Research on Hydroforming Micro-Sized Spiral Pipe With Equal Wall Thickness

Changshuai Shi

Southwest Petroleum University

Jinping Li

Southwest Jiaotong University

Xiaohua Zhu (✉ zxhth113@163.com)

Southwest Petroleum University

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Research on hydroforming micro-sized spiral pipe with equal wall thickness

Changshuai Shi¹, Jinping Li², Xiaohua Zhu^{1,*}

¹ Department of Mechatronic Engineering, Southwest Petroleum University, Chengdu 610500, PR China

² Institute of Advanced Design and Manufacturing, Southwest Jiaotong University, P.R.China, 610031

*Corresponding author: zxhth113@163.com

Abstract: The positive displacement motor is currently the most widely used downhole power tool. In order to reduce the cost of drilling and exploration, small boreholes have been used to replace conventional boreholes. The working conditions are complex, so a high-performance positive displacement motor for micro-holes is required. In order to solve the problem of the difficulty in processing the inner spiral surface of the small size and large aspect ratio, the tiny size spiral tube stator is proposed in this paper and the normal temperature and hot state hydroforming of the small size spiral tube is proposed in this paper. The material is 42crmo, and the uniaxial tensile test is carried out at different temperatures. According to the material mechanical properties experiment and the forming process, the finite element model of the hydroformed spiral tube at different temperatures is established. The study found that the suitable tube size is 48mm in outer diameter, 5.5mm in wall thickness, and 1405mm in length. When the processing temperature is 700°C, the hydraulic pressure required for full expansion of the spiral tube is only 70MPa, and the rebound of the spiral tube is very small. The minimum wall thickness is the maximum of 4.31mm, and the maximum wall thickness is the minimum of 5.356mm, and the wall thickness distribution is relatively uniform. The maximum plastic strain of the spiral tube is 0.65, so the damage to the material during the forming process is small, and when the processing temperature is 700°C, the quality of the spiral tube is better.

Key words: Positive displacement motor; Hydroforming; Inner spiral surface; Spiral tube; numerical simulation

1 Introduction

The positive displacement motor is currently the most widely used downhole power tool. In recent years, in order to reduce the cost of drilling and exploration, micro boreholes are often used to replace conventional boreholes. Due to the complex drilling conditions, there is an urgent need for high-performance positive displacement motors for micro-holes.

Common stator of positive displacement motors include conventional stators (Figure 1(a)) and equal-wall thickness stators (Figure 1(b)). Field engineering application shows that the working life of conventional positive displacement motors is relatively short, in order to improve the short working life and poor performance of conventional positive displacement motors (Figure 1(a)). The researchers processed the inner hole of the stator tube into a spiral surface, a layer of rubber with uniform wall thickness is vulcanized on the inner wall of the spiral curved surface to form a stator of equal wall thickness (Figure 1(b)). Field application and indoor experiment prove that the positive displacement motor of equal wall thickness has excellent working performance and long working life. But the inner spiral surface of the stator is difficult to process, it is more difficult to process the small size and large

length-diameter ratio of the inner spiral surface of the stator.

Liu et al. studied electrochemical machining of positive displacement motor stators, but electrochemical machining requires a lot of electric energy, and the processing efficiency is very low [1-4]. Chen et al. studied the extrusion molding of the spiral tube, the extrusion molding method is relatively simple, but the processing accuracy is very low, and the lead error is large [5]. Wang, Qi, etc. studied the incremental forming of spiral tube with equal wall thickness, but the incremental forming is only suitable for processing two-lobed spiral tubes with equal wall thickness [6,7]. Li et al. have studied roller-core mold composite molding, core mold molding, and outer mold-core mold composite molding spiral pipe, but the core mold is particularly difficult to take out after processing [8,9]. Zhu et al. studied the roll forming of a spiral tube with equal wall thickness of the stator, the research results show that this is a feasible machining method, but the machining accuracy of the stator is low [10-13].

