Numerical Simulation of Hot Extrusion Process of GH3625 Alloy Tubes

Yutian Ding, Bin Meng, Xin Gao, Yubi Gao, Zhengyi Dou and Zhi Jia

Abstract In order to obtain GH3625 superalloy seamless pipe, the GH3625 superalloy seamless pipe with Φ28 × 5.5 mm was developed through short-flow hot extrusion forming and cold rolling molding process. And a comprehensive evaluation to the microstructure and mechanical properties for GH3625 superalloy seamless pipe was conducted. The results show that hollow tube has been successfully extruded the GH3625 superalloy tube with Φ43 × 9.5 mm under the condition of fixed extrusion speed of 50 mm/s, preheating temperature of 1150 °C and extrusion ration of 7.4. The alloy tube is composed of a small amount of deformation twin and a large number of equiaxed crystal mixed crystal structure, the average grain size is about 8.6, and the tensile strength at room temperature and elongation at break are 771 MPa and 52.33%, respectively, and have good cold working performance and mechanical properties. The performance of GH3625 superalloy seamless pipe after cold rolling and annealing is in accordance with ASTM-B163-04 international standard.

Keywords GH3625 alloy · Hot extrusion · Numerical simulation
Orthogonal experiment

Y. Ding (✉) · B. Meng · X. Gao · Y. Gao · Z. Dou · Z. Jia
State Key Laboratory of Advanced Processing and Recycling of Nonferrous Metals,
Lanzhou University of Technology, Lanzhou 730050, China
e-mail: Dingyutian@126.com

B. Meng
e-mail: mengbin1219@126.com

X. Gao
e-mail: 469046647@126.com

Y. Gao
e-mail: gaoyubi1991@126.com

Z. Dou
e-mail: 893342733@qq.com

Z. Jia
e-mail: 419285787@126.com

Y. Han (ed.), *High Performance Structural Materials*,
https://doi.org/10.1007/978-981-13-0104-9_65

Introduction

As a kind of alloy with high strength and excellent oxidation resistance and corrosion resistance under high temperature conditions, GH3625 alloy has attracted worldwide attention since its inception, especially in chemical industry, nuclear power, aerospace and so on [1, 2]. As GH3625 alloy hot extrusion pipe size is larger, the wall is thin, and GH3625 alloy itself, high strength materials, low plastic processing, thermal processing temperature range narrow [3], so in the hot extrusion process is difficult, Accurate control of GH3625 alloy thermal deformation behavior is more difficult. For now, China's preparation of GH3625 alloy pipe extrusion technology is not perfect control. In addition, the hot extrusion program in the factory is usually based on the actual experience of the technical staff and try to experiment several times to develop the trial and error method, but because GH3625 alloy itself is higher cost, labor loss, and the need to start the machine resources, Resulting in its high production costs, low efficiency, long cycle time, it is difficult to solve the actual hot extrusion difficulties [4]. Based on the numerical simulation technology of finite element software, the hot extrusion behavior of GH3625 alloy pipe can be explored from all aspects and angles in a comprehensive, thorough and detailed way without being bound by the actual experimental conditions [5–9]. Therefore, the use of finite element software for numerical simulation analysis has become difficult to deform nickel-based superalloy pipe hot extrusion process research and development of effective path.

By studying the peak temperature and peak squeezing force of the most important billet in the hot extrusion process, the orthogonal test was carried out by ABAQUS. The blank temperature and the peak squeezing force were used as the evaluation indexes to discuss the blank Hot temperature, die angle, extrusion speed, extrusion ratio and friction coefficient on the temperature rise and peak squeezing force of blank. In order to optimize the hot extrusion experiment scheme of GH3625 alloy pipe, the hot extrusion parameters combination is used to provide the basis for the actual hot extrusion experiment.

Materials and Experimental

Extrusion Materials and Dimensions The simulation was carried out for the hot extrusion of $\varphi 152 \times 16$ mm. The experiment was carried out using hollow ingot, blank $\Phi 260 \times 70 \times 350$ mm, extrusion ratio 6.7. The simulation of extruded blank GH3625 alloy, the mold material for the GH4169 alloy, perforated pin for the H13 steel, the basic performance parameters in Table 1.

