The comparison is made between this experiment and previously published papers. Drawing force, die pressure and occurrence of central burst defect are compared. The result of this study states that nose sharp curve is that threshold which divides safe and unsafe zone, reduction ratio below 7% there is no central bursts defects regardless of the die angle in use, periodic decrement in drawing force is seen if central burst occurs, as soon as central bursts grows a damage was emerged to develop in 2 successive defects and effective strain on surface of wire.

Pilarczyk et al.[9] observed the effect of roller die on the properties of high carbon steel wires. In this research residual stresses, surface roughness and mechanical properties are observed. A comparison is made between the results, comes from the roller die set up with conventionally and hydro dynamically set up. Residual stresses and surface roughness are measured or determined respectively with electrochemical reversal pickling in water solution of sulphuric acid and Talysurfprofilographometer. The result of this study shows that the value of residual stresses drops in roller die drawing as compare to conventional die drawing, tensile strength and yield strength also decrease in roller drawing process as compare to conventional drawing process, the value of fatigue resistance is slightly higher in roller die as compare to conventionally wire drawing process.

Tang et al.[10] investigated the electo-plastic effect on the stainless steel wire in wire drawing process. Austenitic stainless steel 1cr18Ni9 is used as a material in this process, initial diameter of the wire is 1.6 mm which is reduced up to 0.4mm diameter without doing any annealing. Yield strength, ultimate tensile strength and elongation ratio are measured with LJ-500 and WE-100, magnetic properties is observed by LDJ-9600 vibrating sample magnetometer and the microstructure is investigated by JEM-200CX transmission electron microscope. The result of this study shows that drawing stress is decreased by about 50% with the help of electric current pulses and the plasticity is also improved as compare to conventional wire drawing process. It also states that surface quality of wire improves and knots are not present in this wire which are manufactured by using electric current pulses, saturated magnetization BS also decreases.

Amine et al. [11] compared the roller die wire drawing process to conventional die wire drawing process, drawing force and resulting wire temperature are compared and the mechanical properties of drawn wire were also analysed. Roller die wire drawing process have two pair of rolls, first pair is used to give an oval form and the second pair is used to give the wire it's round shape. The result of this study shows that conventionally drawn wire has less damaged surface as compare to roller die wire drawing process. There is no significant difference, were seen in any of two process, regarding microstructure and hardness. Tensile strength is almost equal in both type of process.

Process monitoring& Lubrication

Larsson et al. [12] described the technique of process monitoring of wire drawing for carbon steel wire. The comparison is made between the response of vibration signal to force measurement and surface investigation of the product, the reason of poor surface quality of wire is loss or absence of lubrication which is detected by vibration measurement and eddy current testing and optical method using camera arrays in this study. The material of wire is silicon chromium alloyed steel grade oteva 70 and scanning electron microscopy (SEM) is used for surface morphologies. This study gives new technique which is based on vibration sensing, is used for process monitoring of wire drawing.

Larsson et al. [13] investigated whether CCD camera could be able to check or monitor the wire drawing process. The comparison was made between signals from the CCD camera to the signal from a drawing force measurement. The aim of this research was to detect if the process was about to fail, two different wire material and two different lubricant is used for this process. This research concludes this technique can be used by wire drawing industry as it is an inexpensive and robust method to detect changes in the process and it also gives time to sort out the problems.

Mamuda et al. [14] described the drawing process at elevated temperature by using azadirachtaindica and j. curcas lubricants. In this research the material of the wire are mild steel and medium carbon steel, die temperature varies from ambient to 850˙c. In cold drawing process, flow stresses are high so the drawing force. This study shows the effect of increasing the temperature of wire drawing process, it reduces the flow stress of the wire and considerably reduces the drawing force. The result of this study also shows that it not only reduces the drawing force of the wire but also increases the area of reduction in a single die, 40-48% area reduction can be achieved at this elevated temperature and azadirachtaindica and j. curcas lubricants is suitable at this high temperature for tungsten carbide dies.

Tomar et al. [15] simulated the friction stress in drawing process using direct extrusion process in lubrication starvation. In this research paper both tensile load and extrusion pressure are used on the billet material, it not only enhances the quality of wire but also reduces the die wear. In this technique friction stress at die/billet interface is studied in presence of three different lubricants having viscosity 0.1, 0.2 and 0.3 Pa-s considering lubrication starvation at different operating parameter with the help of Lobatto quadrature technique. The result shows that as the semi die angle, material parameter and lubricant's viscosity increases, friction stress increases and as soon as the velocity of the billet increases, friction stress also increases.