Aiming at the difficulty of machining the inner spiral surface of the tiny size stator tube, in this paper, a spiral tube stator is proposed (Figure 1(c)). Tube hydroforming (THF) is a metal forming process that uses pressurized fluid as a force transmission medium to shape the tube into the desired shape. Han et al. studied internal high pressure forming torsion beams, and the results showed that the hydraulic pressure loading path has a significant effect on the forming quality [14]. Wang et al. studied the hot air pressure expansion of welded pipes and found that the weld is an area that is easy to crack [15]. Wu et al. studied the hydroforming of automobile longitudinal beams and found that the hydraulic pressure loading path will significantly affect the maximum thinning rate, and reducing the friction coefficient can increase the minimum wall thickness [16]. Zhang et al. studied corrugated tube hydroforming through a combination of experimental research, theoretical verification and numerical simulation [17-18]. Xu et al. studied hydroforming parts with trapezoidal cross-sections and found that pipes are prone to wrinkles at acute angles [19]. Crapps et al. studied the hydroforming of copper 3-way pipes [20]. Cui et al. studied the double-sided hydroforming of pipe fittings in square section molds [21]. Alzahrani et al. studied the analysis of polygonal arc tube hydroforming [22,23]. Nishant et al. studied the double-sided hydraulic pressure forming of pipes and found that double-sided hydraulic pressure forming delayed the start of plastic instability of the pipe and increased the ductility of the metal [24].

The hydroforming process of pipe fittings can process tube with complex cross-sections. At present, there are few researches on the processing of small-sized inner spiral curved surfaces. In order to solve the problem of difficult processing of small-sized inner spiral surface, therefore, the hydroforming spiral tube of the tiny stator is proposed.

Figure 1 Stator model (a) Conventional stator model (b) Constant wall thickness stator model (c) Spiral tube stator

2 Material mechanical performance test

The tube material is 42Grmo. In order to obtain the stress-strain curve of the material, according to the ATM uniaxial tensile test standard, the 22°C and hot tensile tests were carried out respectively.

2.1 Uniaxial tensile test at 22°C

According to the ATM standard. The uniaxial tensile test of 42Crmo material was carried out using MTS electronic tensile tester (Figure 2).

Figure 2 Uniaxial tensile test and test results at 22°C

2.2 Hot uniaxial tensile test

According to the ATM tensile test standard, the 42Crmo material is subjected to a hot tensile test, the hot uniaxial tensile test temperatures are 300°C, 400°C, 500°C, 600°C, 700°C, 800°C, and the stress-strain curves corresponding to the temperature are obtained. The real stress-strain curve is used for finite element simulation (Figure 3). The mechanical properties of 42Crmo are shown in Table 1.

(a)

(b)

(c)

Figure 3 Hot uniaxial tensile test (a) Hot tensile test (b) Engineering stress-strain curve (c) True stress-strain curve

Table 1 Mechanical properties of 42Crmo

Test temperature (°C)	diameter (mm)	Original gauge length (mm)	Yield Strength $R_{p0.2}$ (MPa)	tensile strength R_m (MPa)	Elongation after breaking A(%)	rate of reduction in area Z(%)
22.0	9.98	50	956	1120	16.5	57
300.0	9.98	25	961	1136	21	75
400.0	5	25	861	958	18.5	76
500.0	5	25	716	734	18.0	79
600.0	5	25	316	343	37.5	83
700.0	5	25	80	114	65.0	88
800.0	4.99	25	43	70	86.5	94

2.3 Hydroforming spiral pipe processing technology

The schematic diagram of the hydroformed metal spiral pipe with equal wall thickness is shown in Figure 4. After the experiment, in order to remove the spiral tube smoothly and avoid interference, the parting surface is the largest section. The first step: Put the tube blank into the mold cavity. Step 2: Close the mold. Step 3: adding high-pressure liquid into the tube blank while venting the air in the tube blank, the increasing hydraulic pressure makes the tube expand gradually, after the tube is fully expanded, the hydraulic pressure is maintained for a period of time, the tube blank is formed into a spiral tube. Step 4: Relieve the pressure, open the mold, and take out the spiral tube.

