

INNOVATIVE DIRECT-QUENCHING STEEL HELPS THE FORGING INDUSTRY ELIMINATE ENERGY- INTENSIVE PROCESS STEPS

Dr Steve Ooi, Group Technical Specialist Ovako R&D

Executive overview

Traditionally, the forging industry has relied on reheating, quenching, and tempering to attain the ideal microstructure for an optimal balance of strength, ductility, 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.

According to Roland Berger’s 2022 analysis, Ovako has achieved the world’s lowest Scope 1 and 2 CO₂e emissions (0.09 tCO₂ per ton of steel produced) in the steel industry and has set an ambitious target of an 80% reduction by 2030. Building on these achievements, we have now turned our focus to pioneering direct-quenching forging steel to help our customers further cut CO₂ emissions by eliminating the energy-intensive reheating process, which also increases productivity.

A further significant advantage of direct-quenching forging is that the elimination of subsequent heat treatment also reduces labor and maintenance costs on existing equipment, as well as the need for capital investment when building a new forging plant.

Utilizing direct-quenching forging steel often faces challenges related to meeting toughness requirements at specified strength levels. Historically, to enhance toughness, the microstructure of direct-quenching forging steels has evolved from micro-alloy precipitation-strengthened ferrite-pearlite to upper bainite microstructures. While successful cases exist using both microstructure types at low strength, many components with a higher demand for strength and toughness

still need to be produced using conventional quench and tempered martensitic steel via energy-intensive processing routes.

Now, through the new alloy design criteria and innovative approaches embodied in direct-quenching steel, both the strength and toughness of the as-forged component can be increased. This allows customers in the forging industry to optimize their use of steel through reduced product size and/or decreased component weight.

The alloy design criteria are focused on the steel’s carbon content for strength and toughness, and its transformation temperature during cooling to achieve the desired microstructure based on the component size and available cooling methods.

This white paper introduces two innovative direct-quenching steel concepts that do not require costly alloying:

- The first achieves high yield strength and Charpy toughness through interrupted water cooling, which is ideal for components up to 80 mm thick. This grade features a controlled transformation temperature of low-carbon martensitic steel, which can be tempered at low temperatures depending on the application. A direct air-cooling steel variant is available, but a higher alloying addition is needed to improve the hardenability.
- The second grade, with medium carbon content and lower alloying content, attains an even greater strength with satisfactory Charpy toughness at room temperature produced via isothermal quenching in a well-agitated salt bath.



1 – Introduction

1.1 The typical Q&T production route

The typical production route for hot forging of quenched and tempered (Q&T) steel (see Figure 1) starts with heating the steel well above its austenitization temperature (around 1200°C). This makes it soft and ductile so it is easily molded 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.

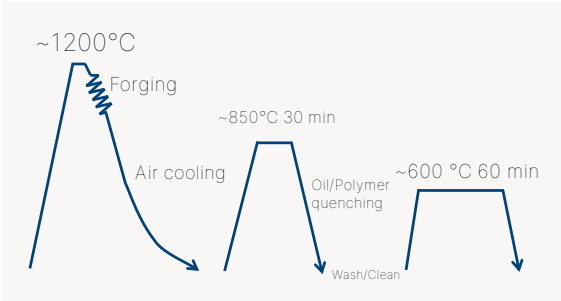


Figure 1 – Typical forging route for Q&T steel.

The next step is re-austenitizing. The forging is heated to above the critical temperature, typically around 850°C, at which its steel microstructure will transform back to austenite. At the same time, depending on the steel’s chemical composition and the initial microstructure, the cementite dissolves into the austenite. The forging must be held at this temperature for a sufficient time to allow the transformation to be completed – the actual time is determined according to the component thickness.

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

The martensite formed from the transformation of a typical Q&T medium carbon (0.3–0.5 wt%) steel in this way makes the forging hard but too brittle for most applications. To address this, the steel is typically tempered by heating it to around 600°C followed by slow cooling. This releases some of the carbon that has been 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 of the steel but a significant improvement in toughness that makes the

forging more suitable for a wider range of applications. Figure 2 shows the typical combinations of hardening and tempering temperatures used for Q&T steel grades. The high tempering temperature also requires the addition of molybdenum (Mo) to the steel to prevent phosphorous grain boundary embrittlement, and molybdenum is one of the expensive alloying elements used in steel.

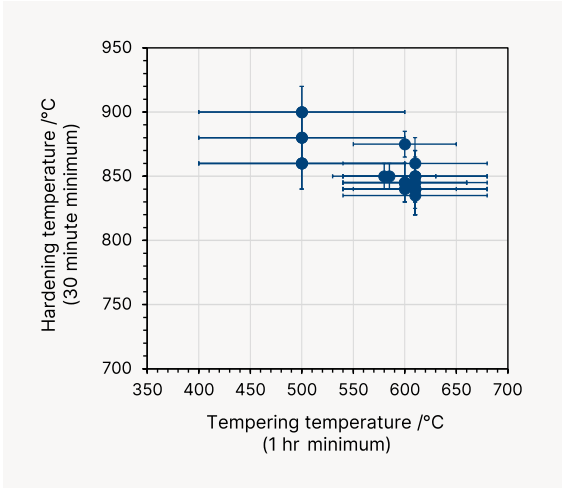


Figure 2 – Typical hardening and tempering temperatures for Q&T steel.