Hayashi et al. [16] investigated the effect of ultrasonic vibration on wire drawing process by using Finite Element Analysis (FEM). 2-D axial symmetry model is used for analysis in which Axial Ultrasonic Vibration Drawing, Radial Ultrasonic Vibration Drawing and Conventional Drawing are used.

Material and initial diameter of wire are Aluminium (A1070-H) and 6mm, frequency and the amplitude of ultrasonic vibration are 15khz and 1micro-m and the reduction ratio is 6.6%. The result of study states that in conventional drawing the value of average drawing force is independent from drawing velocity, In AUD and RUD frequency-avg value of varying drawing force closely matches with experiments value. It also states that amplitude affects the drawing force and stress distribution in wire.

Murakawa et al. [17] observed the effect of radially ultrasonic vibration dies on wire drawing process, here a comparison is also made between axially vibrated dies and radially vibrated dies. In radially vibrated dies, dies vibrates with a sinusoidal vibration transversely to drawing direction. The result of this study states that the critical speed in radially vibrated dies increases and it is 10^{th} times higher as compare to axially vibrated dies.

Liu et al. [18] analyzed the effect of ultrasonic vibration on the drawing force and surface finish. The comparison was done between die without ultrasonic vibration and die with ultrasonic vibration. The study result shows that as soon as longitudinal vibrations and ultrasonic frequency increases, drawing stress decreases. Ultrasonic vibration also improves surface finish, longitudinal ultrasonic vibration with larger amplitude is more effective in reducing wire drawing force. In this study scanning electron microscope (SEM) is used for surface morphology and ANSYS is used for simulation.

Simulation

Sas-boca et al. [19] simulated the wire drawing process with 3D finite element simulation and showed the importance of die geometry on the drawing force for steel wire with 0.5% C. This study shows drawing force for steel wire is influenced by the approached angle and the length of the bearing area, main goal of this simulation is to find out the optimal approach angle and optimal length of bearing zone for steel wire with 0.5% C. The result of this study concludes that drawing force increases, as approach angle and die bearing length increases.

Moon and Kim [20]analyzed the drawing process with thermal and friction conditions obtained by inverse engineering. A comparison is made between the drawing powers, comes from the experiments to the drawing power which we get from the FEA analysis with assigning friction factor. Plastic deformation is responsible for heat generation and friction at the workpiece-die interface, deform 2D is used for simulation. The result of this study shows that inverse engineering is simple and useful method to be applied in actual conditions.

Hassan and Hashim[21] simulated the wire drawing process using a 3 dimensional finite element model and effect of these parameters on drawing force. AL-1100 is used as a material of wire having original diameter is 3mm, values of die angle are 6,8,8.5,9,9.5,10 and 15,values of reduction ratio are 0.1,0.15,0.2,0.25 and 0.3, value of friction coefficient are 0.1,0.08,0.075,0.07,0.065 and 0.06, the value of bearing length are 0.5,0.75,1,1.25 and 1.6 and the value of drawing velocity are 5000,7500,10000,12500,15000,17500 and 20000 mm/sec. The result of this study concludes that increasing the bearing length will increase the drawing force, avoid the increase of drawing force, coefficient of friction and reduction in area should be small with a large die angle, increasing the drawing velocity will decrease the drawing force due to increase in yield strength and ultimate tensile strength, optimum value of die angle are 9.5,9.5,9.5,10 and 10 for each value of reduction in area 0.1,0.15,0.2,0.25 and 0.3, most significant effect on the drawing force is the reduction ratio, followed by the bearing length, and die angle.

Lee et al. [22] analyzed, the changes occurs in high carbon steel wire in multi pass dry drawing process due to non-metallic inclusion in wire. Initial diameter of wire is 3.55mm which converts into 2.115 mm having spherical non-metallic al_2o_3 inclusion, present in centre of steel wire. The value of inclusion size varies 5, 10, 20 and 50 micro-m in initial diameter 3.55mm and normalized Cockcroft and Latham criterion is used for seeing effect. Material of wire is high carbon steel varying carbon percentage 0.75 to 0.88 and deform-2D software is used for simulation. The result of this study shows that ductile fracture is affected by the inclusion present in the wire, there is no deformation takes place in inclusion which presents in the wire due to large elastic modulus and as the deformation process passes, the value of damage increases.