Figure 4 Schematic diagram of the principle of spiral tube hydroforming

3 Finite element model

The grid unit of the tube is C3D8R, and the grid size is 0.8mm. The grid unit of the mold is C3D10M, the grid size is 1.5mm, the number of grids of the tube blank is about 1.8 million, the mold is set as a rigid body, and the number of grids of the mold is about 700,000, and the inner cavity of the mold is an inner spiral surface. The friction coefficient is 0.08. The mold is completely fixed, the inner surface of the tube blank is subjected to hydraulic pressure, and the two ends of the tube blank are free.

The cross section of the spiral tube stator is shown in Figure 5. The design wall thickness of the spiral tube is 5mm. The finite element model of the hydroforming spiral tube with equal wall thickness is shown in Fig.6. The tube blank is inside the mold, and the mold has been completely fixed. The main parameters of the mold are shown in Table 2.

Figure 5 Section size of spiral tube stator (a) Section of spiral tube stator (b) Mold outline (c) Section of spiral tube (d) Section of rubber bushing

Table 2 The main parameters of the mold

Straight section	Transition section 1	Spiral section	Transition section 1	Straight section	Lead	Major diameter	Small diameter	Circumference	Lobes
1 (mm)	(mm)	(mm)	(mm)	1 (mm)	(mm)	(mm)	(mm)	(mm)	
65	20	1100	20	200	360	54	48	283.724	6

4 Analysis of molding sensitive parameters

4.1 The influence of the thickness of the tube blank on the quality

In order to analyze the influence of the thickness of the tube blank on the forming quality, this thesis sets up three types of tube blanks with thicknesses of 5mm, 5.5mm and 6mm respectively. The

outer diameter of the tube blank is the same as 48mm, and the length is the same as 1405mm. The dimensions of the tube blank are shown in table 3. The hydraulic loading path is shown in Figure 7, the maximum hydraulic pressure is 450MPa, 0-0.04s is the loading stage, 0.04s-0.048s is the pressure holding stage, 0.048s-0.05s is the pressure relief stage, and 0.05s-0.1s is the aging treatment stage.

Table 3 Dimensional parameters of tube blank

Serial number	Thickness/mm	Inner diameter/mm	Outer diameter/mm	Length/mm
Tube I	5	Ø38	Ø48	1405
Tube II	5.5	Ø37	Ø48	1405
Tube III	6	Ø36	Ø48	1405

Figure 6 Finite element model Figure 7 Hydraulic pressure loading path (22°C, 450MPa)

The cross-sectional stress and plastic strain cloud diagrams of the spiral tube formed by tube blanks of different thicknesses are shown in figure 8 and figure 9. When the hydraulic pressure is 450MPa, the spiral tube is fully expanded and fully fits the mold, and the rebound of the spiral tube is small, but the plastic strain of the spiral tube is about 1.5, therefore, the thinning rate of the inner surface of the contact area of the spiral tube is larger, the wall thickness is smaller, and a groove is formed on the inner surface of the contact area. The minimum wall thickness and maximum wall thickness of the spiral tube formed by the tube blank thickness of 5mm, 5.5mm, 6mm are 3.31mm, 3.61mm, 4.13mm and 5mm, 5.52mm, 6.05mm respectively. Considering comprehensively, a suitable thickness of the tube blank is 5.5mm.

Figure 8 Spiral tube formed from tube blanks of different thicknesses (22°C)

Figure 9 The influence of tube blank thickness on the quality of spiral tube

4.2 The influence of processing temperature on molding quality

In order to improve the plasticity of the material, reduce the hydraulic pressure required for forming and improve the forming quality of the spiral tube, this paper proposes a hot hydroforming spiral tube with equal wall thickness, the forming temperature of the spiral tube is 22°C, 300°C, 400°C,

500°C, 600°C, 700°C and 800°C.