1.2 What is driving the search for alternative process routes?

The Q&T route requires two additional energy-intensive heat treatment steps after forging, adding cost and complexity to production while generating significant CO₂ emissions from fuel combustion. The advantages of adopting a direct-quenching route become apparent when calculating the CO₂ emissions avoided by eliminating the Q&T process. Ovako estimates the energy requirement for Q&T heat treatment using natural gas to be approximately 700 kilowatt-hours (kWh) per tonne. There are two primary sources for data on CO₂ conversion using natural gas for heating, both yielding relatively similar results:

- 0.18 kg CO₂e/kWh (DEFRA) (Scope 1)
- ~0.2 kg CO₂e/kWh ETS (EU Emission Trading System) (Scope 1)

Based on the above conversion, it is estimated that the potential savings using direct-quenching steel are in the region of 126–140 kg CO₂e/t for the forged component produced.

Figure 3 illustrates the future process routes for direct-quenching steel devised by Ovako. The first process route 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 in the steel 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 enhance fatigue life.

The second process route involves forging followed by isothermal quenching in 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.

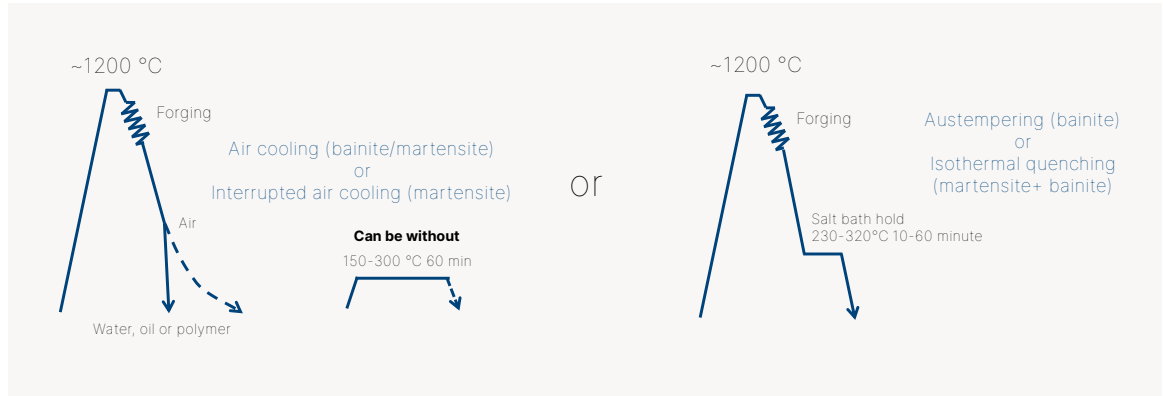


Figure 3 – The future forging process routes for direct-quenching steel devised by Ovako.



2 – Developing direct-quenching steel

2.1 Minimum strength and hardness requirements

Figure 4 shows the minimum strength and Charpy V toughness requirements for a Q&T steel in different thicknesses according to both ISO 683-2:2012 and EN 10083-3:2006. The yield strength requirement, as shown by the dotted red line, of all quench and temper steel is less than 1100 MPa. The Charpy V toughness requirement for the Q&T steel is between 30 and 65J. The toughness requirement in the standard for the specific application is the primary reason Q&T steel has so far not been replaced by another production route. Furthermore, additional component weight reduction may be achieved if higher-strength steel can be produced while meeting these toughness standards.

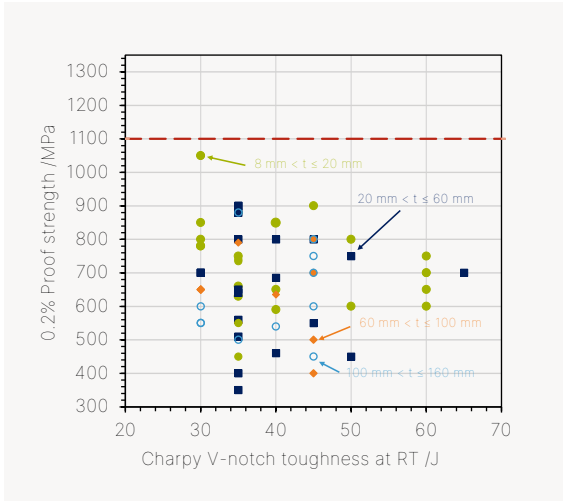


Figure 4 – Minimum strength and Charpy V toughness requirements for Q&T steel.

2.2 How does microstructure affect strength and toughness?

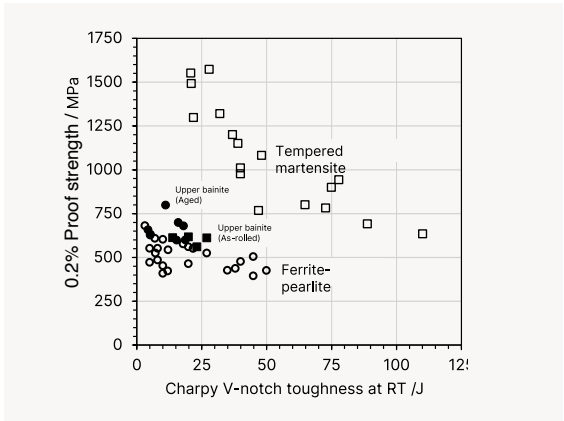


Figure 5 – The influence of microstructure on yield strength and toughness – Ref Grassl:1989.

