

# Forging a route

Dr Steve Ooi of Ovako R&D, Sweden, explains how direct-quenching steel can help the forging industry reduce its CO<sub>2</sub> emissions and increase productivity.

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Traditionally, the forging industry has relied on reheating, quenching and tempering to attain the ideal steel microstructure that delivers an optimal balance of strength and impact toughness in finished components. However, there is growing demand and interest in eliminating the energy-intensive reheating step and reducing production costs through direct-quenching forging.

The reduced need for heat treatment in direct-quenching forging would also mean a decrease in labour and maintenance costs on existing equipment, as well as a reduction in capital investment when building new forging plants.

## The established path

The established production route for hot forging of quenched and tempered (Q&T) steel (see image below) starts with heating the steel well above its austenitisation temperature, around 1,200°C. This makes it soft and ductile, so it is easily moulded to intricate shapes and designs in the forging die. This high forging temperature is preferred as it reduces both the required forging force and die wear. After forging, the hot component is allowed to air cool.

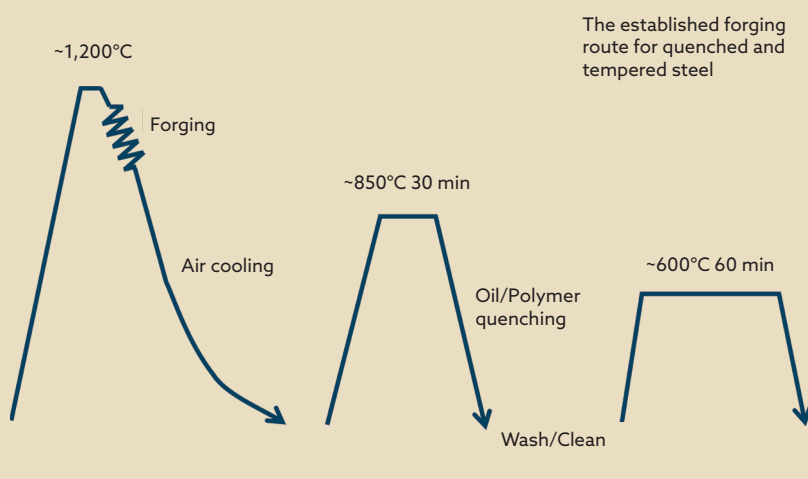
The next step is re-austenitising. The forging is heated to

above the critical temperature, typically around 850°C, at which its steel microstructure will transform back to austenite.

Simultaneously, depending on the steel's chemical composition and initial microstructure, the cementite dissolves into the austenite. The forging must be held at this temperature for a sufficient time so the transformation can be completed – the actual time depends on the component thickness.

Once the austenitising process is complete, the forging is quenched. This rapid cooling process creates a hard microstructure by transforming the austenite into martensite. The quenching medium is usually water, oil, or polymer, and varies according to the component size and alloy to minimise distortion and prevent thermal shock, which can lead to cracking.

