A novel forming technique to coforge bimetal components into complex geometries.

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Abstract
The novel Near Solidus Forming process has been used to coforge stainless steel 304 to encapsulate a core of 42CrMo4 steel in Stainless 304 in the form of a complex spindle. The forging was achieved with a force of 280 t, in a single strike, at a temperature of 1370 °C. The component successfully filled the die and a range of microstructural evaluations showed an inclusion/porosity free interface between the two steels with >3 µm of cross diffusion.

Keywords: Near solidus forming; Bimetal; Coforging; diffusion bonding.

1. Introduction
Recently, a new forming technology called Near Solidus Forming (NSF) that obtains as forged properties (tensile and fatigue) whilst reducing the cost has emerged [1,2]. The NSF is a novel process that operates at temperatures just below the solidus where the material exhibits little or no ductility. Therefore, offering the benefits of both conventional forging (grain refinement from the high strains and, consequently, improved material properties) as well as semi solid processing such as Thixoforming (much lower pressing loads). Due to the extremely low strength materials exhibit in this temperature region, then single deformations can be used to create complex geometries that would take conventional forging techniques multiple strikes, with multiple reheats, thus saving both time and money [1]. This process therefore allows forming of materials that retain a lot of their strength even at conventional forging temperatures.

Apart from the attainable geometrical complexity using NSF, the high temperatures involved as well as the pressures and strains generated during the process offers very interesting opportunities. One of those is the possibility of making bimetal components. To date, the main metal solid state joining processes are friction welding, friction stir welding and diffusion bonding [3], most of which are restricted to simple geometries and require significant machining to remove flash.

2. Materials and Methods

2.1. Steel grades
The two materials selected for this study were commercially available Stainless Steel 304 and 42CrMo4. To determine the temperature for NSF, the solidus of these materials was calculated through a combination of Thermocalc software, using TCFE10 database and Differential Scanning Calorimetry (DSC). DSC was carried out on 100 mg samples at a heating rate of 10 °C/min. The solidus temperatures of both materials can be seen to be around 1395-1425 °C and for this reason then an NSF temperature of 1350-1370 °C was chosen.

2.2. NSF Manufacturing process
To carry out the NSF process then a Fagor 400 t AC servo-mechanical press was used in conjunction with NSF tooling developed by Mondragon University [4,5]. The dies are oil cooled to maintain a

constant 270 °C to prolong die life. The die used has been designed to produce an automotive spindle seen in Figure 1b (this component has been previously produced by conventional NSF in [1] out of a single material). The completed component is around 3 kg.

In previous work on NSF then the billet used comprises of a rod of 69 mm diameter and 93 mm long. For this study, the innovation lies in using a cup of stainless steel 304 (outer diameter of 69 mm and 93 mm long with a hole of diameter 39 mm and 78 mm depth. This leaves a wall thickness of 15 mm) and a rod of 42CrMo4 (39 mm diameter and 78 mm long) inserted inside before placing in the furnace (a schematic of the bimetal billet can be seen in Figure 1a).

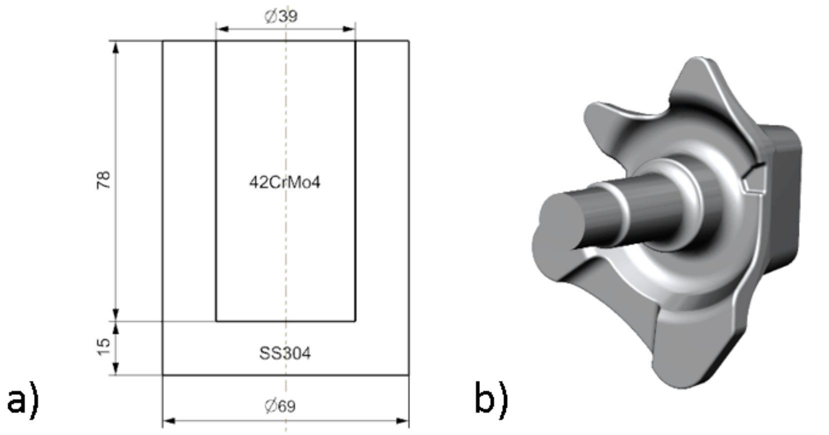

Figure 1: a) Bimetal billet design, and b) final part [1].

The operating sequence of the NSF cell consists of heating the billet in the muffle furnace (Hobersal 9-CRN5X-18) to 1370 °C under an argon flow of 0.5 L/min to prevent the material from oxidising. After a 30 min soak at temperature, the billet is manually dropped into the top of the tooling. The punch is then lowered at an average rate of 200 mm/min where it dwells for 5s before ramping back to the initial position. At this point, the clamping system is retracted, and the tooling opened to remove the component.