Figure 5 illustrates the effect of steel microstructure on 0.2% proof strength and toughness. It is only the tempered martensite that can achieve a high strength and toughness combination, while bainite (presumably upper bainite in this case) and ferrite pearlite microstructures display low strength and poor toughness. This figure does not include data on whether lower bainite or auto-tempered (low-carbon) martensite could match the strength-toughness balance of tempered martensite. In certain applications, a minimum subzero toughness (from -20°C to -101°C) of 27J is required, demanding significantly higher room-temperature Charpy toughness for these extreme conditions.

2.3 The impact of carbon content on martensite strength and toughness

Figure 6 shows the influence of carbon content on the strength and toughness of martensite when the transformation temperature is set between 345°C and 350°C. It demonstrates that high strength and toughness can be achieved in a low-carbon martensitic structure with the addition of nickel (Ni). However, Ni is costly and produces significant CO₂ emissions during its production, making it less viable for cost-sensitive industries.

As a more economical alternative, manganese (Mn) in combination with chromium (Cr) can be used to lower the martensite start temperature (Ms), which is the temperature at which martensite starts to form on cooling. The exceptional toughness obtained in 0.15 wt% C Ni alloy also provides some tolerance in expected toughness reduction when substituting Mn and Cr as alloying elements. Lowering the Ms is crucial, as it refines the martensite lath thickness and packet size, enhancing toughness, though further characterization is required.

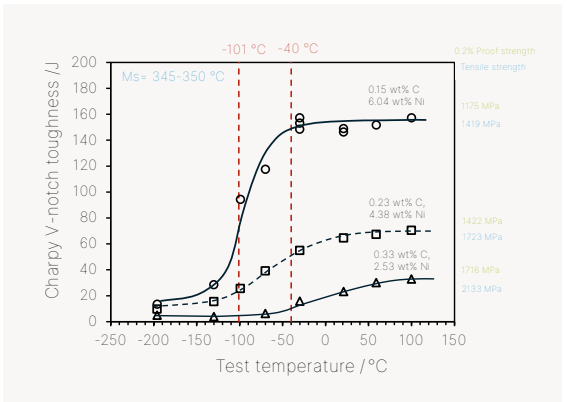


Figure 6 – The impact of carbon content on the as-quenched martensite strength and toughness with the transformation temperature controlled to between 345 and 350°C with Ni addition. – Ref Tanaka 1973.

2.4 The effect of low-temperature tempering on tensile strength and toughness

Figure 7 shows the effect of low-temperature tempering (between 40°C and 450°C for one hour) on the tensile strength and toughness of steels with varying carbon and nickel compositions. Tempering noticeably improves the toughness of medium-carbon steel (>0.23 wt% C) but has minimal impact on the strength and toughness of low-carbon steel (0.15 wt% C).

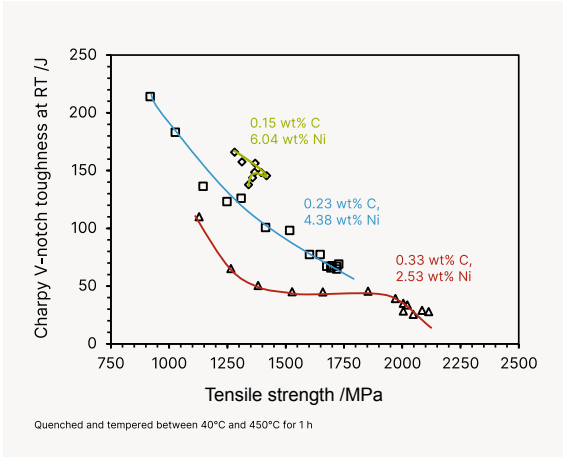


Figure 7 – The effect of low-temperature tempering on tensile strength and toughness for different levels of carbon and nickel – Ref Tanaka 1973.

2.5 Alloying and process design parameters for a direct-quenching steel

Considering the parameters highlighted in sections 2.1 to 2.3, the information we needed from our customers to develop a new direct-quenching steel was:

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

With the above information, Ovako can either develop new or select existing alloys that ensure adequate hardenability without using elements with high CO₂ emissions, such as nickel (Ni), which is also costly. Ni is only added if no cost-effective substitute is available. Similarly, molybdenum (Mo) 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—Mo is generally unnecessary for direct quenching steel.

Since Ovako already offers the lowest CO₂ emissions within Scope 1 and Scope 2 in the steel industry, this combined with the new direct-quenching steel establishes a sustainable supply chain and process for the forging industry.

3 – Examples and approaches to direct-quenching steel

Ovako has a few different approaches to supporting the forging industry with direct-quenching steel.

3.1 Low carbon, high hardenability, martensitic steel

The first approach involves using a low-carbon (0.05–0.2 wt% C) steel with appropriate additions of Mn and in combination with Cr. 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.

The heat treatment process with interrupted air cooling is shown in Figure 8, and Table 1 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. The continuous cooling transformation (CCT) diagram for this steel is shown in Figure 9. It shows that no ferrite formation is expected at the core of 90x70 x1000 mm² bar when air-cooled until 500°C is reached.