The Establishment of Constitutive Equation GH3625 alloy vacuum induction + electroslagre melting smelting ingot, the two-stage homogenization treatment. A high temperature hot compression experiment was carried out at a temperature of 800–1200 °C and a strain rate of 0.01–10 s^{-1} using a Gleeble-3800

Table 1 Properties of Billet, Die and Ram

Properties	Materials	Young's modulus (GPa)	Poisson ratio	Density (kg m^{-3})	Thermal conductivity (W m^{-1} K^{-1})	Specific heat (J kg^{-1} K^{-1})	Thermal expansion coefficient (K^{-1})
Billet	GH3625	159.4	0.308	8.44×10^3	22.8	645	1.58×10^{-5}
Die	GH4169	–	–	8.24×10^3	27.6	704	–
Ram	H13	–	–	7.80×10^3	28.4	560	–

thermal simulation tester. The stress-strain of the alloy was obtained. And the constitutive equation of GH3625 alloy was obtained according to the experimental data.

$$\dot{\varepsilon} = 6.352 \times 10^{14}[\sinh(0.0063\sigma)]^{5.59}\exp\left[-\frac{652.22 \times 10^{3}}{RT}\right]. \quad (1)$$

($(\dot{\varepsilon})$ is the strain rate, s^{-1}. σ is the peak stress, MPa. R is the gas constant, R = 8.314 J (K mol)$^{-1}$.

Establishment and Simulation of Finite Element Model in this paper, finite element software ABAQUS is used to simulate the hot extrusion of GH3625 alloy pipe. Deformation process of the existence of heat exchange and friction heat and other processes, so the use of thermal coupling analysis method. The entire extrusion process is geometrically symmetrical, the model is treated as an axisymmetric model, and the perforations and squeeze pads, extrusion cylinders and molds are treated as a rigid body with heat transfer properties, regardless of their Plastic deformation. Grid unit type selection CAX4RT, mold die angle deformation is large, where the grid density is larger than other places, the blank grid is completely uniform. The extrusion process of metal is a large deformation process, using adaptive grid technology to improve the convergence, and the use of mass scaling technology to improve the efficiency of computing. The simplified finite element model is shown in Fig. 1.

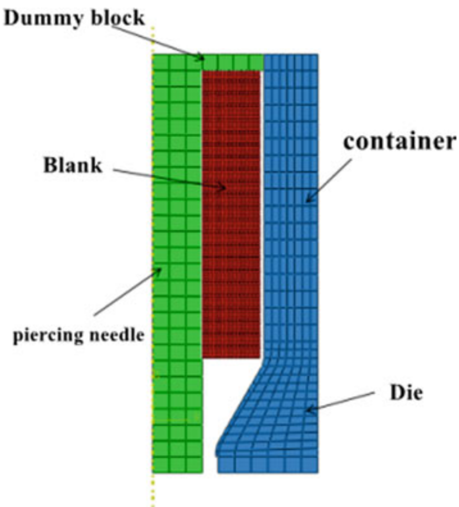

Fig. 1 Geometrical model and mesh design of FE model

Model Reliability Verification by comparing the simulated squeezing force with the theoretical squeezing force to verify whether the finite element model is reasonable. The maximum squeezing force of the preheating temperature of 1100, 1150, 1180, 1200 °C, extrusion ratio 6.7 and extrusion speed of 50 mm/s was calculated by using the theoretical squeezing force calculation formula. Based on the above conditions, the finite element model, In order to verify the extrusion process of geometric model, material model, boundary conditions, the reliability of grid points. Where the theoretical squeeze force formula [10]:

$$P = \beta A_0 \sigma_s \ln \lambda + \mu \sigma_s \pi (D + d) L. \quad (2)$$

where, P is the pressing force, N; A_0 is the extrusion cylinder or extrusion cylinder minus the needle area, mm^2; σ_s is the deformation resistance, temperature and other related deformation resistance, MPa; λ for the extrusion coefficient; μ is the coefficient; D is the length of the ingot, mm; d is the diameter of the extruded needle, mm; β is the correction coefficient (1.3–1.5, where the hard alloy is large, Soft alloy take small), GH3625 belongs to hard alloy, the value of β is set to 1.5.

It can be seen from Table 2 that the peak squeezing force obtained by the theoretical formula is close to the simulated value, the difference is less than 3.85 MN, and the error is less than 8%.