4.2.1 Spiral tube hydroforming (22°C)

The processing temperature is 22°C. Four types of hydraulic pressures of 370MPa, 380MPa, 390MPa, and 400MPa are set in this thesis (figure 10). The study found that with the gradual increase of hydraulic pressure, the expansion height of the spiral tube also gradually increases. When the hydraulic pressure is 380MPa, the expansion height of the spiral tube is smaller (figure 11). When the hydraulic pressure reaches 390MPa, the spiral tube is fully expanded and fully fits the mold. The research results show that when the tube blank enters a certain stage of plastic deformation, a small increase in hydraulic pressure can make the spiral tube fully expand. The plastic strain of the spiral tube is relatively large, about 0.96, so the thinning rate is relatively large, the minimum wall thickness is 4.08mm, and the maximum wall thickness is about 5.52mm. The inner and outer surfaces of the spiral tube are smooth (figure 11 and 12).

Figure 10 Hydraulic pressure loading path (22°C) Figure 11 The influence of hydraulic pressure on the expansion of spiral tube(0.1s)

Figure 12 The influence of hydraulic pressure on the quality of spiral tube (0.1s)

When the processing temperature is 22°C, the residual stress in most areas of the spiral tube is small, and the residual stress in the small areas at both ends of the spiral tube is larger, and the maximum residual stress is 1166MPa. The rebound amount of the spiral tube is very small.

4.2.2 The processing temperature is 300°C

According to the uniaxial tensile experiment at 300°C, the finite element model of the spiral tube hydroforming is established. Six types of hydraulic pressures of 400MPa-450MPa are set (Figure 13).

The study found that as the hydraulic pressure gradually increased, the bulging height of the spiral tube gradually increased. When the hydraulic pressure is 410MPa, the spiral tube is fully bulged, fully fits the mold, and the rebound of the spiral tube is very small. The plastic strain on the surface in the contact area is the largest, about 1.1, so the thinning rate is relatively large, and the minimum wall thickness is only 3.71mm. Due to the large thinning rate of the inner surface of the contact area, the inner surface of the contact area of the spiral tube forms a groove, and the quality of the spiral tube is poor (Figure 15).

Figure 13 Hydraulic pressure loading path

Figure 14 The influence of hydraulic pressure on the

(300°C)

expansion of spiral tube (300°C)

When the hydraulic pressure is 400MPa, the bulging amount of the spiral tube is very small, and the straight tube sections at both ends are easier to bulge, and the middle spiral section is more difficult to bulge (Figure 14). The processing temperature is 300°C, the maximum residual stress of the spiral tube is about 1224MPa, the maximum residual stress at the transition between the spiral section and the straight section (Figure 14).

Figure 15 The influence of hydraulic pressure on the quality of spiral tube (300°C)

4.2.3 The processing temperature is 400°C

The processing temperature is 400°C, and six types of hydraulic pressures of 300MPa-350MPa are set in this thesis (Figure 16). The study found that with the gradual increase of hydraulic pressure, the bulging height of the spiral tube gradually increases. When the hydraulic pressure is 300MPa-320MPa, the bulging height of the spiral tube is smaller, when the hydraulic pressure reaches 330MPa, the spiral tube is fully expanded and fully fits the mold (Figure 17). Once again, it shows that when the tube blank enters a certain plastic stage, a small increase in hydraulic pressure can fully expand the spiral tube. Moreover, after entering the stage where the hydraulic pressure remains unchanged, the tube will continue to bulge. The material in the contact area flows to the bulging area on both sides, so the wall thickness of the contact area is the smallest, and the plastic strain is about 0.9, so the thinning rate is greater, and the minimum wall thickness is 3.98mm. The maximum wall thickness at the bottom of the bulging zone, the maximum wall thickness is 5.522mm, and the inner surface of the spiral tube is smooth (Figure 18).