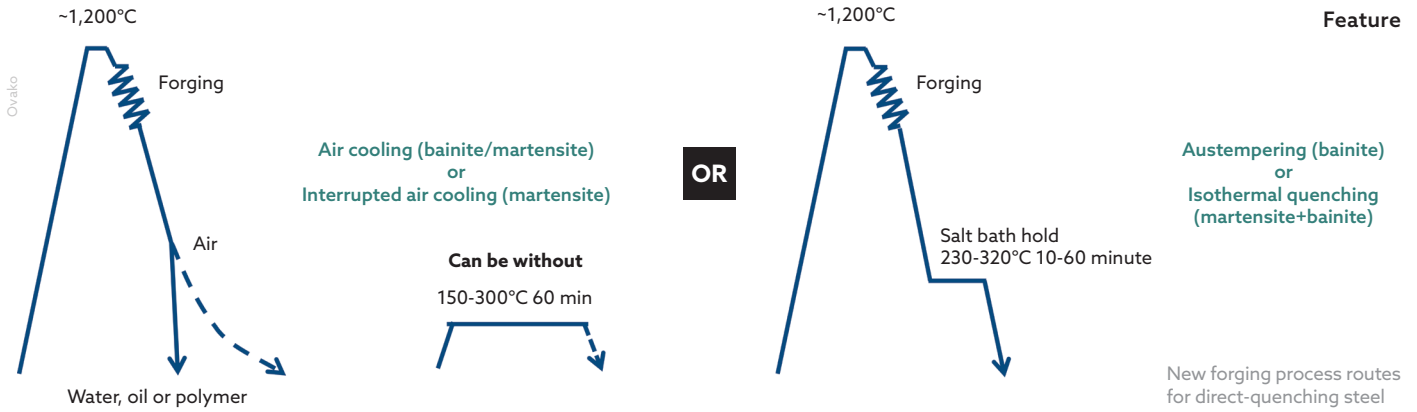
The martensite formed from a typical Q&T, medium-carbon (0.3-0.5wt.%) steel makes the forging hard, but too brittle for most applications. To address this, the steel is typically tempered by heating to around 600°C. This releases some of the carbon trapped in the martensite via cementite precipitation and reduces the stress and dislocation density generated during quenching. The result is a reduction in the hardness and strength, but a significant improvement in toughness, making the forged metal better suited for a wider range of applications.



## Why push for an alternative?

The Q&T route requires two additional energy-intensive heat treatment steps after forging, adding cost and complexity to production, while generating significant CO<sub>2</sub> emissions from fuel combustion. The advantages of a direct-quenching route become apparent when calculating the resulting reduction in carbon emissions.

Ovako estimates that the energy required for Q&T heat treatment using natural gas is approximately 700kWh/t. There are two primary sources for data on CO<sub>2</sub> conversion using natural gas for heating that both yield relatively similar results:



New forging process routes for direct-quenching steel

- 0.18kgCO<sub>2</sub>e/kWh (Scope 1) based on the UK Government’s *Greenhouse Gas Reporting: Conversion Factors 2024*.
- -0.2kgCO<sub>2</sub>e/kWh (Scope 1), as outlined in the *CoM Default Emission Factors for the Member States of the European Union* released in 2017.

The potential savings using direct-quenching steel are in the region of 126-140kgCO<sub>2</sub>e/t.

The image above illustrates two potential process routes for direct-quenching steel. The first involves forging followed by either direct or interrupted air cooling. Interrupted air cooling may then be followed by quenching in water, oil, or polymer, allowing the alloy content to be reduced due to the faster cooling rate. A low-temperature tempering step may also be applied to relieve stress generated from rapid cooling and to enhance fatigue life.

The second process route involves forging followed by isothermal quenching in a salt bath. Depending on the steel’s carbon content, this can be followed by either austempering or isothermal quenching. Austempering holds the forging above the martensite start temperature to achieve a bainitic microstructure, while isothermal quenching holds it below the martensite start temperature to produce a mix of tempered martensite and bainite microstructure.

**Direct-quenching**

Both *ISO 683-2:2012* and *EN 10083-3:2006* indicate the minimum strength requirements for a Q&T steel in different thicknesses. The yield strength requirement is typically less than 1,100MPa, while the Charpy toughness requirement is between 30J and 65J. This toughness requirement is the primary reason Q&T steel has so far not been replaced by another production route. Furthermore, additional component weight reduction can be achieved if higher-strength steel is produced while meeting these toughness standards.

Carbon content is known to influence a steel’s strength and toughness, while the addition of nickel in a suitable amount can produce a low-carbon martensitic structure that is high in both strength and toughness. However, nickel is costly and produces significant CO<sub>2</sub> emissions during its production, making it less viable for cost and environmentally sensitive industries.

As a more economical alternative, manganese in combination with chromium can be used to produce low-carbon martensitic steel. Low-temperature tempering is required to improve fatigue strength if the component is quenched.