Simulation Results and Discussion

The blanking temperature T, the die angle θ, the extrusion speed v, the extrusion ratio λ and the friction coefficient μ were used as the influencing factors. The blank orthogonal test was established by using the blank temperature T and the peak pressing force F_{max} as the evaluation index. The Each group of tests in the orthogonal Table 3 was calculated using ABAQUS, and the blank temperature and peak squeezing force of the 16 groups were filled in the orthogonal test table.

As shown in Table 4, in order to facilitate the comparison of the different factors at different levels on the impact of the different temperature of the blank, the four factors under different factors corresponding to the average billet temperature rise, calculated by the billet preheating temperature factor, The modulo factor, the extrusion speed factor, the extrusion ratio factor and the friction coefficient factor

Table 2 Comparison between theoretical load and simulated load

Billet temperature (°C)	Resistance to deformation (MPa)	Simulated load (MN)	Theoretical load (MN)	Error (%)
1100	149.55	46.6	50.45	7.6
1150	111.22	34.5	37.50	8.0
1180	86.22	28.2	29.07	3.0
1200	78.63	25.2	26.45	4.7

Table 3 GH3625 pipe hot extrusion orthogonal test simulation results

Test No.	Blank preheating temperature (°C)	Angle (°)	Extrusion speed (mm s^{-1})	Extrusion ratio	Coefficient of friction	Blank temperature rise (°C)	Peak squeezing force (MN)
1	1140	20	30	5	0.02	42.85	20.77
2	1140	25	50	7	0.05	53.85	34.21
3	1140	30	70	9	0.08	62.85	53.54
4	1140	40	90	11	0.10	92.85	66.92
5	1160	20	70	11	0.05	55.85	44.03
6	1160	25	90	9	0.02	54.85	25.25
7	1160	30	30	7	0.10	46.85	56.52
8	1160	40	50	5	0.08	48.85	28.56
9	1180	20	90	7	0.08	42.85	41.16
10	1180	25	70	5	0.10	36.85	36.08
11	1180	30	50	11	0.02	46.85	28.94
12	1180	40	30	9	0.05	49.85	29.96
13	1200	20	50	9	0.10	75.85	48.75
14	1200	25	30	11	0.08	54.85	57.98
15	1200	30	90	5	0.05	37.85	17.23
16	1200	40	70	7	0.02	37.85	18.50

Table 4 Blank temperature rise results

Test No.	Blank preheating temperature (°C)	Angle (°)	Extrusion speed (mm s^{-1})	Extrusion ratio	Coefficient of friction
A_1	252.0	217.0	194.0	166.0	182.0
B_1	206.0	200.0	225.0	181.0	197.0
C_1	176.0	194.0	193.0	243.0	209.0
D_1	206.0	299.0	228.0	250.0	252.0
A_2	63.1	54.0	48.6	41.6	45.6
B_2	51.6	50.1	56.4	45.4	49.4
C_2	44.1	48.6	48.4	60.9	52.4
D_2	51.6	57.4	57.1	62.6	63.1
Range	19.0	8.8	8.7	21.0	17.5

are 19.0, 8.8, 8.7, 21.0, 17.5 °C, respectively. Therefore, the preheating temperature, the extrusion ratio and the friction coefficient of the blank have a great influence on the temperature rise of the blank, and the effect of the die angle and the extrusion speed on the blank temperature is small. The effect of the blank temperature on the temperature rise is: Preheat temperature > Coefficient of friction > Mold angle ≈ Extrusion speed.

Similarly, as shown in Table 5, the difference between the preheating temperature factors, the die angle factor, the extrusion speed factor, the extrusion ratio factor and the coefficient of friction factor is calculated as 9.82, 3.07, 6.19, 23.81 and 28.70 MN The Therefore, the extrusion ratio and the friction coefficient have a great influence on the peak squeezing force, and the preheating temperature, the die angle and the extrusion speed have little effect on the blank temperature rise. The influence of the peak squeezing force is: the friction coefficient > Extrusion ratio > preheating temperature of the blank > extrusion speed > die angle.

