Numerical and experimental research of the process of reducing the diameter of a S355J2G2W steel pipe by necking

K Wojtko¹, P Frąckowiak¹ and D Bartkowski¹

¹Poznan University of Technology, Faculty of Mechanical Engineering and Management, Piotrowo 3, 60-965 Poznan, Poland

E-mail: kamil.wojtko@put.poznan.pl

Abstract. The article presents the results of research the process of reducing the diameter of pipe ends using the necking method, which are applied to the ends of pressure hoses. The aim of the research was to determine the possibility of reducing the diameter of the S355J2G2W steel pipe by cold necking. The research was carried out using numerical analysis, which was verified experimentally. The software Simufact.forming was used for numerical research of the pipe endnecking process. Experimental tests were carried out using specially designed and made dies and a hydraulic press. As a result of the tests, we determined the pushing force for various friction conditions and the clamping force of the die for four types of grease. The article also presents experimental results of measurements of wall thickness of the pipe being reduced (diameter before and after leaving the die). The test results showed a large influence of the type of grease on: upsetting and elongation of the pipe, flow and the quality of the material surface. The test results showed the effect of the cone angle of the standard die made on the buckling phenomena during the necking process. On the basis of the conducted research, tools for changing the diameter of pipes with theoretically unlimited length were designed.

1. Introduction

Necking is a shaping method, used to reduce diameter or cross-section of pipes, rods and vascular elements by acting on them with an external compressive force. The necking process can be carried out using rotary shaping on roll crushers equipped with a specified number of forming rollers (neck-spinning) [1,2,3,4], or with the use of stationary tools, i.e. dies with appropriate geometry [5].

Neck-spinning is most often used in the production of vascular components such as pressure containers - fire extinguishers, industrial gas cylinders, gas storage cylinders. On spinning lathes, operations are performed to close the bottom of the vessel and necking operations, which are usually carried out on a hot surface with simultaneous flame heating where the tool contacts the material.

The necking with dies consists in applying pressure to the face of the blank and pressing it into the conical die hole [8]. The process is most often carried out on vertical or horizontal hydraulic presses. The change in diameter can be carried out only on a specific part of the pipe or on its entire length, then a very important aspect is the correct guiding of the pipe, in order to prevent its loss of stability and buckling. The length of the shaped part of the pipe is also dependent on the machine construction and the maximum stroke. The limiting deformation during pipe necking operation is limited by the loss of stability which occurs at \( \frac{g}{d} = 0,025 \). In addition, the reduction of the pipe diameter by this method can be carried out as free and with the internal pipe guide using a rod. The method with guiding is used in cases of possible loss of stability of the pipe after leaving the die.
Necking of tube elements by means of dies can be carried out for pipe ends, which can serve as connectors or reducing elements in hydraulic installations. The analyzed case concerns the pipe end used as the end of the pressure hose.

2. Theoretical analysis of pipe end necking process

2.1. Pipe end diameter reduction

The purpose of the necking process of pipe ends is to reduce the diameter of the pipe at its end due to plastic deformation of the material. Until the pipe end is placed in the conical entry of the necking ring, a biaxial compression occurs, which leads to an increase in the wall thickness. As the pipe approaches the outlet of the cone and the calibration part of the cylindrical axial stress, it gradually decreases. There may be various limitations in the process of crimping pipe ends:

- folding of the periphery of the necked cylindrical shell due to compressive stresses at low wall thickness,
- pipe plasticization before the tool, under the influence of compressive force $P$, greater than $P_{cr}$,
- buckling the cylindrical shell under the influence of compressive force $P$.

According to [5,6], the critical parameter for crimping the pipe end is the ratio of the initial diameter $\phi_D$ to the final diameter $\phi_d$, called the necking factor $K$:

$$K = \frac{D}{d}$$ (1)

The necking factor $K$ is dependent on the following factors [5]:

- The geometry of the necked tube, more specifically the ratio $\frac{\phi_D}{D}$. For small values of the coefficient $\frac{\phi_D}{D}$, obtaining high values of the factor $K$ is limited by the formation of transverse folds. The phenomenon of longitudinal folding can occur at $\frac{\phi_D}{D} \leq 0,02$. The coefficient $K$ has a higher value, the greater the ratio $\frac{\phi_D}{D}$.
- Material type - increasing the tensile strength $R_m$ and the power factor $n$ of the curve of strengthening the material leads to a reduction in the coefficient $K$.
- Angle of opening the conical part of the die - increasing the opening angle of the tool’s cone reduces the $K$ factor.