Considering the parameters highlighted above and advancement in alloy design and computer simulation, the information needed from industry to develop new direct-quenching steels was:

- Target strength
- Target dimensions
- The capability of the existing cooling methods in the forge shop

This makes it possible to either develop new, or select existing, alloys that ensure adequate hardenability without using elements with high CO<sub>2</sub> emissions, such as nickel – which is only added if no cost-effective substitute is available.

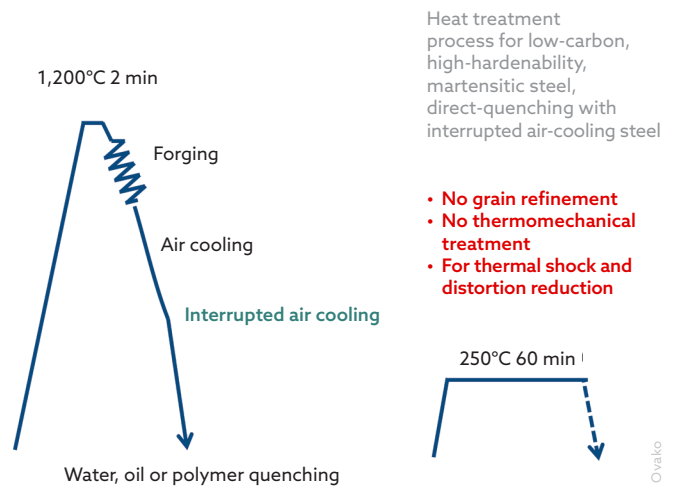
Similarly, molybdenum is added to prevent phosphorous grain boundary embrittlement. Since the steel may or may not require tempering – and if so, only low-temperature (below 300°C) tempering for a short duration – molybdenum is generally unnecessary for direct-quenching steel.

In practice, there are three different approaches to achieving direct-quenching steel.

**Low-carbon, high-hardenability, martensitic steel**

The first approach (see image below) uses a low-carbon steel with 0.05-0.2wt.% of carbon and appropriate additions of manganese in combination with chromium. These elements delay the ferrite transformation, allowing forgings with relatively large dimensions to be air cooled to lower temperatures before quenching.

Interrupted air cooling can also reduce thermal shock and distortion for components with complex geometries, though direct-quenching after forging remains an option for simpler geometries. This flexibility provides forgers with more options during production.



- No grain refinement
- No thermomechanical treatment
- For thermal shock and distortion reduction

Right: Mechanical properties of low-carbon, high-hardenability, martensitic steel, where the alloy did not undergo thermomechanical treatment for grain refinement during forging

Yield strength	Ultimate tensile strength	Elongation, %	Charpy notch toughness, J		
			RT	0°C	-20°C
1,200MPa	1,450MPa	13	50	35	30

The table above shows the mechanical properties of this alloy, which has not undergone any thermomechanical treatment for grain refinement during forging. This suggests that further toughness improvements are achievable through prior austenite grain refinement.