Table 5 Peak squeeze results

Test No.	Blank preheating temperature (°C)	Angle (°)	Extrusion speed (mm s^{-1})	Extrusion ratio	Coefficient of friction
A_3	175.44	154.71	165.00	102.64	93.00
B_3	154.36	154.00	140.46	150.39	125.43
C_3	136.14	156.23	152.15	157.50	181.24
D_3	142.46	143.94	150.56	197.87	208.27
A_4	43.86	39.00	41.31	25.66	23.37
B_4	38.59	38.38	35.12	37.60	31.36
C_4	34.04	39.06	38.04	39.38	45.31
D_4	35.62	35.99	37.64	49.47	52.07
Range	9.82	3.07	6.19	23.81	28.70

Observation of the orthogonal test results can be found in the tenth group of the blank temperature is the lowest temperature of 36.85 °C, but the peak extrusion force of 36.08 MN, and the fifteenth group of the blank temperature is very low to 37.85 °C, but its Peak extrusion force is only 17.23 MN, so taking into account the billet temperature rise and peak squeeze force size, you can visually find the results of the fifteenth group is optimal, the thermal extrusion parameters are: blank preheating temperature 1200 °C, die angle 30°, extrusion speed 90 mm/s, extrusion ratio 5, friction coefficient 0.02. According to the influence of various factors on the temperature rise of the blank and the peak squeezing force, the following types of speculation may be obtained by combining the different factors. The temperature of the blank and the lower pressing force may be obtained. The parameters are shown in Table 6. The optimum parameters of the hot extrusion of GH3625 alloy pipe were obtained by simulating the combination of the hot extrusion process parameters of the following five groups of GH3625 alloy.

Analysis of Peak Squeezing Force Since the combination of parameters in each group is optimized by the orthogonal test method, and the whole orthogonal test is also the peak extrusion force as a test index, as shown in Table 6, each group of parameters under the Peak squeezing force is relatively small. Figure 2 shows the time-squeezing force curve of the combination of excellent factors. The peak squeezing force of these five groups is 17.23, 16.47, 16.15, 14.40 and 15.68 MN respectively. It can be found that the peak squeezing force of group 15 is greater than The first group, group II, group III, group IV peak squeezing force, this is because the 15th group of parameters is the initial orthogonal test obtained the best combination of parameters, and the latter four groups are considering the preheating temperature of the blank, The factors such as the angle factor, the extrusion speed factor, the extrusion ratio factor and the friction coefficient factor on the peak squeezing force are obtained. In the five sets of experiments, the hot extrusion parameters of the GH3625 alloy pipe with the smallest peak pressing force were combined with the preheating temperature of the material 1200 °C, the angle of 30°, the extrusion speed of 50 mm/s, the extrusion ratio of 5, the friction coefficient of 0.02 The peak extrusion force is 14.40 MN. The second is the preheating temperature 1180 °C, the angle of 30°, the extrusion speed of 70 mm/s, the extrusion ratio of 5, the friction coefficient of 0.02, the combination of the peak extrusion force of 15.68 MN.

Analysis of Temperature Rise of Blank As shown in Table 6, under the optimized hot extrusion parameters, the local temperature rise of the blank was not overgrown during the hot extrusion of the GH3625 alloy pipe during the hot extrusion process. As shown in Fig. 3, the peak temperatures of Group 15, Group I, Group II, Group III and Group IV were 1237.85, 1194.85, 1195.85, 1229.85 and 1197.85 °C respectively, and the temperature of the blank reached 37.85, 14.85, 15.85, 29.85, 17.85 °C. The temperature of the billet preheating temperature is 1200 °C, while the preheating temperature of the billet is 1180 °C, the temperature rise is small, indicating that the lower preheating temperature of the blank can be effectively reduced The local temperature rise of the blank. It is suitable to optimize

Table 6 Outstanding factor level combination list

Test No.	Blank preheating temperature (°C)	Angle (°)	Extrusion speed (mm s^{-1})	Extrusion ratio	Coefficient of friction	Blank temperature rise (°C)	Peak squeezing force (MN)
15 groups	1200	30	90	5	0.02	37.85	17.23
I	1180	40	50	5	0.02	14.85	16.47
II	1180	30	50	5	0.02	15.85	16.15
III	1200	30	50	5	0.02	29.85	14.40
IV	1180	30	70	5	0.02	17.85	15.68