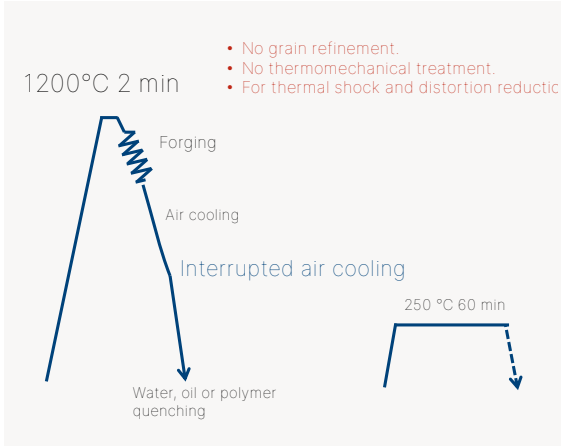


Figure 8 – Heat treatment process for low carbon, high hardenability, martensitic steel direct-quenching with interrupted air cooling steel.

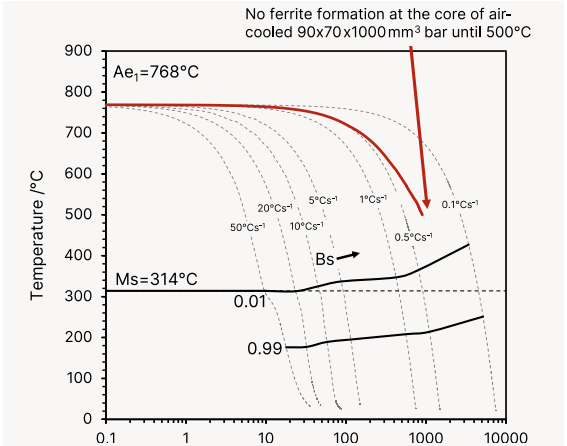


Figure 9 – Continuous cooling transformation (CCT) diagram for low carbon (0.2 wt% C), high hardenability, martensitic steel.

Yield strength	Ultimate tensile strength	Elongation, %	Charpy notch toughness, J		
			RT	0°C	-20°C
1200 MPa	1450 MPa	13	50	35	30

Table 1 – Mechanical properties of low-carbon, high-hardenability martensitic steel, where the alloy did not undergo thermomechanical treatment for grain refinement during forging.

3.2 Hybrid® steel – low-carbon, high hardenability and corrosion resistant

Ovako has developed Hybrid Steel to combine the unique properties of high-performance engineering steel, tool steel, maraging steel, and stainless steel. The result is a single high-performance steel grade with the production cost-effectiveness of conventional engineering steel. Although it contains much lower chromium, tests have confirmed that alloying with aluminum (Al) provides 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. Hybrid Steel was designed to achieve ultra-high strength with carbide and NiAl intermetallic precipitation after tempering above 500°C. Due to its high hardenability, the martensitic structure is achieved even after air cooling of steel bars with very large dimensions.

Figure 10 displays the obtained strength and Charpy V-notch toughness of Hybrid steel with different carbon content after air cooling of 65 mm diameter bar. This shows that low-carbon Hybrid Steel (0.04–0.18 wt% C) exhibits impressive toughness in air-cooled conditions. The mechanical properties of low-carbon (0.2 wt% C), high-hardenability martensitic steel after interrupted cooling and tempering at 250°C are also shown. The future direct air-cooled hardening forging steel can be further optimized to achieve the desired strength, toughness, and hardenability, while minimizing the need for costly alloying elements that promote secondary hardening in Hybrid steel.

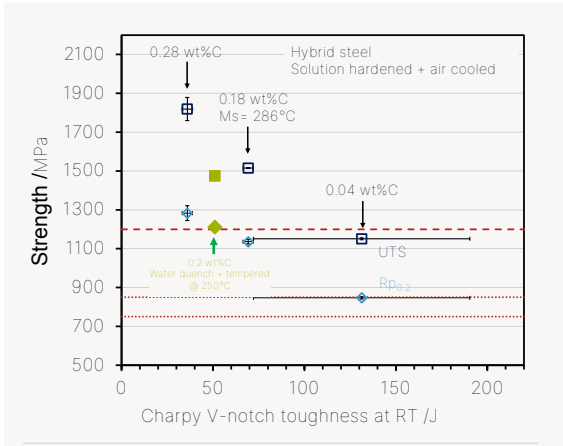


Figure 10 – The measured strength and toughness of Hybrid Steel after air cooling. The mechanical properties of low carbon (0.2 wt% C), high hardenability, and martensitic steel are shown.

3.3 Direct salt bath treatment steel

The final approach involves directly quenching the forging in a well-agitated salt bath, where it is held for a specified duration, as shown in Figure 11. This process is effectively austempering or isothermal quenching: the forging is rapidly cooled from the austenitizing temperature to avoid ferrite formation, then held at a constant temperature to allow lower bainite transformation during austempering.

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. The dilatometer can be used to analyze the kinetics of the transformation and ensure the bainite transformation is complete.

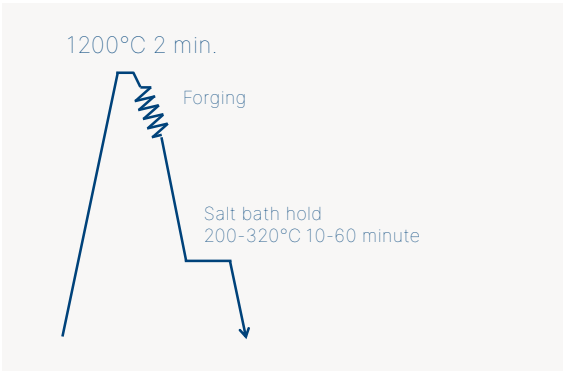


Figure 11 – Process route for direct-quenching steel with salt bath treatment.