During the crimping process of steel pipes, the critical value of $K$ coefficient falls within the $1,25 \div 2,45$. However, the ratio $\frac{\phi_D}{D}$ is in the range of $0,021 \div 0,920$ [5,6].

The largest change in wall thickness occurs during the crimping process on the site of the smallest diameter of the conical part of the tool, and the wall thickness $g_1$ at this point can be determined from the formula:

$$g_1 = g_0 \sqrt{\frac{D}{d}}$$ (2)

2.2. Friction during necking process

Friction is one of the most important factors that should be taken into account when developing plastic forming processes. First of all, we are talking about the friction between the workpiece and the tool. Friction affects the course of the process, which ultimately also affects the quality of the product and its functional properties, as well as the condition and durability of the tools used for the process.

The friction phenomenon that occurs in plastic forming processes cannot be compared to the friction between cooperating elements (friction in the nodes of mechanisms). Both types of friction differ, among others surface pressures, plastic deformation, contact surface geometry as well as temperature. In most processes, friction is an undesirable phenomenon. However, for some of the plastic forming processes it is necessary for their proper implementation [7].
2.3. Parameters of material used in process
The material used during the necking process of the pressure hose end is a seam-free pipe made of stainless steel constructional alloy hard-rusting S355J2G2W (in accordance with PN-EN 10155: 1997). This steel is usually used in applications exposed to corrosion - mainly atmospheric, as well as in welded, welded and bolted constructions.

| Table 1. Chemical composition of S355J2G2W steel [10]. |
| Chemical composition [%] |
| C | Mn | Si | P | S | Cr | Ni | Cu | Al |
| ≤ 16 | 0,50 – 1,50 | ≤ 0,50 | ≤ 0,035 | ≤ 0,035 | 0,40 – 0,80 | ≤ 0,65 | 0,25 – 0,55 | ≥ 0,02 |

| Table 2. Mechanical properties of S355J2G2W steel [10]. |
| Thickness [mm] | Yield Strength $R_{yH}$[MPa] | Tensile Strength $R_m$[MPa] | Fracture Elongation A [%] | Notch Impact Energy |
| 3 | 355 | 510 - 610 | 22 | - |

3. Numerical and experimental research results

3.1. Experiment
The aim of the research was to design and optimize the process of reducing the diameter of pipes by necking. For this purpose, one of the necking methods was used - cold necking without a rod. This method is aimed at reducing the pipe diameter with low material losses, favorable product properties and simple, cheap tools.

In addition, the aim of the research was to check the possibility of performing pipe necking operations in order to prepare a blank for the manufacture of connectors and ends of hydraulic hoses. The research aimed to present potential problems during research and the construction process that may occur during the necking process, and which have not been described in the literature.

The necessary tools in the form of two dies and a frame were designed and made for both numerical and experimental research. The tools were designed to study the course of the process of shaping the final section of pipes by the method of cold necking without the rod through the die. Three-dimensional models of test specimens and tools were made in the Autodesk Inventor 2018 program. Numerical tests were carried out in the Simufact.forming 14.0 software, while experimental research on the P125 hydraulic press with the necessary equipment.

3.2. Determining the pushing force
Numerical models of designed and made tools were used during numerical tests of the necking process of pipe ends. The process simulation was carried out in a program for numerical testing of plastic forming processes Simufact.forming v. 14.0, in a cold processing module. For this process the finite elements analysis was used. Before conducting the simulation, it was necessary to perform the meshing process in order to divide the sample model into finite elements. The size of a single finite element equal to 1.5 mm was adopted, which is sufficient for a pipe with a thickness of 3 mm, and also due to the simple simulation of changing the geometry of the pipe.

Figure 1. Ready product (pipe after necking + turning) [9].
Due to the lack of data on the coefficient of friction obtained for various oils and lubricants during experimental tests, simulations were carried out for three different friction conditions, using an automatic mode where the exact friction coefficient can be used to determine the approximate friction conditions based on the amount of oil used.

The program dialog shown in the figure allows using the slider to determine the conditions of friction during the process. This coefficient reaches values in the range (0.0-1.0), where the minimum value 0.0 corresponds to the conditions of very low friction, while the value 1.0 corresponds to a very large friction. Additional help for technologists or for workshop working conditions are icons indicating the amount of lubrication (in the form of oil drops).

The obtained test results will be used to determine the approximate friction conditions corresponding to the different lubricants used in the experimental tests. The results of the process simulation of three different coefficients of friction are presented below.

For both numerical and experimental tests, a sample was used as well as a die A with the dimensions shown in the figure below. The concept was adopted that in die A (angle of the working cone is $2\alpha = 24^\circ$) the diameter of the pipe is reduced to the required value and the required length in one treatment.

