

ENERGY FLOW AND PROCESS HOTSPOTS IN FORGED STEEL SHAFT MANUFACTURING: A PRODUCT-LEVEL ANALYSIS OF UPSTREAM AND DOWNSTREAM OPERATIONS

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<https://doi.org/10.37904/metal.2026.5272>

Abstract

Energy analyses in the metallurgical sector traditionally focus on upstream processes such as steelmaking and refining. However, when energy consumption is evaluated at the level of individual products, downstream manufacturing stages can represent a significant share of the total energy demand. This study investigates the energy flow associated with the manufacturing of a large forged steam turbine shaft using industrial production data from a European forging facility.

The analysis covers the complete manufacturing route of the shaft, including electric arc furnace (EAF) steelmaking, casting, reheating, forging, multiple heat treatment stages, machining operations and final heat stability testing. The results reveal that downstream thermal operations dominate the energy profile of the finished shaft, with heat stability testing identified as one of the main contributors to the overall energy demand, followed by reheating and heat treatment stages. In contrast, upstream steelmaking represents a relatively minor contribution when energy demand is allocated to the final product.

These findings demonstrate that analysing energy flow at product level changes the identification of energy hotspots compared with plant-level assessments. The results highlight the importance of optimising downstream thermal operations, furnace utilisation and process scheduling to improve the energy efficiency of forged component manufacturing and support ongoing decarbonisation efforts in the steel industry.

Keywords: Energy flow analysis, forged steel manufacturing, downstream thermal processes, energy hotspot analysis, heat stability testing

1. INTRODUCTION

Energy consumption is a key aspect of steel manufacturing due to the high thermal requirements associated with the transformation of steel into finished products. Many studies analysing energy use in the metallurgical sector focus primarily on upstream operations, particularly steelmaking processes such as electric arc furnace (EAF) production and secondary metallurgy [1]. These stages are well known to be energy-intensive at plant level and have therefore received significant attention in both academic research and industrial optimisation efforts.

However, steel components often undergo multiple downstream processing stages after steelmaking, including reheating, forging, heat treatment and machining operations [2]. These manufacturing steps frequently involve prolonged thermal cycles and dedicated furnace operation, which can represent substantial energy consumption when evaluated at product level.

In heavy forging applications, the manufacturing route of large components such as steam turbine shafts may include several heating and heat treatment stages before the final product is obtained. Despite this, the contribution of these downstream operations to the overall energy demand of the product is rarely analysed in detail [3]. As a result, the identification of energy hotspots within the process chain can differ depending on whether the analysis is performed at plant level or product level.

Understanding how energy consumption is distributed across the complete manufacturing route is therefore important for identifying opportunities for energy optimisation and for improving the efficiency of industrial forging processes.

This study analyses the energy flow associated with the production of a large forged steam turbine shaft using industrial data from a European forging facility. The objective is to identify the main energy hotspots across both upstream and downstream processes and to evaluate how the relative contribution of these stages changes when energy consumption is analysed at product level.

2. MATERIALS AND METHODS

2.1 Industrial process description

The case study analysed in this work focuses on the manufacturing route of a large forged steel shaft produced in an industrial forging facility. Such components are typically used in heavy-duty applications such as steam turbines and power generation equipment, where strict mechanical and dimensional stability requirements must be satisfied.

The system boundary considered in this study includes both upstream steel production and downstream manufacturing processes associated with the fabrication of the shaft. **Figure 1** illustrates the analysed manufacturing route and summarises the main stages involved in producing the shaft. For clarity, internal transport and machining operations are not shown in the figure, as their contribution to the overall energy demand is negligible compared with thermal processing stages.