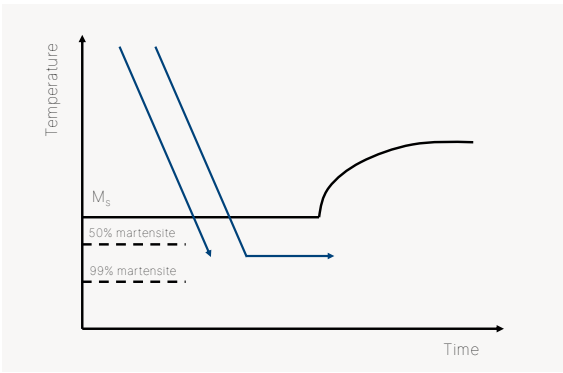


Figure 12 – Formation of martensite in continuous cooling transformation(CCT) diagram.

When considering this approach, it's important to address some common misconceptions about martensite formation (see Figure 12):

- **Martensite transformation is a diffusionless phase transformation.** This statement is generally true. However, if the Ms (martensite start) and Mf (martensite finish) temperatures are relatively high (>200°C), transformed martensite may undergo auto-tempering, leading to cementite precipitation and carbon partitioning into retained austenite.
- **Martensite transformation is an athermal transformation; the extent of transformation depends solely on temperature, with no further transformation expected when holding at temperatures below Ms.** This is accurate for certain steel grades, particularly very low-carbon and highly alloyed steels. However, in medium-carbon steels, a lower bainite transformation is expected to occur.
- **Martensite is hard and brittle.** This is true mainly for steels with relatively high carbon content (>0.45 wt%), but low-carbon martensitic steels can achieve high toughness.

In medium-carbon steel with a martensite start (Ms) temperature of 350–380°C, the martensite volume fraction rises as the temperature falls below Ms, as described by the Koistinen and Marburger equation. Once the temperature stabilizes at an isothermal quenching temperature, the remaining austenite will gradually transform into lower bainite. Since the carbon remains highly mobile at the holding temperature in the transformed martensite, tempering of martensite also takes place.

The tempering of the martensite involves the competition between carbon partition into the retained austenite and cementite formation at this temperature range. In addition, the dislocation density and stress generated during martensite transformation are gradually reduced during the holding period at the isothermal quenching temperature. The carbon content in the steel also plays a crucial role in determining its strength and toughness; low-carbon (0.2-0.3 wt%) steel, in particular, can deliver both high strength and high toughness after isothermal quenching.

Table 3 shows the chemical composition of the steel selected for investigation in direct salt treatment. The dilatometer was used to measure the small dimensional changes resulting from heat treatment and phase transformations. The steel was subjected to identical austenitization conditions (950°C for 2 minutes) but underwent different cooling profiles, as illustrated in Figure 13. The first(green) cooling profile involved a constant cooling rate of 20 °Cs⁻¹ to room temperature, producing a martensitic structure. The second(blue) cooling profile is an isothermal quenching process and involves a constant cooling rate of 20 °Cs⁻¹ down to 230 °C and held for 1 hour. The third(orange) cooling profile is the simulated salt bath cooling profile, derived from temperature measurements taken with a thermocouple inserted into the core of a 60 mm diameter, 25 mm thick disk of the same steel, quenched in a salt bath at 230°C; the sample is also held at 230 °C for 1 hour.

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

Table 2 – Chemical composition of steel selected for direct salt treatment.

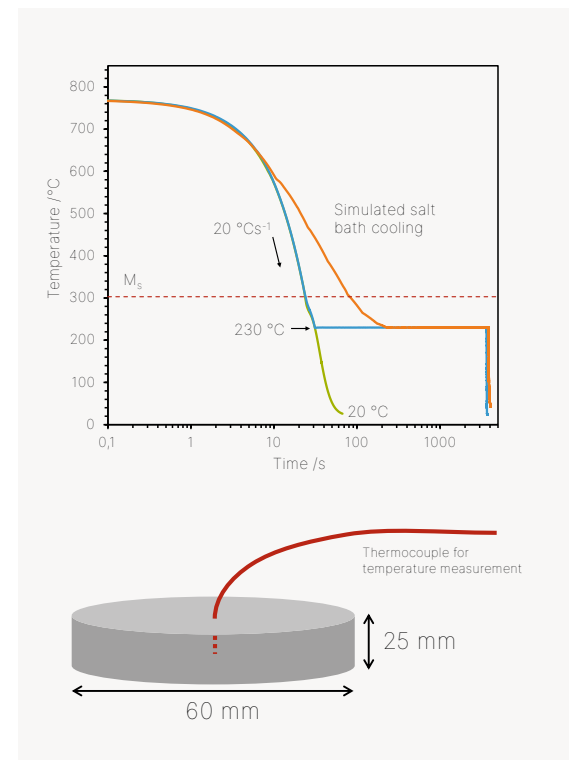


Figure 13 – Cooling profile during the dilatometer investigation of steel for direct salt treatment. The steel sample was heated to 950 °C for 2 minutes before cooling. The large disk was austenitized at 850 °C for 60 minutes prior to salt bath quenching.