In addition to evaluating the geometry of the pipe being processed (diameter, upsetting, length), the forces occurring in the crimping process were analyzed. Due to the change in the coefficient determining friction conditions, the forces in the process were also changed, needed to push the tube through the die. The force values for several different coefficients set in the program are shown in Figure 5.

![Figure 2. Pipe model after meshing process.](image)

![Figure 3. Scaling factor for friction for determining friction conditions.](image)

![Figure 4. Dimensions of the die A and pipe sample.](image)
Figure 5. Plot of pushing forces for different values of scaling factor for friction in Simufact.forming software.

As the coefficient of friction increases, the increase in force necessary to push the pipe through the die can be seen. The obtained force graphs have similar waveforms, and their values in the studied range depend to a large extent on the coefficient of friction.

Experiments of pushing were carried out in order to determine the lowest friction resistance for four types of grease when crimping a pipe with diameter $D_0 = 27.1\ mm$ on $D_1 = 21.3\ mm$. The following lubricants were used: PRESOL SC oil (used for cold pressing), gear oil, Promar oil (used for wire drawing), TAWOT LT-43 grease (used for bearing lubrication). The tests were carried out on the P125 hydraulic press. The die A was placed in a special tool holder, and additionally the tooling was equipped with two bumpers defining the maximum pushing depth of the pipe.

During the process, the pushing force was measured, and then after the tube end was reduced, the outer diameter of the upsetted tube (cylindrical part of a pipe before conical part of a die) and length after necking was measured. The measurement results are shown in Table 3.

Figure 6. Toolholder and the die [9].  
Figure 7. Working area of hydraulic press [9].

Analyzing the obtained results, one can notice the smallest diameter of the pipe at the point of its upsetting equal to 28.01 mm and at the same time the largest total pipe length equal to 84.14 mm for PRESOL SC oil. The value of the pushing force was then 64 kN. For further investigation of the crimping process, PRESOL SC oil will be used, which has the lowest friction properties to be the best in terms of other lubricants, which can be observed after samples No. 1 and 2.

When comparing numerical and experimental tests, it can be noticed that the values of the pushing force for the PRESOL SC grease are closest to the $k = 0.3$ factor.
Table 3. Pushing force and pipe dimensions after necking with different types of lubricants.

| Nr | Lubricant                | Pushing force F [kN] | Pipe diameter after process D₀ [mm] | Pipe total length after process L [mm] |
|----|--------------------------|----------------------|------------------------------------|---------------------------------------|
| 1  | PRESOL SC oil            | 65                   | 28,38                              | 83,65                                 |
| 2  | PRESOL SC oil            | 64                   | 28,01                              | 84,14                                 |
| 3  | Gearbox oil              | 64                   | 29,10                              | 82,10                                 |
| 4  | Gearbox oil              | 65                   | 28,87                              | 82,37                                 |
| 5  | PROMAR oil               | 64                   | 28,73                              | 82,57                                 |
| 6  | PROMAR oil               | 64                   | 28,70                              | 82,65                                 |
| 7  | TAWOT ŁT-43 grease       | 62.5                 | 28,43                              | 83,17                                 |
| 8  | TAWOT ŁT-43 grease       | 62.5                 | 28,60                              | 83,15                                 |

3.3. Reducing the diameter in two operations

Another aspect of the conducted research was the design of dies for the process of reducing pipe diameters in two operations. Simulation tests showed that it would be impossible to obtain a diameter directly from $D₀ = 27,1\ mm$ into $D₂ = 17\ mm$, therefore it was proposed to make two dies with an intermediate diameter reduction. For this purpose, two dies with different working cones and output diameters were designed. The first die with a working cone equal to $2α = 24°$ was responsible for diameter reduction from $D₀ = 27,1\ mm$ into $D₁ = 21,3\ mm$, while the second die with a working cone $2α = 30°$ reduced the diameter to $D₂ = 17\ mm$.

In the next step, the simulation of pipe crimping was again performed using die II (shown in Figures 8 and 9) from diameter $D₁ = 21,3\ mm$ into $D₂ = 17\ mm$. The simulation conditions were left the same as for necking with the die A. The possibilities of the Simufact.forming program enabled the use of the previously worked pipe model together with the stored state of stresses and strains for the second stage of processing on die B. The results of the simulation are shown in Figures 10 and 11.
3.4. Reducing the diameter in one operation

The last stage of numerical tests assumed the simulation of a continuous process of reducing the diameter of a pipe in one operation by combining earlier made dies (A and B). The tests were aimed at checking whether it is possible to obtain the target pipe geometry in one operation.