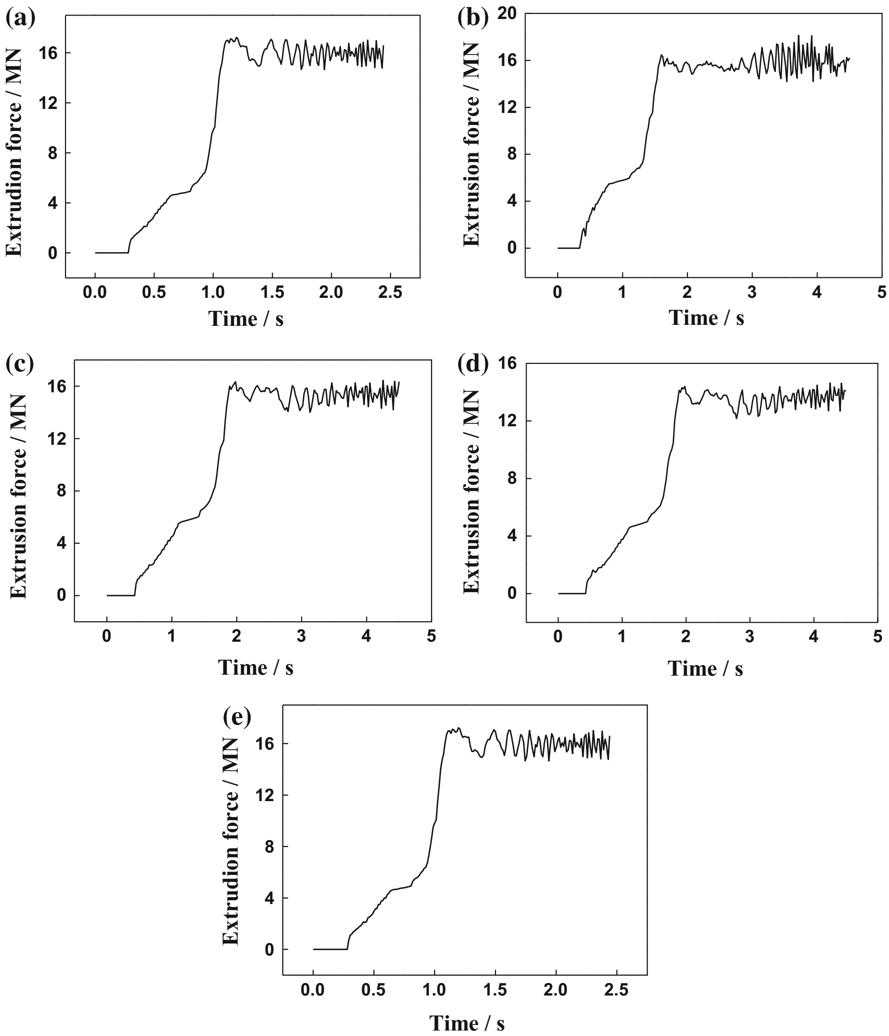

Fig. 2 Time-squeezing force variation under different parameter combinations. **a** 15 group, **b** I group, **c** II group, **d** III group, **e** IV group

the preheating temperature of the preform to 1180 °C. In the multi-index orthogonal test, the impact of different factors on different indicators is different. Therefore, by analyzing the peak squeezing force and the change of the billet temperature, taking into account the hot extrusion process of the GH3625 alloy pipe, the peak squeezing force change should be given priority, and then the temperature of the blank should be taken into account. The peak temperature of the group III reached 1229.85 °C, the temperature rose 29.85 °C, the peak temperature of the IV group reached 1197.85 °C, the temperature rise was 17.85 °C, so we

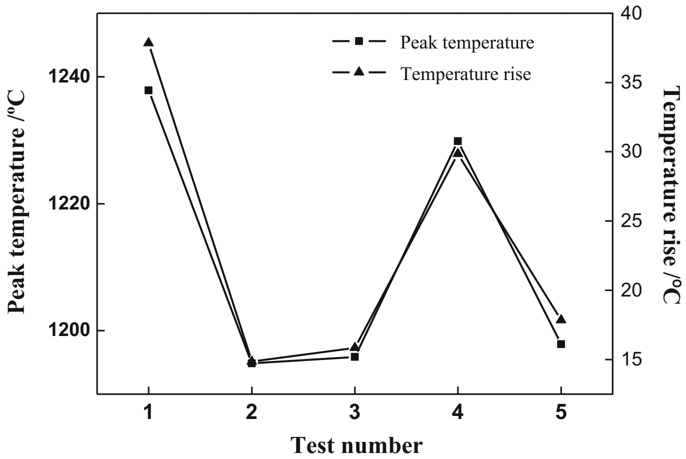

Fig. 3 Combination of different parameters of the blank peak temperature, temperature changes. 1-15 group, 2-I group, 3-II group, 4-III group, 5-IV group