Figure 16 Hydraulic pressure loading path (400°C)

Figure 17 The influence of hydraulic pressure on the expansion height of spiral tube

Figure 18 The influence of hydraulic pressure on the forming quality of spiral tube (400°C)

4.2.4 The processing temperature is 500°C

The processing temperature is 500°C. This thesis sets five types of hydraulic pressures of 220MPa, 225MPa, 230MPa, 240MPa, and 250MPa (Figure 19). When the hydraulic pressure is 220MPa-225MPa, the bulging amount of the spiral tube is small (Figure 20). When the hydraulic pressure reaches 230MPa, the spiral tube is fully bulged and fully fits the mold. The maximum plastic strain of the section is about 0.58, the thinning rate is small, the minimum wall thickness is about 4.29mm, the

maximum wall thickness is about 5.48mm, and the inner and outer surfaces of the spiral tube are smooth. The amount of rebound is very small (Figure 21).

Figure 19 Hydraulic pressure loading path (500°C)

Figure 20 The influence of hydraulic pressure on the expansion height of spiral tube

Figure 21 The influence of hydraulic pressure on the forming quality of spiral tube (500°C)

The residual stress in most areas of the spiral tube is small, and the residual stress in a small area is larger, after the spiral tube is fully expanded, the residual stress is about 700 MPa (Figure 20).

4.2.5 The processing temperature is 600°C

When the processing temperature is 600°C, four types of hydraulic pressures of 130MPa, 140MPa, 150MPa, and 160MPa are set in this thesis (Figure 22). The study found that as the hydraulic pressure gradually increases, the bulging height of the spiral tube gradually increases, the gap between the spiral tube and the mold is gradually reduced (Figure 24). When the hydraulic pressure reaches 160MPa,

the spiral tube is fully expanded and fully fits the mold, the maximum plastic strain of the section is about 0.7, so the thinning rate of the spiral tube is larger, the minimum wall thickness is 4.14mm, and the maximum wall thickness is 5.44mm. It can be seen from the plastic cloud diagram that the material in the contact zone flows to the two bulging zones, the amount of flow on the inner surface of the contact zone is the most obvious. The rebound amount of the spiral tube is very small (Figure 24). When the hydraulic pressure is 160 MPa, the maximum residual stress of the spiral tube is 392.2 MPa (Figure 23).

Figure 22 Hydraulic pressure loading path (600°C)

Figure 23 The influence of hydraulic pressure on the expansion height of spiral tube

(a)130MPa

(b)140MPa

(c)150MPa

(d)160MPa

Figure 24 The influence of hydraulic pressure on the forming quality of spiral tube (600°C)

4.2.6 The processing temperature is 700°C

The processing temperature is 700°C, and six types of hydraulic pressures of 50MPa-100MPa are set in this article (Figure 25). The study found that as the hydraulic pressure increases, the expansion height of the spiral tube gradually increases. when the hydraulic pressure reaches 70MPa, the spiral tube is fully expanded and fully fits the mold , the maximum plastic strain of the section is about 0.61, the thinning rate of the spiral tube is small, the minimum wall thickness of the spiral tube is the maximum value of 4.31mm, and the maximum wall thickness is the minimum value of 5.356mm (Figure 26), the inner and outer surfaces of the spiral tube are smooth. The wall thickness distribution of the spiral tube is more uniform, and the quality of the spiral tube is better (Figure 27).

Figure 25 Hydraulic pressure loading path (700°C)

Figure 26 The influence of hydraulic pressure on the forming quality of spiral tube (600°C)

When the hydraulic pressure is 70MPa, the maximum plastic strain of the entire spiral tube is only 0.65. The plastic strain of the spiral tube in most areas is small, the damage to the material during the forming process is small, and the rebound of the spiral tube is small. Therefore, the quality of the spiral tube is better when the processing temperature is 700°C (Figure 27).