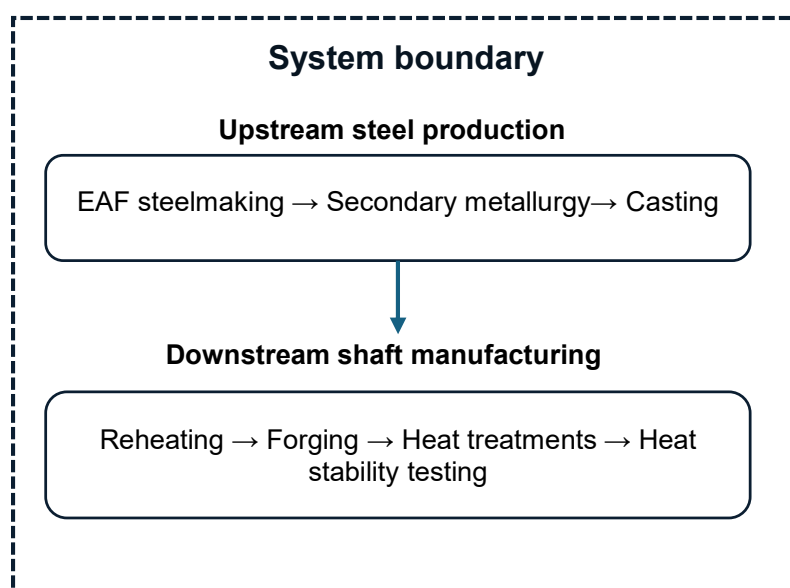


Figure 1 System boundary and manufacturing route of the analysed forged shaft

The upstream part of the system includes electric arc furnace (EAF) steelmaking followed by secondary metallurgy operations used to adjust the chemical composition of the steel. The molten steel is subsequently cast into a large ingot, which serves as the starting material for the forging process.

The downstream manufacturing stages begin with reheating of the ingot to the required forging temperature. The ingot is then subjected to forging operations that progressively shape the material into the required shaft geometry. After forging, several thermal treatments are applied to obtain the desired microstructure and mechanical properties. These include multiple heat treatment cycles and stress-relief operations, with intermediate machining steps performed between selected stages.

The final stage of the manufacturing route is heat stability testing, during which the shaft is exposed to a controlled thermal cycle in order to verify its dimensional stability under near-operating conditions.

2.2 Data and energy calculation method

The energy analysis presented in this study is based on industrial production data corresponding to the manufacturing of a forged steam turbine shaft in a European forging facility. The data were obtained from process-level production records and from a detailed process model representing the main stages of the manufacturing route described in Section 2.1.

To allow comparison between different manufacturing stages, the energy consumption associated with each process was normalised to the mass of the finished shaft. All energy flows were therefore expressed per tonne of finished product.

Several energy carriers are used throughout the manufacturing route, including electricity, natural gas and fuel oil. Since the available industrial data were reported in different physical units (kWh, m³ and kg), all energy flows were converted to a common energy unit. Natural gas consumption was converted using a calorific value of 11.7 kWh per cubic metre, while heavy fuel oil consumption was converted using a calorific value of 11.86 kWh per kilogram.

The total energy demand associated with the manufacturing route was calculated by summing the energy contributions of each process included within the system boundary. The relative contribution of each manufacturing stage was then determined as the percentage share of the total energy demand.

To preserve industrial confidentiality, the results are presented as relative energy contributions rather than absolute energy consumption values. This approach allows for the identification of the main energy hotspots across the manufacturing route while protecting sensitive industrial data.

3. RESULTS AND DISCUSSION

3.1 Energy flow across the manufacturing route

The results clearly show that downstream thermal operations dominate the overall energy profile of the manufacturing route. Heat stability testing represents the largest individual energy consumer, accounting for approximately 29% of the total energy demand per tonne of finished shaft in the current analysis. Although this value is influenced by the assumptions applied in the energy estimation, it highlights the significant contribution of this stage to the overall energy demand. Reheating and preliminary heat treatment also represent major contributions, accounting for 21% and 20%, respectively.

In contrast, upstream steelmaking operations account for a relatively small share of the product-level energy demand. The contribution of electric arc furnace (EAF) steelmaking represents approximately 4% of the total energy demand when allocated to the finished shaft [4], reflecting the distribution of its energy consumption across the total mass of steel produced. The distribution of energy consumption across the analysed manufacturing processes is presented in **Figure 2**, which shows the relative contribution of each process to the total energy demand associated with the production of the forged shaft.