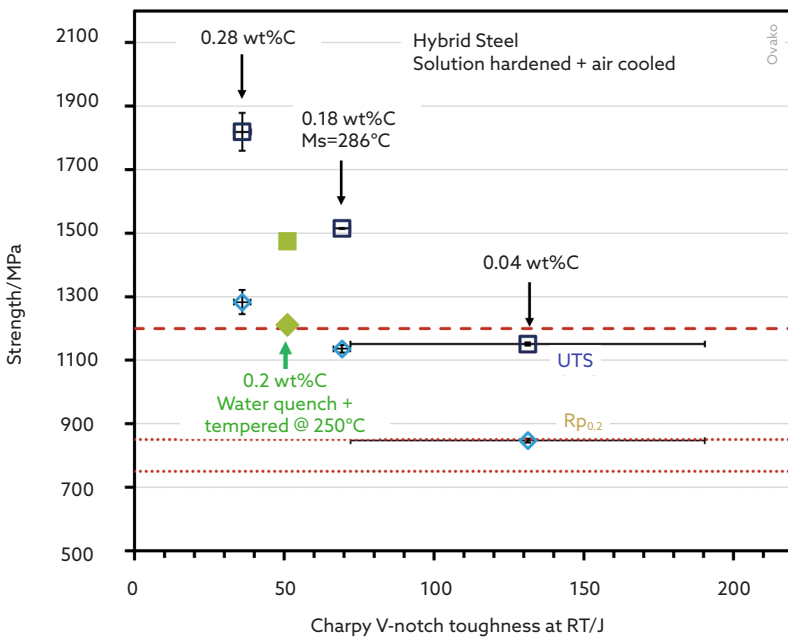
### A hybrid steel

The second approach is a Hybrid Steel that combines the unique properties of high-performance engineering steel, tool steel, maraging steel and stainless steel into a single steel grade. Although it contains much lower chromium, tests confirm that alloying with aluminium provides a Hybrid Steel with corrosion resistance comparable to lower-end stainless steels.

The development of Hybrid Steel has yielded interesting knowledge in the context of direct-hardening steel. It was designed to achieve ultra-high strength with carbide and nickel-aluminium intermetallic precipitation after tempering above 500°C. Due to its high hardenability, the martensitic structure is achieved even after air cooling steel bars with very large dimensions.

The image below displays the obtained strength and Charpy V-notch toughness of Hybrid Steel with different carbon content (0.04–0.18wt.%) after air cooling a 65mm-diameter bar.

Below: The measured strength and toughness of Ovako's Hybrid Steel after air cooling. The mechanical properties of low-carbon (0.2wt.%), high-hardenability martensitic steel are shown



The mechanical properties of low-carbon (0.2wt.%), high-hardenability, martensitic steel after interrupted cooling and tempering at 250°C are also shown. The steel can be further optimised to achieve the desired strength, toughness and hardenability, while minimising the need for costly alloying elements that promote secondary hardening in Hybrid Steel.

### Salt bathing

In the final approach, the forging is direct-quenched in a well-agitated salt bath, where it is held for a specified duration (see image opposite). This process is effectively austempering or isothermal quenching. The forging is rapidly cooled from the austenitising temperature to avoid ferrite formation, then held at a constant temperature to allow lower bainite transformation.

For isothermal quenching, martensite forms as the material cools below the martensite start temperature. Since the holding temperature is above the martensite finish temperature, some retained austenite remains. Holding the forging at the isothermal quenching temperature converts this retained austenite into lower bainite and tempers the martensite formed during cooling.

The ratio of tempered martensite to bainite can be adjusted by modifying the salt bath temperature. Another benefit of isothermal quenching is that it reduces thermal shock to the component.

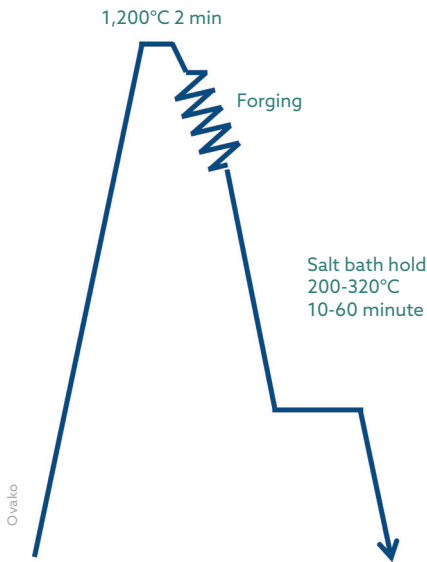
Tempering the martensite involves the competition between carbon partition into the retained austenite and cementite formation at this temperature range. Typically, following quenching, a certain amount of retained austenite remains alongside the martensite. Since martensite is supersaturated with carbon, tempering allows the carbon to either partition into the retained austenite or precipitate as cementite within the martensitic laths.

In addition, the dislocation density and stress generated during martensite transformation are gradually reduced during the holding period at the isothermal quenching temperature.