chose the peak temperature (the temperature) of the first group was 14.40 and 15.68 MN respectively. Lower temperature rise in group IV. The optimum parameters are the preheating temperature of 1180 °C, the angle of 30°, the extrusion speed of 70 mm/s, the extrusion ratio of 5, the friction coefficient of 0.02 °C. Under this parameter, the peak pressing force is 15.68 MN, the peak temperature is 1197.85 °C, the temperature rise is 17.85 °C.

Conclusion

(1) The rank of impacting factors of the temperature rise for GH3625 alloy pipe hot extrusion parameters is: extrusion ratio > preheating temperature of the blank > coefficient of friction > die angle ≈ extrusion speed.
(2) The rank of the effect of hot extrusion parameters of GH3625 alloy pipe on the peak extrusion force is: friction coefficient > extrusion ratio > preheating temperature of the blank > extrusion speed > die angle.
(3) The hot extrusion process parameters of GH3625 alloy pipe have been obtained by orthogonal test. The specific parameters are as follows: preheating temperature 1180 °C, die angle 30°, extrusion speed 70 mm/s, extrusion ratio 5, friction coefficient 0.02. Under the above parameters the peak pressing force is 15.68 MN, the peak temperature is 1197.85 °C, the temperature rise is 17.85 °C.

Acknowledgements This study was funded by the National Natural Science Foundation of China (No. 51661019), The Science and Technology Projects of Gansu Province (No. 145RTSA004), the State Key Laboratory of Advanced Processing and Recycling of Nonferrous Metals, Lanzhou University of Technology.

References

1. S.K. Rai, A. Kumar, V. Shankar, Characterization of microstructures in Inconel 625 using X-ray diffraction peak broadening and lattice parameter measurements, J. Scripta Materialia. 51 (2004) 59–63.
2. J.B. Singh, A. Verma, B. Paul, Failure of Alloy 625 tube stub ends–Effect of primary nitrides, J. Engineering Failure Analysis. 32.3 (2013) 36–247.
3. W.D. Cao, R. Kennedy, Role of Chemistry in 718-type Alloys: Allvac 718 Plus TM Alloy Development, J. The Minerals, Metals & Materials Society. (2004) 91–99.
4. S. Zhang, Z. Wang, B. Qiao, Processing and Microstructural Evolution of Superalloy Inconel 718 during Hot Tube Extrusion, J. Journal of Materials Science & Technology. 21.2 (2005) 175–178.
5. Z.T. Wang, Y.G. Deng, S.H. Zhang, Numerical Simulation of Tube Forming of IN690 Superalloy, J, Special-cast and Non-ferrous Alloys. 31.10 (2011) 895–898.
6. J. Wang, J.X. Dong, M.C. Zhang, Numerical Simulation for Optimization if the Extrusion Process of GH4169 Trubs, J. Journal of University of Science and Technology Beijing. 32.1 (2010) 83–88.
7. Dang L, Yang H, Guo L G, Simulation research of damage behavior of lame-scale thick-walled Inconel 625 pipe during extrusion process, J. Journal of Plasticity Engineering. 22.5 (2015) 29–34.
8. L. Dang, H. Yang, L.G. Guo, DRX rules during extrusion process of large-scale thick-walled Inconel 625 pipe by FE method, J. Transactions of Nonferrous Metals Society of China. 25.9 (2015) 3037–3047.
9. S.C. Yan, High-temperature High-speed Hot Deformation Behavior of Inconel625 Alloy and Optimization of High-speed Extrusion Process for Tube of This Alloy, D. Dalian University of Technology. (2010).
10. J.L. Wen, H. Ding, F.R. Cao, Extrusion and Drawing Technology of Nonferrous Metals, M. Chemical Industry Press, 2007.