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Metallurgical Changes and Process Optimization During Forging of Connector Box-Pin- A Comprehensive Study

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ABSTRACT

This paper investigates the forging process and its effect on the metallurgical properties of connector box-pin, essential components in oil and gas during oil drilling operations. The study focuses on understanding the microstructural changes and the changes in mechanical properties that occur during different stages of forging and how these changes influence the mechanical properties. Key process parameters such as temperature, strain rate, reduction ratios and cooling methods were evaluated for their impact on the final product. Mechanical testing, including tensile, hardness, and Impact test, was carried out to assess and validate its performance in real-world applications. The results show that optimal process control during forging leads to improved microstructure, mechanical properties, and product reliability.

Keywords: *Forging, Reduction Ratio, Connector Box-Pin, Microstructure, Mechanical Properties, Process Control*

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1. INTRODUCTION

Forging is a manufacturing process that transforms raw metal into near-net shape components with enhanced mechanical properties. Connecting pin jigs, which play a crucial role in various mechanical assemblies, particularly in the automotive industry, must exhibit high strength, toughness, and wear resistance. The forging process significantly alters the microstructure of the material, directly impacting its performance under real-world conditions. This paper aims to explore the metallurgical changes that occur during forging and their implications for the final mechanical properties of connecting pin jigs. Special attention is given to process optimization and testing to ensure the pins meet rigorous application demands.

2. MATERIALS AND METHODS

2.1 Materials

The material selected for the forging process was medium carbon steel (0.28% C), which is widely used for components requiring a balance of strength, toughness, and machinability. The raw material used for the forging process is billet of the size 250 mm diameters. The billet is then taken through four stages of forming process to give its final shape of connector box. The box and pin assembly is required to thinning of the pipe wall length if the pipes are threaded directly over each other.

Drill pipes are connected to each other for digging deeper to reach the oil reservoir under the ground. Threads inside the connector pins accommodate the threaded ends of the two pipes

Fig 1: Representation of connector pins used during drill operations for connecting pipes

Also, this improves the handling, and wearing out the surface in long term application because of corrosion and the material is also heat treated to give its final mechanical and metallurgical properties. It is then threaded to be used at the sites for final application.

2.3 Process Parameters

Key process parameters investigated include:

Forging Temperature: The influence of temperatures ranging from 1250°C to 1300°C was studied. The temperature shall be in the austenitic region of the Fe-C diagram above A_{C3} temperature.

This ensures complete austenitic transformations and homogenous distribution of the forces. Heating to this temperature is necessary for better diffusion and flow stress. Heating above 1300°C is avoided to avoid grain coarsening which in turn deteriorates the mechanical properties. The temperature naturally comes down during different stages. At any time where the temperature drops below 950°C, the billet is further heated in the furnace to reach 1250°C to 1300°C.

Material Load: The material is loaded during different forging process to give it shape as desired. 1000 Tones hydraulic press is used for pancaking, blanking and piercing. This load ensures better flow of grains. When the billet is forged, the defects like pin holes and get welded thus increasing the soundness of the quality of the final product.

Heat Treatment: Heat treatment for the forged material is essential part to sustain the mechanical properties of the material and metallurgically enhance the material. Heat treatment consists of two cycles, hardening and annealing. Hardening is a heat treatment process where material is heated to a temperature above the A_{C1} temperature (753°C) for the composition given in table . The transformation completion temperature of ferrite to austenite is given by A_{C3} (835°C for the present composition). However, a superheat of nearly 30-40°C is maintained so as to compensate for the latent heat of solidification.

$$A_{C1}=727-10.7C-16.9Ni+29.1Si+16.9Mn-6.1Cr-10.9Cu-19.5Mo-7.0Nb-7.5Ti-6.5V$$

$$A_{C3} = 910 - 203\sqrt{C} - 15.2Ni + 44.7Si + 104V + 31.5Mo + 13.1W.$$

Cooling Rate: Both air cooling and controlled cooling in a furnace were explored to examine microstructural transformations post-forging. Heat treatment process was carried out in two steps of hardening and annealing. For hardening, the ring is soaked at temperature 850-890°C and quenched. Quenching with water and polymer in different ratio was explored (9-1%) to meet the desired metallurgical changes achieving mechanical properties. Annealing is performed at temperature range of 550-630°C. Material is then normalized by air cooling. Annealing helps the material regain its ductility and lower the hardness.