Figure 27 The influence of hydraulic pressure on the forming quality of spiral tube (700°C) (a) Mises stress cloud diagram of spiral tube (b) Plastic strain cloud diagram of spiral tube

4.2.7 The processing temperature is 800°C

The processing temperature is 800°C, and six types of hydraulic pressures of 50MPa-100MPa are set in this thesis (Figure 28). The study found that at 0.045s, when the hydraulic pressure is 60MPa, the spiral tube has been fully expanded and fully fits the mold. However, at 0.1s, when the hydraulic pressure is 60-90MPa, there is a gap between the spiral tube and the mold (Figure 30). Therefore, when the processing temperature is 800°C, the rebound amount of the spiral tube is relatively large.

Comparing the cross-sectional cloud diagram of the spiral tube under the same hydraulic pressure

loading conditions at 0.045s and 0.1s (Figure 30 and 31), it can be seen that the rebound of the spiral tube is more obvious when the processing temperature is 800°C. Therefore, when the processing temperature is 800°C, the hydraulic pressure required for full expansion of the spiral tube should not be less than 100MPa (Figure 30 and 31).

When the hydraulic pressure increases from 50 MPa to 80 MPa, the plastic strain of the spiral tube section gradually increases from 0.82 to 0.88. When the hydraulic pressure increases to 90MPa, the plastic strain is about 0.9, the thinning rate is larger, the minimum wall thickness of the spiral tube is 4.21mm, since the inner surface of the contact area has the largest thinning rate, the inner surface of the contact area of the spiral tube has grooves, and the spiral tube has a large rebound amount . Therefore, the quality of the spiral tube is poor (Figure 32). When the processing temperature is 800°C, the residual stress of the spiral tube is very small, and the maximum residual stress is only 72MPa (Figure 29).

Figure 28 Hydraulic pressure loading path (800°C)

Figure 29 The influence of hydraulic pressure on the expansion height of spiral tube (0.1s)

(a)50MPa

(b)60MPa

(c)70MPa

(d)80MPa

(e)90MPa

(f)100MPa

Figure 30 The influence of hydraulic pressure on the forming quality of spiral tube (0.045s)

(a)50MPa

(b)60MPa

(c)70MPa

(d)80MPa

(e)90MPa

(f)100MPa

Figure 31 The influence of hydraulic pressure on the forming quality of spiral tube (0.1s)

(a)50MPa

(b)60MPa

(c)70MPa

Figure 32 The influence of hydraulic pressure on the forming quality of spiral tube (0.1s)

5 Conclusions

The hydroforming of the stator spiral tube of small size and equal wall thickness is proposed in this paper, the influence of tube blank size and processing temperature on the quality of spiral tube is studied, and the following research conclusions are drawn based on the research results.

(1). Appropriate tube blank size is the outer diameter is 48mm, the wall thickness is 5.5mm, and the length is 1405mm. The processing temperature is increased from 22°C to 300°C, and the hydraulic pressure required for full expansion of the spiral tube is increased from 390MPa to 430MPa. When the processing temperature is gradually increased from 300°C to 700°C, the hydraulic pressure for full expansion of the spiral tube is gradually reduced, and the required hydraulic pressure is gradually reduced from 430MPa to 70MPa. However, when the processing temperature is increased from 700°C to 800°C, because the material is too soft, the hydraulic pressure required for full expansion of the spiral tube increases from 70Mpa to 100MPa (Figure 33 (a)).

(2). As the processing temperature increases from 22°C to 300°C, the maximum residual stress of the spiral tube increases from 1172MPa to 1224MPa. When the processing temperature increases from 300°C to 800°C, the maximum residual stress of the spiral tube gradually decreases from 1224MPa to 69.15MPa. The residual stress in most areas of the spiral tube is small, and the residual stress on the convex arc surface at both ends of the spiral section is relatively large (Figure 33 (b)).