Kim et al.[23] predicted the die wear in wire drawing process, in this technique the process is simulated by the rigid-plastic finite element method. Abrasive wear theory is used in this prediction of die wear, in this the impact of temperature rise on the wear profile are studied. The result of this study states that measured result and predicted die wear profile are close enough, the wear profile are greater with consideration of heat generation as compare to without consideration of heat generation during wire drawing process, in other forming process this method is used to predict die wear and this method can also give the idea about the dimensional accuracy of the product.

Houtte et al. [24] described the effect of strain rate in high speed wire drawing process. In this research, simulation is done on low carbon and high carbon steel with the help of quasiststic stresses and dynamic stresses which comes by the split Hopkinson pressure bar tests. The result of this study shows that as the drawing speed increases and the dimension decreases, the strain rate can be very high, as the strain rate increases so the stress level also increases but there is a decrement in the hardening at high strain rates for low carbon steel and it also states that no much difference have been found in flow stresses between low strain rates and high strain rates.

KazutakeKomari [25] analyzed the effect of ductile fracture in wire drawing process using finite element analysis. In this research a computer program has been developed involving finite element analysis, in this program behaviour of crack propagation is observed after ductile fracture. There is comparison made between different criterion and the experimental result. The result of this study shows that experimental result follows the Gursan's fracture criterion and oyane's fracture crieterion, experimental result also follows somewhat Cockcroft and latham's fracture criterion and Brozzo et al's criterion and it also states that experimental result does not follow the Freudenthal's fracture criterion.

Luis et al. [26] Compared the different analytical methods to finite element method in wire drawing process, in this research different analytical methods such as homogeneous deformation method, slab method and upper bound method are used for finding out the stresses and deformation in plastic strain processes. In finite element method the value of reduction ratio are 10%,20%,30%,35%,45% and 50% and the value of die angle are 12,14,16 and 18. The result of this study shows that the result of upper bound method and finite element method are accurate since energy involved in the deformation process are different, the result of slab method is not accurate due to internal energy.

Rubio et al.[27] calculated the forward tension in wire drawing process with the help of simulation, slab method and finite element method is used for simulation to find out the forward tension. Aluminium is used as a material in this process which behaves like rigid- perfectly plastic. A comparison is made between the experimental result and Wistreich's solution and with green and hill. The result of this study shows that finite element method gives better result as compare to slab method because experimental results are closer to the real result. It also states that with the help of simulation it can be seen that forward tension also presents at the deformation zone as well.

Houtte et al. [28] studied the residual stresses in steel wire with the help of FEM simulation and X-ray diffraction, X ray diffraction were used for getting the distribution of the lattice spacing versus $\sin^2\Psi$ with the help of this residual stresses were calculated. Plastic anisotropy also plays an important role in this, plastic anisotropy refers that the flow stress depends on the orientation of the axis of the loading system. 2D isotropic and 3D texture- based anisotropic model were constructed, in 2D isotropic axi- symmetry model is constructed in which die is rigid, coulomb friction law having friction of coefficient 0.03 is used and the material is non-linear isotropic having 201 GPa elastic modulus and Poisson ratio is 0.3. The result of this study shows that a good description of the material is required for achieving high accuracy, for textured material anisotropic yield locus is required to describe the anisotropic plastic behaviour of the material.

Tzou et al.[29] analyzed the effect of approach angle, angular velocity of roller, coefficient of friction and die filet with the help of FEM simulation, deform 3D software is used for simulation. The material of the wire is SWRCH22AB whose chemical composition is c=0.18-0.23%, si=0.1%, Mn=0.7-1%, P=0.03%, s=0.035% and the flow stress of wire is σ = 832.233 ε 0.382. Initial diameter of wire is 6.4mm, meshing= 60000, drawing velocity = 33.50 mm/sec, half approach angle = 10,14,18, angular velocity = 0.5,2.5,6.5 coefficient of friction = 0.05,0.1,0.15 and die filet = 3,5,7 mm. The result of this study shows that friction stress between die and material affects drawing torque, material flow becomes smoother as die filet increases so the value of drawing force decreases. As soon as the angular velocity increases, the value of drawing force decreases because the flow of material becomes smoother. After optimum half approach angle, as the value of half approach angle increases, drawing force decreases.