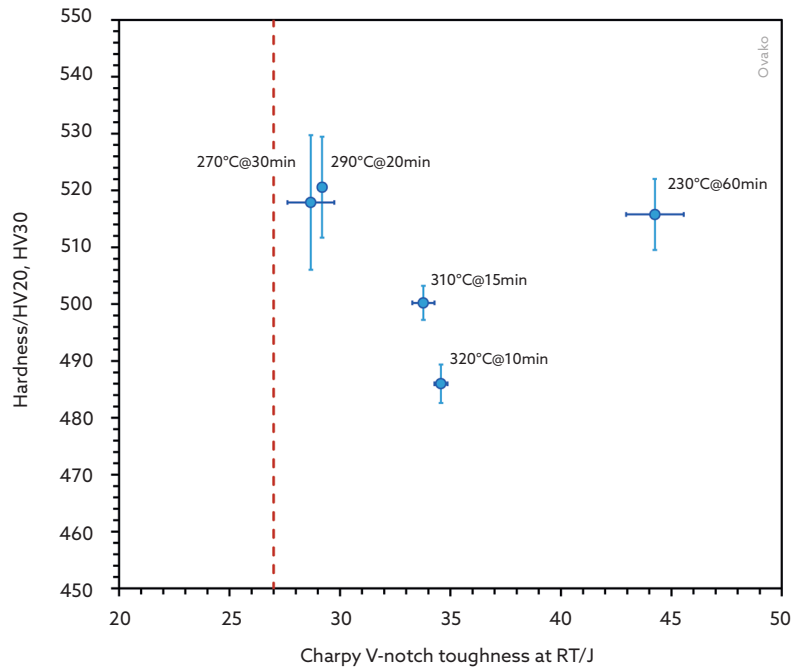
The table on the next page shows the example steel's chemical composition for direct salt bath treatment. The carbon content plays a crucial role in determining its strength and toughness. Low-carbon steel with 0.1-0.3wt.% of carbon can deliver both high strength and high toughness after isothermal quenching.

Medium carbon steel	C	Si	Mn	Cr	Ti	B	Cu
	0.36	0.18	1.17	0.71	0.016	0.003	0.22

Left: Chemical composition of steel selected for direct salt treatment



Above: Process route for direct-quenching steel with salt bath treatment



Above: Effect of isothermal quenching on the hardness and toughness of steel for direct salt bath treatment. The sample dimension for the salt bath quenching is 11x11x180mm<sup>3</sup> quenched into 25L molten salt set at a specified temperature

At low holding temperatures with shorter holding times, incomplete austenite transformation is likely. Excessive, unstable, retained austenite may then transform into martensite under stress. This can be detrimental to fatigue life and should therefore be minimised.

The graph above shows how isothermal quenching temperature and duration influence the steel's hardness and toughness.

All heat treatment conditions result in toughness values exceeding 27J, meeting the application requirements while possessing significantly high strength. Isothermal quenching at a holding temperature close to the martensite finish temperature yields the best combination of hardness and toughness. This suggests that achieving a predominantly martensitic structure is key to optimising strength and toughness during isothermal quenching. For applications with less stringent requirements, the salt bath holding time can be reduced to just 10 minutes to produce a predominantly bainitic structure.

Key observations from the test programme include:

- Higher holding temperatures require shorter durations for complete transformation, though lower hardness is expected.
- Lower holding temperatures require longer durations to promote lower bainite transformation and temper the transformed martensite, typically resulting in higher hardness and a finer bainite plate structure.

In short, there are three key findings:

- A variety of chemical compositions can be tailored to suit different forging shop set-ups.
- Low-carbon martensitic steel of 0.05-0.2wt.% carbon can be employed in either direct or interrupted air-cooled set-ups, with an option for low-temperature tempering. The interrupted air-cooling route requires leaner steel compared to direct air cooling.
- Low- to medium-carbon steel of 0.1-0.35wt.% carbon, aimed at achieving a mixed, tempered martensite and lower bainite microstructure, can be processed using direct salt bath treatment – i.e., isothermal quenching. The tempered martensite-dominant microstructure provides the optimal balance of strength and toughness.

The results of this programme indicate that it is possible to eliminate the Q&T step following forging, through a combination of innovative alloy design supported by controlled phase transformation during direct or interrupted air cooling, or isothermal quenching. 