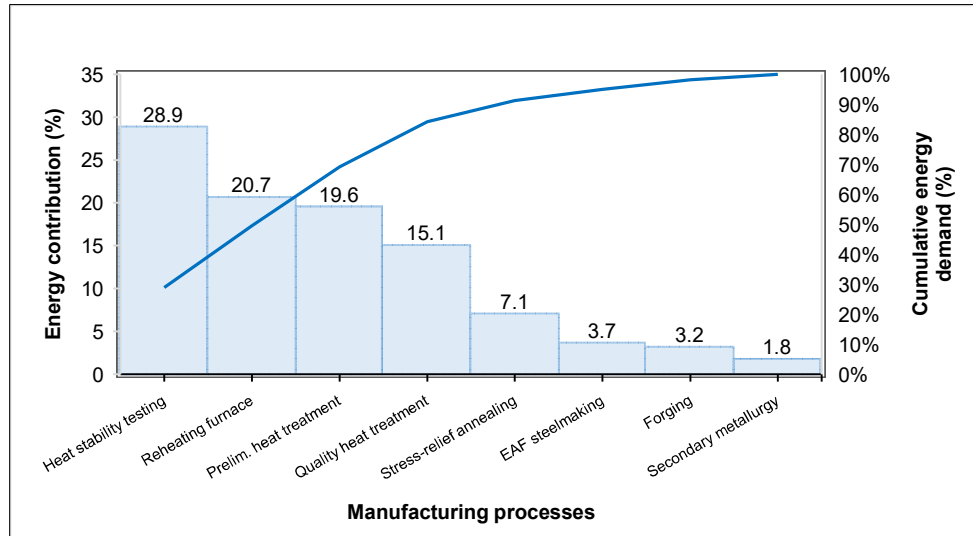


Figure 2 Energy contribution by process and cumulative share

The cumulative curve further shows that the first four processes already account for more than 80% of the total energy demand, confirming the dominant role of downstream thermal operations within the analysed manufacturing route. Similar observations have been reported in recent studies highlighting the importance of furnace operation, heating patterns and thermal cycle control in determining the overall energy performance of steel processing routes [5,6].

3.2 Sensitivity of heat stability testing energy estimation

The energy demand associated with heat stability testing (HST) strongly depends on the operational profile of the testing furnace and on how energy consumption is estimated and allocated to individual shafts. In the analysed case, the HST stage is performed externally by a specialised service provider, following a thermal cycle schematically illustrated in **Figure 3**.

In the absence of detailed power–time measurements from the furnace, the energy consumption was initially estimated assuming constant operation at nominal power throughout the entire testing duration. This approach represents a conservative upper-bound estimate of the energy demand associated with the HST process.

To better reflect the physical behaviour of the furnace, an alternative estimation approach can be introduced based on the effective operating time at high power levels. The total energy consumption can be approximated as shown in equation (1):

$$E = F * P * D \quad (1)$$

where:

- E – total energy consumption (kWh)
- F – utilisation factor (-)
- P – nominal furnace power (kW)
- D – total duration of the HST cycle (h)

The utilisation factor is defined as shown in equation (2):

$$F = \frac{t_{\text{heating + soaking}}}{D} \quad (2)$$

where:

- $t_{\text{(heating + soaking)}}$ – effective heating and soaking time (h)
- D – total duration of the HST cycle (h)

This formulation accounts for the fact that the furnace does not operate at full power during the entire cycle. As the shaft approaches the target temperature, the electrical resistance system progressively reduces its power input. In addition, during the cooling phase, energy consumption is expected to be negligible, as cooling is typically driven by controlled heat dissipation rather than active heating [6].

As illustrated in **Figure 3**, the assumption of constant nominal power throughout the full cycle therefore leads to an overestimation of the actual energy consumption.

