WARWICK
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NEAR SOLIDUS FORGING

The Knowledge Transfer Partnership Programme between WH Tildesley and Warwick Manufacturing Group (WMG) & the University of Warwick. This project was funded by UK Research and Innovation (UKRI) through Innovate UK.

THE CHALLENGE

W.H.Tildesley (WHT) are closed die drop forging experts and one of the leading forged component manufacturers in the UK. They were established in 1874, making them one of the oldest drop forging companies remaining in the United Kingdom.

For the past few years, they have been trying to focus on forging more bespoke, difficult-to-forge materials. In the past, 90% of all forgings were made of carbon steel, now the production of ferrous and non-ferrous materials lies around 50/50. The company's aim is to be considered as experts in forging non-ferrous and difficult-to-forge materials.

WHT undertook a Knowledge Transfer Partnership with WMG to improve their competitiveness in the forging market through implementing a new, innovative forging technology, Near Solidus Forging (NSF) to allow further capability to produce these difficult materials.

Michal Filipowicz, an Engineering Master's Graduate with wide expertise in metal processing, was appointed as the KTP associate on this 28-month project and tasked to introduce metallurgical fundamentals to optimise conventional forging, in addition to assessing opportunities that NSF could have to the WHT portfolio.

w.h.tildesley ltd
Drop Forging Specialist

UK RI Innovate UK

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THE PROJECT

Hot forging simulation

Finite element simulations offer great insight into processes such as forging, allowing a range of parameters to be changed to optimise the final component. With this the KTP Associate implemented the use of DEFORM 3D into the company to help die design as well as property optimisation. DEFORM 3D is a complex software which helps to understand important aspects during a metal formation process such as stress/strain distribution, temperature evolution and stress flow during the forging operation. It also helps design the tooling and estimate the die life.

A hammer at WHT was instrumented with force transducers, accelerometers, laser displacement transducers and strain gauges to create a digital twin of the system. The data obtained on the R&D hammer was implemented into the DEFORM software and trials carried out demonstrated a high accuracy in the prediction of the forging process via simulations. Furthermore, the simulation software was equipped with the Avrami model of high-temperature grain evolution. The empirical equations described the kinetics of recrystallisation and grain growth mathematically which allowed the calculation of the final grain size of a processed component.

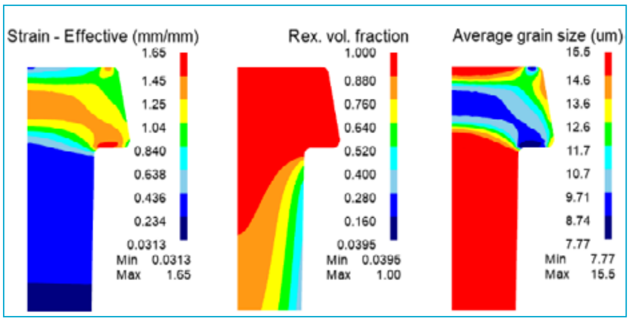


Figure 1 Simulation view

M20 stainless steel bolt study

The bolt examination was one of the main intermediate goals of the project where the aim was to give a systematic study into how forging parameters can influence the microstructure (and therefore the mechanical properties) of a component, giving confidence in conventional forging before using the predictions to aid NSF processes.

Conventionally, for parts such as bolts, material selection would consist of buying cold rolled material with a diameter as close to the bolts shank as possible. Cold rolled stainless steel offers the benefit of typically a very fine grain size and a good surface finish, but equally has a high yield strength, even at high temperatures and therefore more difficult to forge. Cold rolled steel is typically less readily available and more expensive than its hot rolled counterpart. Its cost in the UK lies around **£6000 per ton** where the hot rolled product **costs £3800 per ton**. However, these different source materials can give different final mechanical properties if not processed correctly.

This research looked at applying recrystallisation theory to a commodity product to observe if an improvement to performance, or a reduction in cost of stock material can be achieved by using cheaper and readily available hot rolled material. This was carried out through a combination of finite element analysis and experimental verification.

As a result, critical forging parameters were defined that ensured the correctly metallurgical phenomena occurs and as such the same microstructure can be achieved from both starting materials. T**his results in a cost saving of £35,000 for a batch of 60,000 bolts.**

> *"If WHT can take this research forward and control all necessary variables it could allow us to greatly expand our production capacity in areas we originally thought very unlikely. A new standard and meaning could be associated with WHT and safety critical fastener items. "*
>
> ***Steven Hill (Manufacturing Engineer, WHT)***

The results of the research were presented at the 9th International Conference on Modelling and Simulation of Metallurgical Processes in Steelmaking STEELSIM2021 and published under the title: "Bolt forging process optimisation using simulation software with applied Avrami model for recrystallisation".