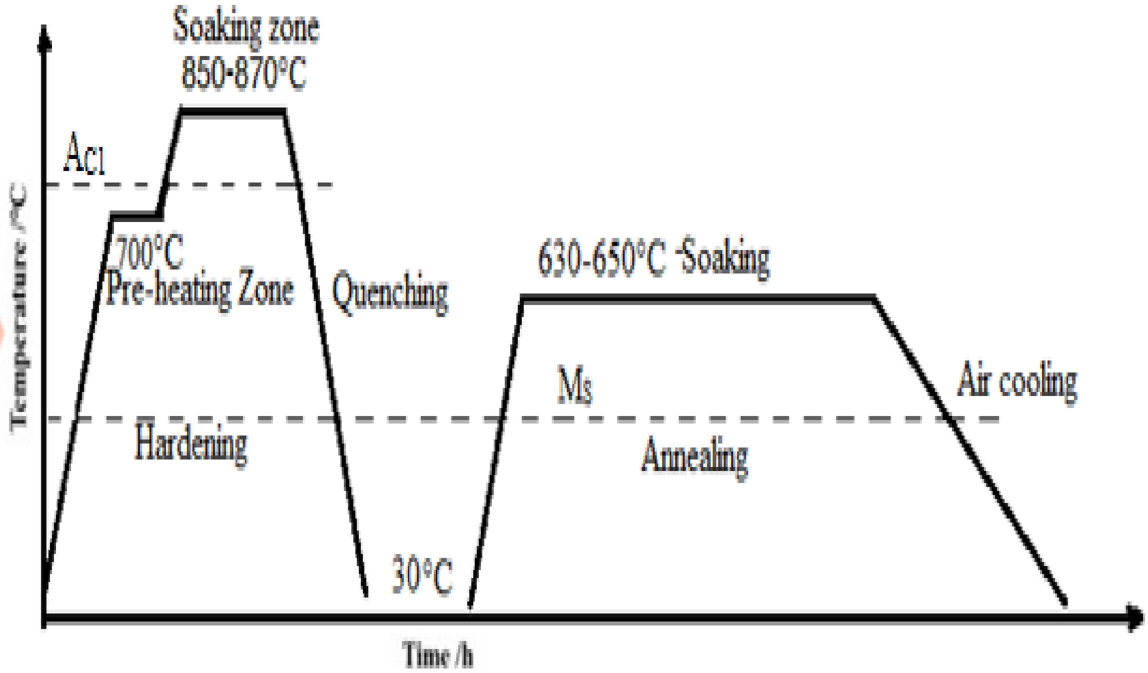

Fig 2: (a) Representing heat treatment cycle (a) Hardening at 850-890°C (b) Annealing at 550-630°C

3. EXPERIMENT

3.1 Experimental materials and design of experimental parameters

The chemical composition of the experimental steel is presented in Table 1, determined using a direct-reading spectrometer. In this study, medium carbon steel (0.22%C) steel was chosen. The carbon content and other alloying elements of the experimental steel are within the specified range for low-alloy high strength steel in general technical conditions. To prepare the experimental steel, cylindrical steel ingots of Ø250 mm × 300 mm were made using vacuum induction melting and electro-slag re-melting. The steel ingot was heated to 1250 °C at a rate of 60 min/in and held at that temperature for 3.5 h to ensure homogenization. After homogenization, employing varying forging ratios, these ingots underwent forging processes, adherence to the principle of volume invariance, resulting in PIN of size Ø100 mm × 130 mm and BOX of size of Ø160 mm × 120 mm. The initial forging temperature was above 1180 °C, and the final forging temperature exceeded 950 °C, followed by air cooling. As depicted in Fig. 4, the schematic illustrates the forging process of S1 steel with a forging ratio of 5.

Table 1: Chemical compositions of high strength steel (wt. %).