(3). When the processing temperature is 700°C, the minimum wall thickness of the spiral tube is the maximum value of 4.31mm, and the maximum wall thickness is the minimum value of 5.356mm, so the wall thickness of the spiral tube is more uniform. When the processing temperature is 800°C, because the material becomes very soft, the rebound of the spiral tube is relatively large. When the processing temperature is 700°C and 800°C, the maximum plastic strain of the entire spiral tube is less than 1, about 0.65 and 0.925, respectively. Since the straight pipe section is easier to bulge than the spiral section, when the hydraulic pressure continues to increase to make the spiral section fully expand, the plastic strain of the straight pipe section is greater than 1 at other processing temperatures. (Figure 33 (c) and (d)). Therefore, when the processing temperature is 700°C, the quality of the spiral tube is better.

(a)

(b)

(c)

(d)

Figure 33 Processing temperature is the influence of spiral tube hydroforming (a) The influence of processing temperature on the hydraulic pressure required for full expansion of the spiral tube (b) The influence of processing temperature on the residual stress of spiral tube (c) The influence of processing temperature on the wall thickness of spiral pipe (d) The influence of processing temperature on plastic strain of spiral tube

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a. Funding (information that explains whether and by whom the research was supported)

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b. Conflicts of interest/Competing interests (include appropriate disclosures)

Research on hydroforming micro-sized spiral pipe with equal wall thickness (Not applicable)

c. Availability of data and material (data transparency)

Detailed data is given in the paper.

d. Code availability (software application or custom code)

Research on hydroforming micro-sized spiral pipe with equal wall thickness (Not applicable)

e. Ethics approval (include appropriate approvals or waivers)

We respect all ethical standards.

f. Consent to participate (include appropriate statements)

Agree to participate.

g. Consent for publication (include appropriate statements)

Consent for publication.

h. Authors' contributions (optional: please review the submission guidelines from the journal whether statements are mandatory)

In order to solve the problem of the difficulty in processing the inner spiral surface of the small size and large aspect ratio, the tiny size spiral tube stator is proposed in this paper and the normal temperature and hot state

hydroforming of the small size spiral tube is proposed in this paper.

>If any of the sections are not relevant to your manuscript, please include the heading and write 'Not applicable' for that section.

References

- [1] Qu, W. T. , Liu, S. Y. , & Xu, Z. S. . (2015). Research on corrosion rate of sucker rod steel 20ni2mo in wet h₂s environment. *Materials Science Forum*, 814, 319-324.
- [2] Wen Gangzhu, Jin Jian, Li Ou, & Pang Zhihui. (2013). Research on Electrochemical Machining Technology of Constant Wall Thickness Positive Displacement Motor Stator. *Petroleum Field Machinery*, 42(4), 33-39.
- [3] Peng Gang, Zheng Hualin, He Wei, & Chen Jian. (2010). Research on the layout of the EDM machine tool for the stator of screw drilling tools. *Mining Machinery* (10), 41-43.
- [4] Zhang Mingqi, Cheng Xiaoyuan, Pan Zhifu. (2011) Electrochemical machining technology of constant wall thickness stator of positive displacement motor[J]. *Electrical Machining and Die*, (06): 29-32.
- [5] Chen Jin, Wang Ke, Sun Xingwei. (2015). Finite element analysis of extrusion forming of spiral curved surface in stator of multi-lobe positive displacement motor[J]. *Mechanical Engineering and Automation*, (05):56-57.
- [6] Wang Xinyun, Qi Zimei, Jin Junsong. (2015). Design of incremental forming die for spiral pipe with equal wall thickness [J]. *Die & Mold Industry*, 000(005): 17-21.
- [7] Qi Zimei. (2016).Research on Incremental Forging Process and Mechanism of Constant Wall Thickness Spiral Pipe [D]. *Huazhong University of Science and Technology*.
- [8] Li Xuejiao. (2013).Research and finite element analysis of thick-walled spiral tube forming equipment[D]. *Jilin University*.
- [9] Liu Xiaolin. (2016). Research on forming process and device of J55 steel spiral pipe with equal wall thickness [D]. *Harbin Institute of Technology*.
- [10] Shi, C., Li, J., & Zhu, X. (2021). Liquid filling and external extrusion composite forming tiny size spiral tube with equal wall thickness. *The International Journal of Advanced Manufacturing Technology*, 1-19.
- [11] Zhu, X., & Ji, W. (2017). Finite element analysis and experimental study on roll-forming method in iso-wall thickness stator bushing of screw drilling. *The International Journal of Advanced Manufacturing Technology*, 93(5), 1939-1952.
- [12] Shi, C., Li, J., Deng, J., Zhu, X., & Jia, Y. (2020). Study on multi-roller rotary feed forming mechanism of spiral tube with uniform wall thickness. *The International Journal of Advanced Manufacturing Technology*, 106(9), 4593-4610.
- [13] Shi, C., Li, J., Deng, J., & Zhu, X. (2021). External high-pressure forming of metal spiral tube of equal wall thickness. *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering*, 235(2), 536-547.
- [14] Han Cong, He Jiuqiang, Yuan Shijian. (2016). Research on internal high pressure forming of 780MPa ultra-high strength steel torsion beam[J]. *Precision Forming Engineering*, 8(5):53-59.