The volume increase detected by the dilatometer during constant cooling or simulated salt bath cooling is attributed to the martensitic transformation. Conversely, the volume increase observed during isothermal holding is associated with a lower bainite transformation in this steel. As shown in Figure 14, when cooled at a constant rate of 20 °C/s⁻¹, martensitic transformation initiates at approximately 280 °C and continues as the temperature decreases. The bainite transformation begins when the temperature stabilizes at 230 °C for both isothermal quenching and simulated salt bath cooling, indicated by a continued increase in volume. The bainite transformation following simulated salt bath cooling progresses more slowly compared to the sample cooled at a constant rate of 20 °C/s⁻¹. This slower transformation suggests carbon partitioning into austenite during the slower cooling rate, with carbon enrichment in the retained austenite decelerating the bainite transformation.

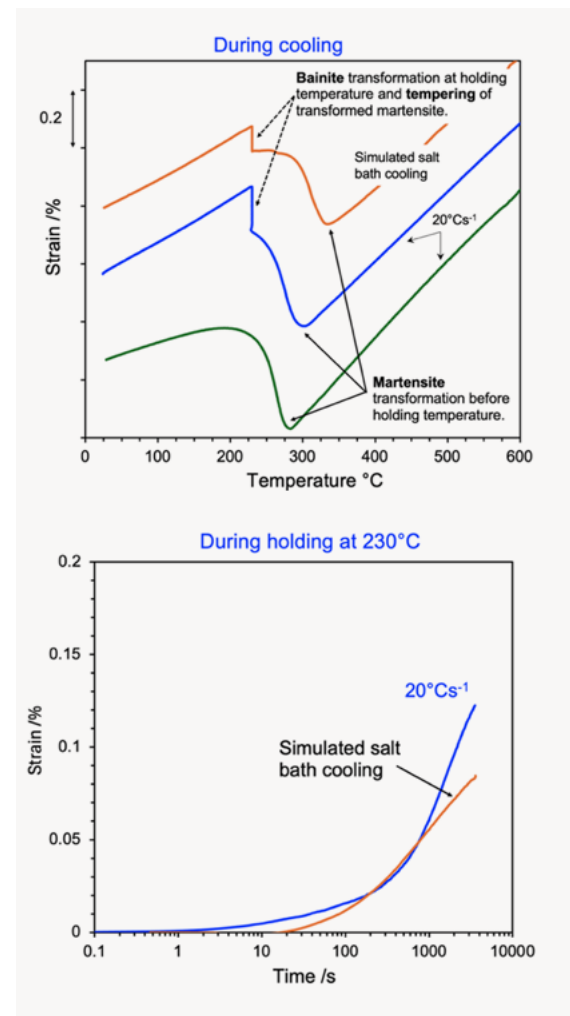


Figure 14 – The dilation of the steel during cooling to room temperature and holding at 230 °C. The detected volume expansion during cooling is due to the martensite transformation, while the volume expansion during holding at 230 °C is due to the lower bainite transformation.

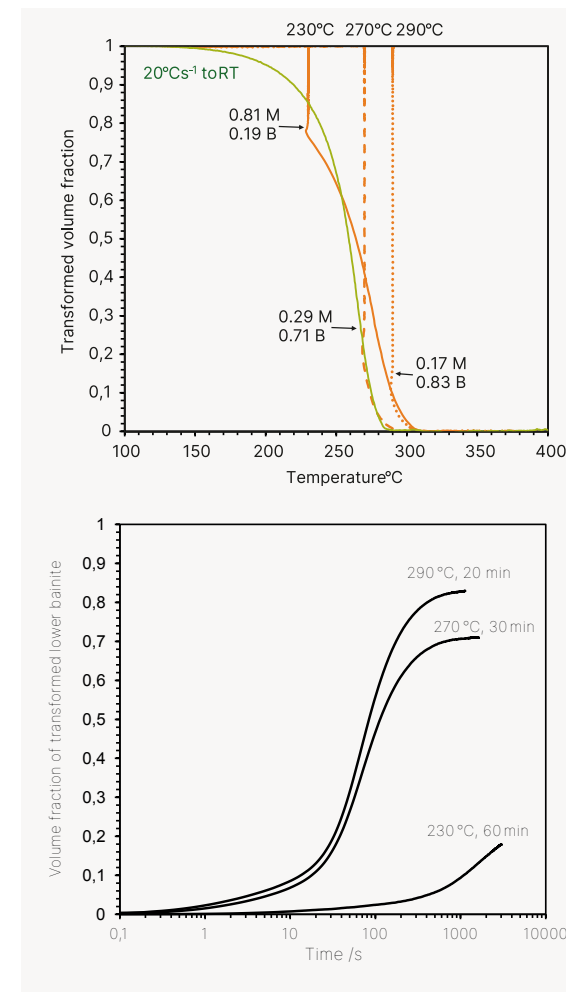


Figure 15 – The volume fraction of martensite formed below M_s temperature after constant cooling at 20 °C/s⁻¹ and the lower bainite formed during holding at various isothermal quenching temperatures and durations.

Figure 15 illustrates the volume fraction of martensite formed below the M_s temperature and the volume fraction of lower bainite during holding at various isothermal quenching temperatures for the same steel. As shown, holding at different temperatures for varying durations produces distinct mixtures of lower-bainite and tempered martensite microstructures.

Key observations 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 bainitic structure.