C	Si	Mn	Cr	Ni	V	Cu	Mo	P	S	Fe
0.22	0.26	1.56	0.62	0.007	0.01	0.008	0.02	0.018	0.004	97.2

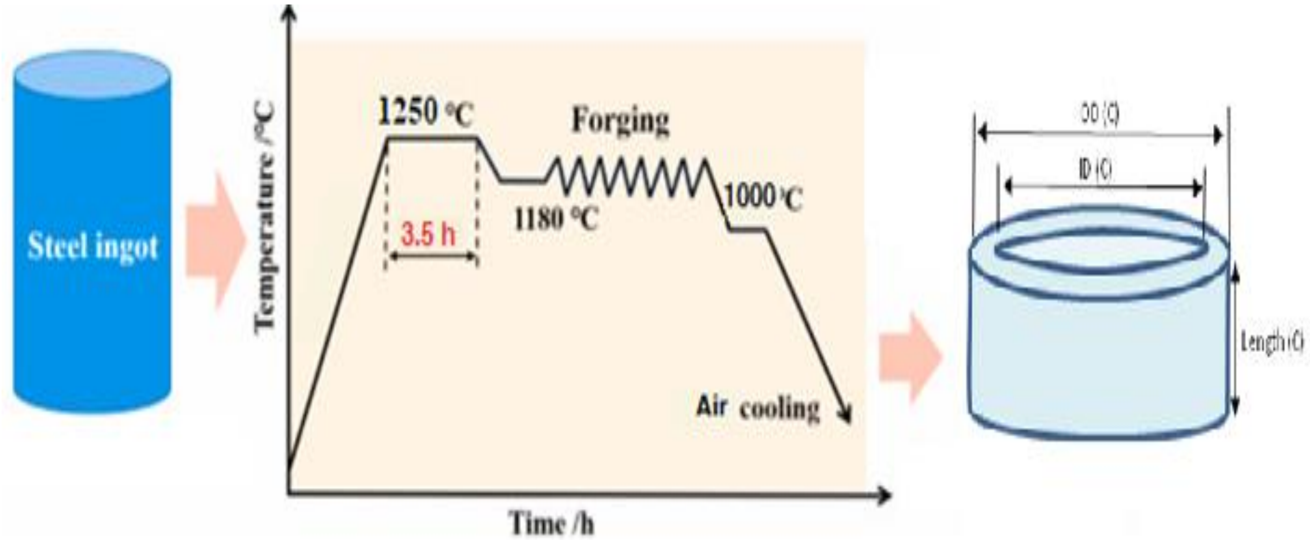

Fig 3: Representing temperatures in furnace and complete forging processes including ring rolling

3.2 Testing Methods

Mechanical and metallurgical tests were conducted to evaluate the quality of the forged connecting pin jigs:

Microstructural Analysis: Samples were etched and analyzed using optical microscopy to observe grain structure, recrystallization, and phase changes.

Tensile Testing: Tensile tests were conducted as per ASTM standards to determine yield strength, ultimate tensile strength (UTS), and elongation.

Hardness Testing: Rockwell hardness testing was performed on the cross-sections of the pins to measure hardness variation throughout the component.

Impact Testing: Charpy V-notch impact tests were carried out to assess toughness at various temperatures.

4. RESULTS AND DISCUSSION

4.1 Microstructural Evolution

The microstructural analysis revealed distinct changes as a result of the forging process. At forging temperatures above 1200°C, significant grain growth occurred, leading to coarser structures, while forging at 1150-1100°C resulted in finer grains due to dynamic recrystallization.

Grain Size: After hardening and quenching the martensite is formed. As the material is annealed at temperature of 620-650°C, stress relieving occurs and martensite is tempered with final grain size as 9 as per ASTM E112. At this temperature, recrystallization occurs to form ferrite and pearlite matrix.

Phase Transformation: Optical microstructure analysis revealed the presence of tempered martensite in samples after tempering at 620-650°C and matrix of ferrite and pearlite. Heat treatment enhanced the hardness of the pin and box while sufficiently improving the ductility. A balance between strength and toughness was achieved with pearlitic structures in controlled cooling conditions.