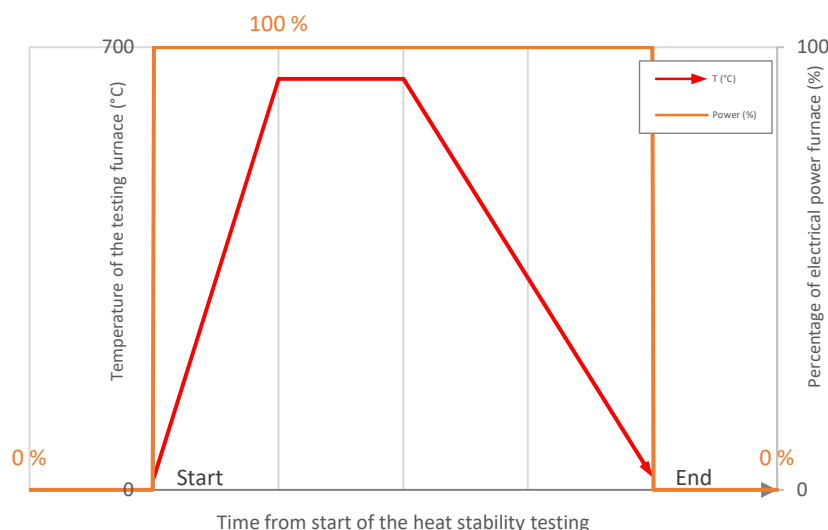


Figure 3 Operational profile in the heat stability testing furnace and power estimation

To evaluate the impact of this assumption on the identification of energy hotspots, a sensitivity analysis was performed by considering reduced effective energy consumption scenarios. In addition to the base case (corresponding to $F = 1$), two alternative scenarios were analysed using lower effective utilisation factors, representing more realistic furnace operation conditions.

The utilisation factor (F) assumed for each scenario, reflecting different levels of effective furnace operation, together with the resulting contribution to the total energy demand, is summarised in **Table 1**.

Table 1 Influence of testing energy assumptions on the total energy demand

Testing energy assumption	Utilisation factor F (-)	Contribution to total energy demand (%)
Base case	1	28.9
Reduced utilisation	0.75	23.4
Conservative estimate	0.50	16.9

Despite the reduction in estimated energy consumption, heat stability testing remains one of the most significant contributors to the overall energy demand of the shaft. However, the results also indicate that its relative importance is sensitive to the assumptions used in the estimation of furnace operation.

These findings highlight the need for more accurate operational data when assessing the energy performance of downstream thermal processes. They also demonstrate that the identification of energy hotspots at product level depends not only on the absolute energy consumption of individual processes, but also on the modelling assumptions used to represent industrial equipment behaviour.

4. CONCLUSION

This study analysed the energy flow associated with the manufacturing of a large forged steam turbine shaft using industrial production data. The results show that downstream thermal operations dominate the energy profile of the manufacturing route when energy consumption is evaluated at product level.

Heat stability testing was identified as one of the most significant contributors to the total energy demand of the shaft, together with reheating and heat treatment stages. However, the results also highlight that its relative contribution is strongly influenced by the assumptions used to estimate furnace energy consumption, particularly regarding the operational profile of the testing process.

The sensitivity analysis performed for the heat stability testing stage demonstrates that its contribution may vary significantly depending on modelling assumptions and energy allocation approaches. Despite this variability, downstream thermal operations remain the dominant contributors to the overall energy demand across all evaluated scenarios.

From an industrial perspective, the results indicate that optimisation efforts should prioritise furnace-based operations, where improvements in furnace utilisation, process scheduling and thermal cycle control can significantly reduce product-level energy demand.

Overall, the results demonstrate that analysing energy consumption at product level can lead to a different identification of energy hotspots compared with plant-level assessments. The findings highlight the importance of improving energy efficiency in downstream thermal operations as part of broader efforts to enhance the sustainability of forged steel manufacturing.

ACKNOWLEDGEMENTS

This work was carried out within the AID4GREENEST project and has received funding from the European Union's Horizon Europe Research and Innovation programme under Grant Agreement No. 101091912.

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