During the simulation, combined die models, identical friction and temperature conditions were used as in previous studies. The behavior of the pipe under these conditions was analyzed and changes in its geometry were observed.

Numerical tests have demonstrated too much frictional resistance, which in turn leads to upsetting of the cylindrical part of the pipe (before entering the cone) and ultimately loss of its stability.

The experimental verification of numerical tests also confirms that during one operation of reducing the diameter of the pipe, it comes to upset just before the cone. For fear of excessive loading of the tools and the possibility of their damage, the experimental tests were interrupted at the stage of pipe upset – stability was not lost.

![Figure 11. Simulation of the pipe diameter reducing process using die B.](image11)

![Figure 12. Dimensions of the dies (A and B) for continuous diameter reducing.](image12)

![Figure 13. Simulation of the pipe diameter reducing process in one operation using die A and die B.](image13)
4. Conclusion

The presented results of the experimental analysis of the problem of necking of pipe ends are in accordance with the results of numerical tests. The use of software for simulation and support of plastic forming processes can, to a large extent, contribute to the reduction of costs associated with the production of tools and semi-finished products necessary to conduct technological trials and to prepare the target technological process.

The geometric measurements of the sample after necking, i.e. wall thickness at various points, to a large extent coincide with the results of computer simulations. A very important aspect of the problem is to ensure proper friction conditions. Incorrect choice of process lubricant may contribute to the loss of stability of the sample before or after leaving the die, as well as rapid wear of the die work surfaces - the conical part and the cylindrical calibration part.

The friction surface lubrication has a significant influence on the correct process. Correctly selected lubricant allows to increase the material elongation, prevents the upsetting of the pipe, facilitates flow of the material and positively affects the product surface quality and durability of the tools.

During the pushing of pipes with diameter $D_0 = 27.1 \text{ mm}$, the phenomenon of loss of pipe wall stability on the length segment $L \approx D_0$, located just before the entry of the pipe into the working cone of the matrix was observed. An increase in the outer diameter of the pipe with $\Delta D_0 \approx 0.6 \text{ mm}$ was observed.

Numerical studies of reducing the diameter of the pipe with the simultaneous use of two dies showed the inability to perform the assumed operation with the assumed parameters. In this case, simulations for other friction conditions should be carried out. An additional factor facilitating the process could be the induction heating of the pipe after leaving the first matrix. However, this should be verified numerically and experimentally in the next stages of work on this issue.

References

[1] Xue Z, Ren Y, Luo W and Ren Y 2016 Effect of Feed Speed on Aluminum Alloy Pipe Neck-Spinning Process and Deformation Analysis Via Simulation, MATEC Web of Conferences 67 05011-1–05011-6
[2] Takahashi Y, Kihara S, Nagamachi T, Mizumoto H and Nakat Y 2011 Effects of Forming Conditions on Wrinkling in Necking of Tube End, Materials Transactions 52(1) 31-36
[3] Tomczak J 2016 Study of Rotary Necking Processes for Hollow Shafts (Studium procesów obciskania obrotowego odkuwek drążonych), Lublin University of Technology
[4] Chałupczak J, Pacanowski J and Milek T 1998 Assessment of the Possibility of Making Reducers by Necking and Rolling on a WPM-120 Eccentric Profiled Press (Ocena możliwości wykonania zwężek rurowych metodą obciskania oraz walcowania na walcańcę profilowej mimośrodowej) WPM-120, Rudy i Metale 43(10) 486-489
[5] Ziółkiewicz S, Czartotyska I and Gronowski W 2008 Investigation of the Process of Pipe End Diameter Reduction by the Method of Necking, Obróbka Plastyczna Metali t. XIX(1)
[6] Chałupczak J and Thomas P 2000 The influence of Angle of the Working Part of The Tool, the Kind of Material and Relative Thicknesses of the Pipes on Selected Process-Parameters of Necking the Reducing Pipes, Rudy i Metale 45(10-11) 556-559
[7] Pater Z and Samołyk G 2011 Fundamentals of the Theory and Analysis of Metal Forming (Podstawy teorii i analizy obróbki plastycznej metali), Lublin University of Technology
[8] Romanowski WP 1976 Guide to Cold Forming (Poradnik obróbki plastycznej na zimno), WNT
[9] Gapa D 2015 The Technology PF Change of the Diameter of Pipes the Method of Clasping, Poznań University of Technology, MSc Thesis
[10] http://www.bebonchina.com/Steel-plate-sheet/S355J2G2WSMA50CP.html (accessed on March 2018)