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

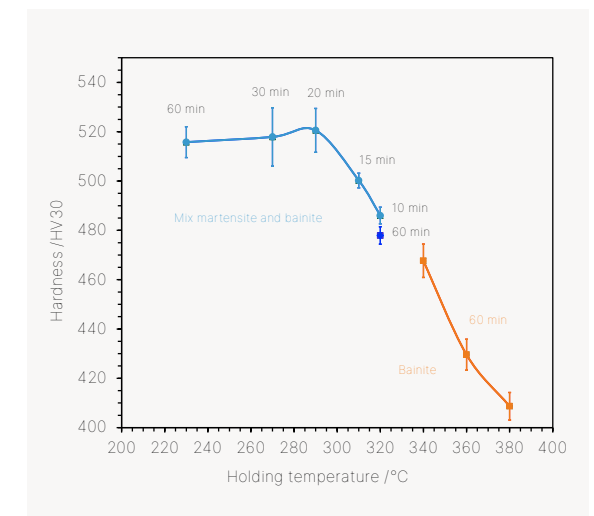


Figure 16 – Effect of isothermal quenching and austempering on the hardness of steel for direct salt bath treatment, the duration of the holding is also shown in the figure.

Figure 16 shows the effect of isothermal quenching and austempering on steel hardness. Reducing the holding temperature down to 290 °C increases hardness, but this increase plateaus at temperatures below 290 °C. Holding at 270 °C and 230 °C leads to a slight decrease in hardness.

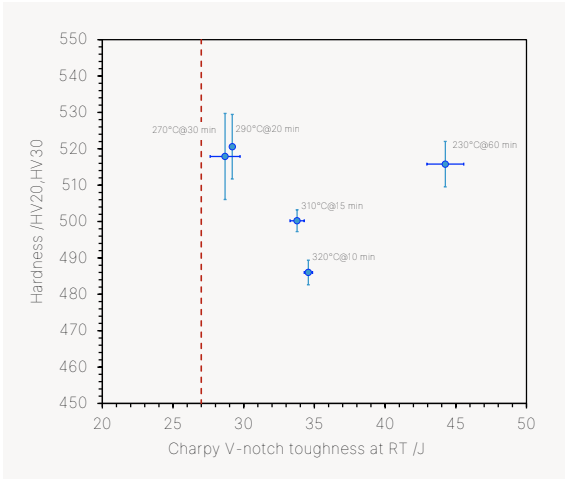


Figure 17 – Effect of isothermal quenching on the hardness and toughness of steel for direct salt bath treatment. The sample dimension for the salt bath quenching is 11x11x180 mm³.

Figure 17 shows how isothermal quenching temperature and duration influence the hardness and toughness of the steel. All heat treatment conditions result in toughness values exceeding 27J, meeting certain application requirements while possessing significantly high strength. As shown, isothermal quenching at a holding temperature close to the martensite finish temperature yields the best combination of hardness and toughness, suggesting that achieving a predominantly martensitic structure is key to optimizing strength and toughness during isothermal quenching. For applications with less stringent strength and toughness requirements, the salt bath holding time can be reduced to just 10 minutes to produce a predominantly bainitic structure.

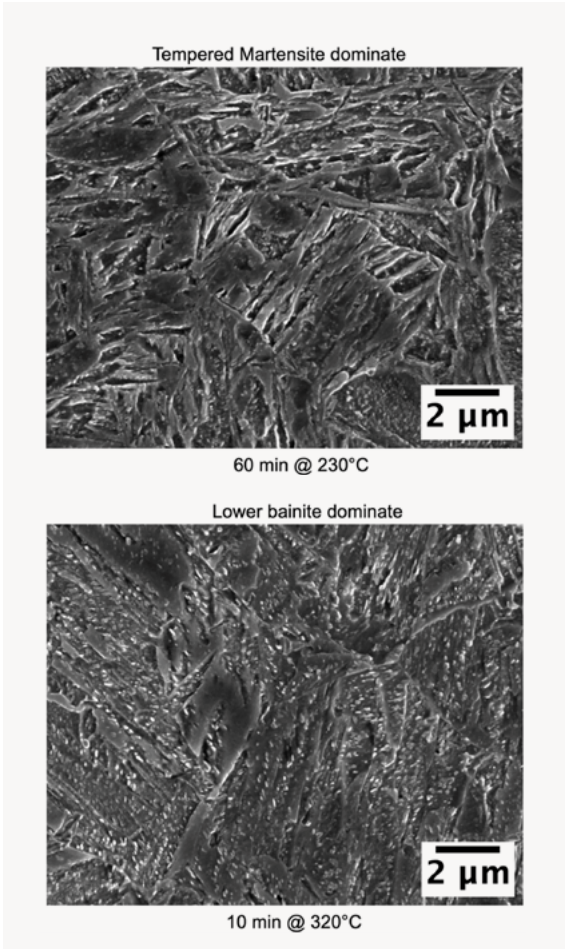


Figure 18 – Microstructure after isothermal quenching of steel for direct salt bath treatment.

Figure 18 illustrates microstructural variations resulting from different holding times and temperatures. Holding at a lower temperature (230°C) produces a tempered martensite-dominant microstructure, while holding at a higher temperature (320°C) results in a lower bainite-dominant microstructure. As shown, the lower bainite microstructure contains more and larger cementite precipitates.