Near Solidus Forging

The conventional forging (CF) of steel is routinely carried out at temperatures between 900 and 1200°C and the forgings are made using multiple blows (sometimes up to 40) in 2 or 3 cavities in the set of dies. The Near Solidus Forging process is raising the temperature much higher, close to the melting point, where the material loses most of its strength. The workpiece is being pushed into the cavity using sufficient force to create the component with just one blow. This method enables the forging of parts with very complex shape which would not be possible traditionally, using materials considered as un-forgeable or hard-to-forge as well as allowing for significant material savings being recognised as a near net-shape manufacturing method.

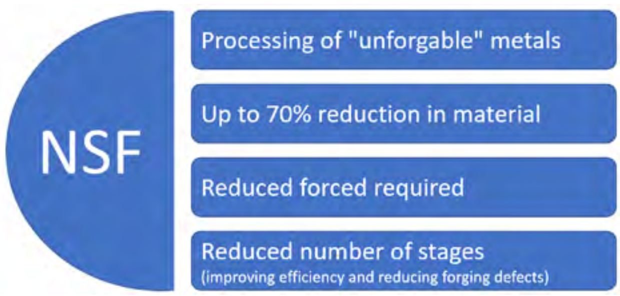


Figure 2 Near Solidus Forging benefits

The chosen part for the NSF process has been made at Tildesley for many years for the Oil & Gas industry as a T-piece pipe joiner. The part was made both conventionally and by the Near Solidus Forging method from two materials: 316 Stainless Steel (original material of the part) and F44 Super Austenitic Stainless Steel as the hard-to-forge material which is in growing demand. Fig. 3 shows the part's shape and the difference in how the force was applied in the two forging processes, the comparison of forming conditions is shown in the table 1.

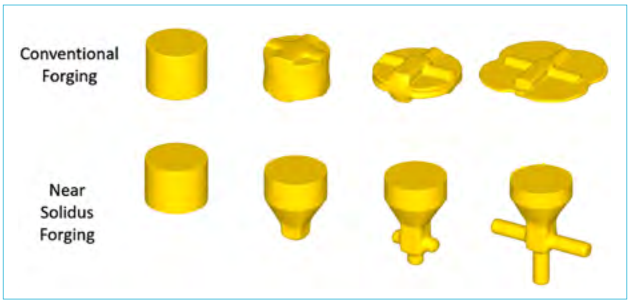


Figure 3 Processes of the Conventional Forging (CF) and the Near Solidus Forging (NSF) shown in steps

The billets for the NSF process were brought to the near solidus temperature of 1365°C and deformed using a hydraulic press, almost nine times slower than a power hammer used for the conventional forging. The required shape was obtained in a single-cavity set of dies with just one strike, as opposed to five blows in two cavities used conventionally.

Process	Conventional Forging	Near Solidus Forging
Machinery	Power hammer 36 kJ	Press 400 t
Ram speed	7000 mm/s	800 mm/s
Heating method	Rotary gas furnace	Electric muffle furnace
Billet temperature	1180°C	1365°C
Die configuration	Moulder + finisher	Single cavity
No. of blows	5 blows	1 blow
Produced parts		

Table 1 Comparison of CF and NSF processes conditions

The components were tested both before and after heat treatment. Initially we can see that the NSF is in a much lower stress state, showing a profile similar to that after heat treatment. If this is proven to be true, then removing the heat treatment stage has huge economic and environmental benefits reducing CO2 emissions and therefore the cost moving forward. After heat treatment the profiles show that the arms (which are later threaded and therefore crucial to the Inservice performance) have a hardness increase of 40HV or 20%, this translates to about a 130MPa increase in strength (Fig. 4), potentially allowing a redesign of the component to be lighter or of a more complex design. Whilst this specific component may not benefit from these advantages, translating this to other components such as automotive/aerospace then these improvements are truly exciting.

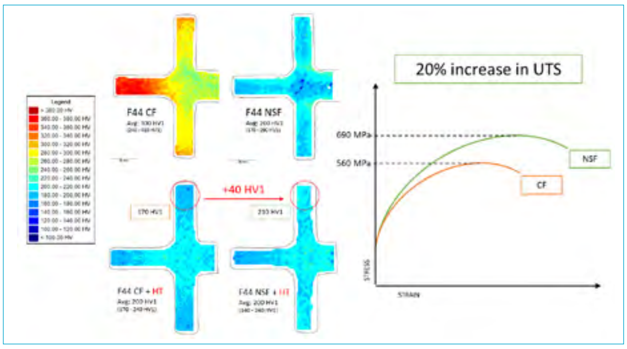


Figure 4 Hardness profiles of F44 parts and strength improvement

The final aim of the project was to see how far this technology can be pushed by producing a component using more exotic materials. The shape was obtained from different nickel alloys, grade 5 titanium and bi-metal where the component was formed with a stainless steel outside layer and mild steel core. The finite element analysis was used to optimise the shape and remove identified dead spots by increasing the deformation in the arm.