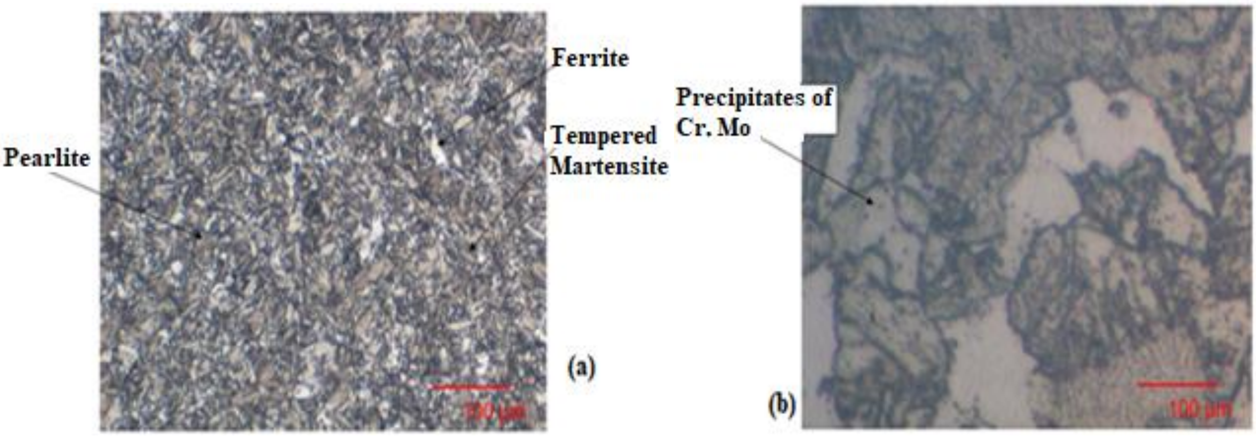

Fig 4: (a) Microstructure @100X, showing phases present and grain size of 9and (b) Microstructure @1000X, showing precipitates of Cr and Mo.

4.2 Mechanical Properties

The tensile tests showed a strong correlation between the microstructure and mechanical performance:

Ultimate Tensile Strength (UTS): The UTS ranged from 650-750 MPa, with the highest values observed in samples forged at 1150-1180°C and cooled under controlled conditions.

Hardness: The hardness values ranged between 91-96 HRB. Bainitic structures exhibited higher hardness but lower elongation, whereas pearlitic-ferritic structures showed better toughness.

Impact Toughness: The Charpy V-notch tests demonstrated that controlled cooling yielded impact energies of 70-80 Joules, suitable for applications that demand both strength and toughness.

Table 2: Results of tensile test, Charpy Impact test (V- notch) and Hardness test

Tensile Test						
Test Method	ASTM A370:2024, Test Specimen As per ASTM E8 : 2024					
Parameters	UOM	Specification	Actual			Remark
Yield Stress(0.5%EUL)	MPa	448	475			
U.T.S	MPa	552	663			
Reduction in Area	%	NA	---			
Elongation	%	20 (min)	32			
Results in Joules	J	Min. Ind. 38 J Min. Avg. 50 J	77	73	79	76 (Avg)

Observed Hardness (HRB)				
1	**2**	**3**	**4**	**5**
94.9	95.0	93.5	95.2	95.0
91.6	92.5	93.7	93.0	91.2

4.3 Effect of Process Parameters

The forging temperature significantly influenced the final mechanical properties. Higher forging temperatures led to coarse grains, reducing toughness. However, optimized forging at 1150°C provided a refined grain structure with superior mechanical properties. The cooling rate was another crucial factor; controlled cooling allowed for a pearlite-rich structure, improving toughness and elongation. Rapid cooling, though increasing strength, compromised the ductility of the connecting pin jigs, limiting their application in dynamic load-bearing systems.

5. CONCLUSION

This study highlights the importance of controlling key forging process parameters, such as temperature, strain rate, and cooling methods, to optimize the microstructural and mechanical properties of connecting pin jigs. A balance between strength, toughness, and wear resistance was achieved by carefully managing the forging temperature and cooling rate. The controlled cooling process resulted in a pearlite-rich microstructure that enhanced the toughness and fatigue resistance of the jigs, making them suitable for demanding applications in the automotive and heavy machinery industries. Future work could explore further refinements in material composition and heat treatment processes to enhance performance further.

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