CONCLUSION

This paper presents the review on literature published in the context of wire drawing process. The literature review revels the effects of process parameter on quality of wire drawn, different technique applied to reduce the stresses in the wire during drawing operation, different wire drawing process monitoring technique and the use of finite element method (FEM) and software for modelling the drawing process. Major input parameters are observed to be approach angle, drawing speed, reduction ratio and bearing length. The use of roller dies and electric current pulses applied to drawing dies have been reported for reducing the residual stresses as well as surface roughness of drawn wire. Vibration and CCD camera technique have been use to monitor the wire drawing process. FEM approach and simulation have been applied effectively for optimizing the process parameter, the use of software like Deform3-D, ANSYS for this purpose have been reported.

TABLE 1

OVERVIEW OF REVIEWED WIRE DRAWING PROCESS

Objective	**Inputs**	**Outputs**	**Results**
Study the effect of process parameter of wire drawing process [1-7]	Drawing velocity Reduction ratio Approach angle Friction coefficient Bearing length	Yield strength Ultimate strength Drawing force Strain	Tensile strength of wire increases Drawing force decreases Friction force decreases
Study the effect of different technique on wire drawing process [8-11]	Roller die Electric current pulses	Residual stress Surface Roughness Microstructure	Fatigue resistance increases Residual stresses drops Drawing stress decreases Surface quality of wire improves
Process monitoring of wire drawing process [12-13]	Vibration signal CCD Camera	Drawing stress Friction stress	Improve the quality of wire Lubrication
Lubrication of wire drawing process [14-15]	Ultrasonic vibration Azadirachtaindica J. curcas lubricants	Drawing stress Surface Finish	Drawing stress decreases Surface finish improves Area of reduction in a single die increases
Simulation of wire drawing process [19-29]	Approach angle Die fillet Angular velocity of roller X-ray diffraction Bearing length	Drawing force Flow of material Forward tension Residual stresses	Die geometry improves Drawing force changes

REFERENCES

[1] VLE, N. L. H., MALOOGLJI, E., JEKLENE, N., & PROCESA, N. P. (2013). Tensile properties of cold-drawn low-carbon steel wires under different process parameters. Materiali in tehnologije, 47(2), 245-252.

[2] Vega, G., Haddi, A., &Imad, A. (2009). Investigation of process parameters effect on the copper-wire drawing. Materials & Design, 30(8), 3308-3312.

[3] Cetinarslan, C. S. (2012). A study on influences of some process parameters on cold drawing of ferrous wires.

[4] Tittel, V., Zelenay, M., &Kudelas, Ľ. (2012). Effect of drawing angle size of a die on wire drawing and bunching process. *Mater. Met*, 1-6.

[5] Abbas, A. R., Li, M. H., & Tai, K. C. (2008). Optimizing SUS 304 wire drawing process by grey relational analysis utilizing Taguchi method. *Journal of University of Science and Technology Beijing, Mineral, Metallurgy, Material*, *15*(6), 714-722.

[6] Suliga, M., Muskalski, Z., &Wiewiórowska, S. (2008). The influence of drawing speed on properties of TRIP steel wires. *Journal of Achievements in Materials and Manufacturing Engineering*, *26*(2), 151-154.

[7] Lee, S. K., Ko, D. C., & Kim, B. M. (2009). Pass schedule of wire drawing process to prevent delamination for high strength steel cord wire. *Materials & Design*, *30*(8), 2919-2927.

[8] Mcallen, P., & Phelan, P. (2005). Ductile fracture by central bursts in drawn 2011 aluminium wire. *International journal of fracture*, *135*(1-4), 19-33

[9] Pilarczyk, J. W., Dyja, H., Golis, B., &Tabuda, E. (1998). Effect of roller die drawing on structure, texture and other properties of high carbon steel wires. *Metals and Materials*, *4*(4), 727-731.

[10] Tang, G., Zhang, J., Yan, Y., Zhou, H., & Fang, W. (2003). The engineering application of the electroplastic effect in the cold-drawing of stainless steel wire. *Journal of materials processing technology*, *137*(1-3), 96-99.

[11] El Amine, K., Larsson, J., &Pejryd, L. (2018). Experimental comparison of roller die and conventional wire drawing. *Journal of Materials Processing Technology*, *257*, 7-14.