Figure 5 NSF component made from Incoloy 825

"The trials from NSF have shown the exciting prospect of utilising this technique, not just in manufacturing current components more efficiently, but also it has the capability of unlocking materials that previously were not utilised in the forging industry but also obtaining fine microstructures resulting in impressive mechanical properties. "

Carl Slater (Assistant Professor, WMG)

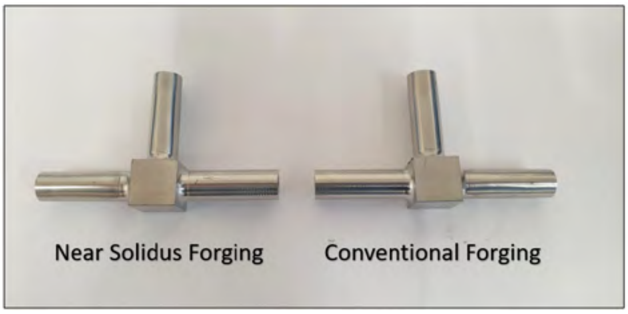
Impact and results

It has been shown in this KTP that NSF is a viable method going forward to producing complex components from hard to manufacture metals. However, there are further benefits to this process.

Conventional forging requires the use of a 1000g billet to produce the component, where 540g is a flash (waste) being immediately clipped off (**>50% scrap per component**). The Near Solidus Forging does not produce a flash, there is very little excess material at the top of the component in the shape of a cone. The optimised NSF process would require a 500g billet to produce the same component and only 50g of material would be a surplus (**<10% scrap per component**).

With the increasing demand on reducing CO2 emissions then forging quickly, efficiently and sustainable is becoming ever more important. Table 2 shows the calculations of the energy required to raise proposed billet to forging temperatures and the carbon dioxide produced by these operations. The calculations indicate that the optimised NSF process reduces the CO2 footprint by 42%. Furthermore 50% less material would be required to produce the part with 91% waste reduction!

This Knowledge Transfer Partnership project has demonstrated that the Near Solidus Forging can be moved to a production facility. The investments of high-temperature, reliable heat source and tooling set-ups are needed to start a new production line of the innovative forging method at WH Tildesley. Further optimisations and investigations into the NSF process together with the use of a faster power hammer instead of a hydraulic press for this method can lead to new capabilities of forming more complicated shapes, producing components out of hard-to-forge or unforgeable materials and achieving better or even outstanding mechanical properties. This method, when optimised, can provide significant material savings and has been shown to be environmentally friendly.
The innovation could also help find new customers and elevate the company's position on the local, or perhaps even global market.



"The implementation of the NSF process to the forging industry brings about significant changes to the CO2 emissions from forged products. The reduction in initial billet size and waste material generated significantly reduces the embedded carbon footprint of the whole manufacturing activity. "

Paul Lansdell (Innovation Manager, WMG)

"WH Tildesley has gained leading-edge science in hot forging and NSF from the KTP with WMG. The outcomes are significant; economies in manufacture, an ability to forge difficult materials, environmental improvements and opportunity for increased market share and profitability. Unique opportunity for the Associate to study, transfer knowledge, gain valuable experience and credibility in his field. "

Russ Bromley (Knowledge Transfer Advisor, KTN)

"In order to survive and grow in an increasingly competitive manufacturing marketplace WHT has to continue to develop niche process capability and niche product offerings to customers, NSF completely fills these criteria. Additionally, NSF adds to our on-going Net Zero Carbon initiatives by reducing carbon requirements for potentially all our forged products"

David Lunn (General Manager, WHT)

Table 2 Energy consumption and carbon footprint of CF and NSF processes

	Conventional Forging	**Optimised Conventional Forging**	**Original NSF Trial**	**Optimised NSF projection**
Billet weight [g]	1000	850	900	500
Required temperature [°C]	1180	1180	1365	1365
Energy [KJ] required to raise proposed billet to forging temperature	580	493	605	336
CO2 footprint [g] to heat each billet	33	28	34	19
CO2 footprint [g] (full batch of 200 off)	6542	5561	6827	3793
Average value of Stainless Steel Specific Heat used in calculations - 500 J/kg°C				

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