- [15] Wang Zhibiao, Fan Xiaobo, Qi Zhongkuan, He Zhubin, & Yuan Shijian. (2017). Research on the hot air pressure bulging behavior of BR1500HS high-strength steel welded pipe. Innovative plastic processing technology to promote the development of intelligent manufacturing-National Society of Plasticity Engineering Annual Conference and Global Chinese plastic processing technology exchange meeting.
- [16] Wu Liang, Luo Jianbin, Li Jian, Su Haidi, Zhu Shujian, & Chang Xue. (2018). Simulation study of automobile longitudinal beam hydroforming. *Forging Technology*, 043(005), 68-75.
- [17] Zhang Weiwei, Han Cong, Han Huaizhi, Yuan Shijian, & Li Bingxi. (2013). The influence of the shape of the corrugated tube on the stability and heat transfer characteristics of the corrugated tube. *Journal of Harbin Institute of Technology* (07), 57-62.
- [18] Peng Heli, Zhang Xiaolong, Li Zhongquan, Xu Aijie, Shi Zhengbo, & Feng Sule. (2015). Numerical simulation and experiment of corrugated pipe hydroforming. *Aerospace manufacturing technology* (2).
- [19] Xu, X. , Zhang, W. , Li, S. , & Lin, Z. . (2009). Study of tube hydroforming in a trapezoid-sectional die. *Thin-Walled Structures*, 47(11), 1397-1403.
- [20] Crapps, J., Marin, E. B., Horstemeyer, M. F., Yassar, R., & Wang, P. T. (2010). Internal state variable plasticity-damage modeling of the copper tee-shaped tube hydroforming process. *Journal of Materials Processing Technology*, 210(13), 1726-1737.
- [21] Cui, X. L., Wang, X. S., & Yuan, S. J. (2014). Deformation analysis of double-sided tube hydroforming in square-section die. *Journal of Materials Processing Technology*, 214(7), 1341-1351.
- [22] Alzahrani, B., Ngaile, G., & Yang, C. (2013). Part 1: Analytical modeling of symmetric multi-nose tube hydroforming. *Journal of Manufacturing Processes*, 15(2), 273-286.
- [23] Alzahrani, B., & Ngaile, G. (2013). Part 2: Analytical modeling of regular planar polygon tube hydroforming as a special case of symmetric multi-nose tube hydroforming. *Journal of Manufacturing Processes*, 15(2), 287-297.
- [24] Nishant Jain; Jyhwen Wang (2005). Plastic instability in dual-pressure tube-hydroforming process. , 47(12), 1827–1837. doi:10.1016/j.ijmecsci.2005.07.010.