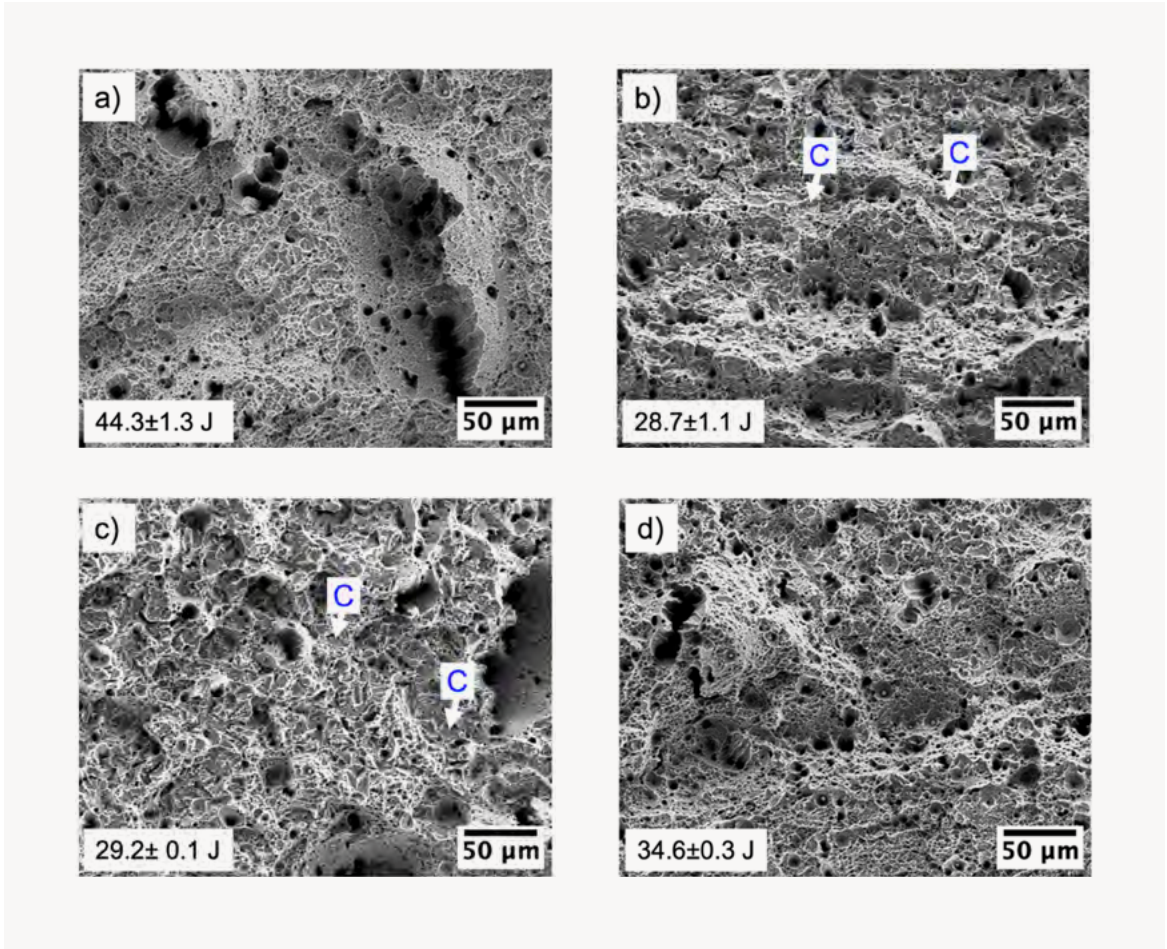


Figure 19 – Fracture surfaces of medium carbon steel after isothermal quenching under different conditions: (a) 230°C for 60 min, (b) 270°C for 30 min, (c) 290°C for 20 min, and (d) 320°C for 10 min. The label “C” indicates areas where cleavage fractures were observed.

Figure 19 shows the fracture surfaces of medium carbon steel after isothermal quenching, as observed after Charpy toughness testing. While most of the fracture

surface exhibits ductile characteristics, some cleavage fractures appear when the toughness value is below 30J.

4 – Conclusion – innovative steel can help forging companies eliminate energy-intensive heat treatment processes

The results of this work show that the quenching and tempering (Q&T) step following forging can be eliminated by innovative alloy design combined with the control of the phase transformation during direct or interrupted air cooling or isothermal quenching.

- A variety of chemical compositions can be tailored to suit different forging shop setups.
- Low-carbon (0.05-0.2 wt%) martensitic steel, with transformation temperatures between 280 and 350 °C, can be employed in either direct or interrupted air-cooled setups, with an option for low-temperature tempering. The interrupted air-cooling route requires leaner steel compared to direct air-cooling.
- Medium carbon (0.2-0.35 wt%) steel, aimed at achieving a mixed tempered martensite and lower bainite microstructure, can be processed using direct salt bath treatment (isothermal quenching). The tempered martensite-dominant microstructure has been shown to provide the optimal balance of strength and toughness.



5 – About the author



Dr Steve Ooi is Group Technical Specialist with Ovako R&D, based at Cambridge University. He obtained his BEng, MPhil, and Ph.D. from Swansea University. His work specializes in alloy and process design in the context of steels for complex engineering applications where component failure can lead to major consequences. Much of his research is therefore focused on critical components in industrial applications.

Disclaimer

The information in this document is for illustrative purposes only. The data and examples are only general recommendations and not a warranty or a guarantee. The suitability of a product for a specific application can be confirmed only by Ovako once given the actual conditions. The purchaser of an Ovako product has the responsibility to ascertain and control the applicability of the products before using them.

Continuous development may necessitate changes in technical data without notice. This document is only valid for Ovako material. Other material, covering the same international specifications, does not necessarily comply with the properties presented in this document.

Ovako Head Office

Box 1721
SE-111 87 Stockholm, Sweden

+46 8 622 13 00
ovako.com