[12] Pejryd, L., Larsson, J., & Olsson, M. (2017). Process monitoring of wire drawing using vibration sensoring. *CIRP Journal of Manufacturing Science and Technology*, *18*, 65-74.

[13] Larsson, J., Jansson, A., &Pejryd, L. (2017). Process monitoring of the wire drawing process using a web camera based vision system. *Journal of Materials Processing Technology*, *249*, 512-521.

[14] Mamuda,Yawas D.S, Dauda M. and Ause T., "Elevated Temperature Wire Drawing Process Using AzadirachtaIndica And J.Curcas Seed Oil As Lubricants", *Journal of Mechanical and Civil Engineering*, Vol.13,2016, pp.72-78.

[15] Tomar, P., Pandey, R. K., &Nath, Y. (2013). Numerical simulation of friction stress in wire drawing produced by direct extrusion process in presence of lubricant starvation. *Procedia Engineering*, *64*, 1320-1328.

[16] Hayashi, M., Jin, M., Thipprakmas, S., Murakawa, M., Hung, J. C., Tsai, Y. C., & Hung, C. H. (2003). Simulation of ultrasonic-vibration drawing using the finite element method (FEM). *Journal of Materials Processing Technology*, *140*(1-3), 30-35.

[17] Murakawa, M., &Jin, M. (2001). The utility of radially and ultrasonically vibrated dies in the wire drawing process. *Journal of Materials Processing Technology*, *113*(1-3), 81-86.

[18] Liu, S., Shan, X., Guo, K., Yang, Y., &Xie, T. (2018). Experimental study on titanium wire drawing with ultrasonic vibration. *Ultrasonics*, *83*, 60-67.

[19] Sas-Boca, I. M., Tintelecan, M., Pop, M., Iluţiu-Varvara, D. A., &Mihu, A. M. (2017). The wire drawing process simulation and the optimization of geometry dies. *Procedia Engineering*, *181*, 187-192.

[20] Moon, C., & Kim, N. (2012). Analysis of wire-drawing process with friction and thermal conditions obtained by inverse engineering. *Journal of mechanical science and technology*, *26*(9), 2903-2911.

[21] Hassan, A. K. F., &Hashim, A. S. (2015). Three dimensional finite element analysis of wire drawing process. *Universal Journal of Mechanical Engineering*, *3*(3), 71-82.

[22] Ji, S. I., Lee, K. H., Yang, Y. S., Lee, C. Y., Bae, C. M., & Kim, B. M. (2014). The effects of non-metallic inclusion on ductile damage of high carbon steel wire in multi-pass dry drawing process. In *Key Engineering Materials* (Vol. 622, pp. 155-161). Trans Tech Publications.

[23] Kim, T. H., Kim, B. M., & Choi, J. C. (1997). Prediction of die wear in the wire-drawing process. *Journal of Materials Processing Technology*, *65*(1-3), 11-17.

[24] He, S., Van Houtte, P., Van Bael, A., Mei, F., Sarban, A., Boesman, P., ...& Atienza, J. M. (2002). Strain rate effect in high-speed wire drawing process *Modelling and Simulation in Materials Science and Engineering*, *10*(3), 267.

[25] Komori, K. (2003). Effect of ductile fracture criteria on chevron crack formation and evolution in drawing. *International Journal of Mechanical Sciences*, *45*(1), 141-160.

[26] Luis, C. J., Leon, J., &Luri, R. (2005). Comparison between finite element method and analytical methods for studying wire drawing processes. *Journal of materials processing technology*, *164*, 1218-1225.

[27] Rubio, E. M., Camacho, A. M., Sevilla, L., & Sebastian, M. A. (2005). Calculation of the forward tension in drawing processes. *Journal of Materials Processing Technology*, *162*, 551-557.

[28] Van Houtte, P., He, S., Mei, F., &Sarban, A. (2002). Residual stress determination in cold drawn steel wire by FEM simulation and X-ray diffraction. In *Materials science forum* (Vol. 404, pp. 205-214). Trans Tech Publications.

[29] Tzou, G. Y., Chai, U. C., Hsu, C. M., & Hsu, H. Y. (2017). FEM simulation analysis of wire rod drawing process using the rotating die under Coulomb friction. In *MATEC Web of Conferences* (Vol. 123, p. 00033). EDP Sciences.