2.3. Component evaluation methods

In order to perform a complete microstructural and compositional analysis of the different areas of the component, several state-of-the-art equipment has been used. In order to observe compositional differences in a macro level, XRF evaluation of half of the component will be performed using a Bruker Tornado M4 with the following settings: 100 µm step size was used with a 100 ms dwell time on each point. Electron microscopy was then carried out using a FEI NovaNanoSEM 450 Scanning Electron Microscope (SEM) equipped with an Oxford X-max 50 X-Ray detector (EDX)

3. Results and Discussion

The component produced can be seen in Figure 2a and a maximum load required was measured at 277 t. This load is significantly lower than that required to conventional forge a component (typically around 2500 t [2]). Figure 2b shows an XRF map taken from a slice through the centre of the forged component. Here it can be seen that the stainless 304 fully covers the outside of the component (depicted by the high Cr Regions) and thus offering the corrosion resistance to the part. It should be noted that the relative sizes of the starting stainless 304 and 42CrMo4 ingots have not been optimised in this case and further minimisation of the volume of the stainless steel is expected.

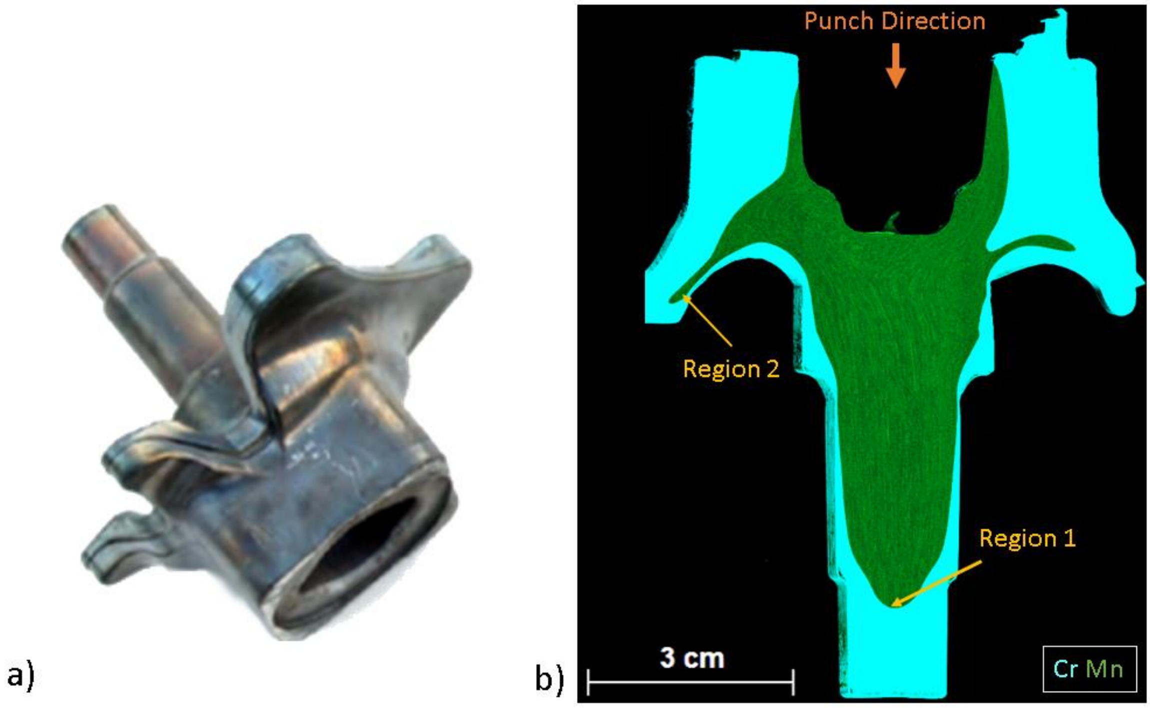

Figure 2: a) Final component and b) XRF image take from a slice of the forged component.

SEM and EDX lines scans were taken from the slice seen in Figure 2b. This can be seen in Figure 3. Here no porosity was seen at the interface and there was no observable presence of any intermetallics. Region 1 shows a much smoother interface due to the unidirectional nature of the compression in this region which can be seen by the orientation of the Mn flow lines. Region 2 conversely shows a much more serrated interface (Figure 3b) as these regions are likely to exhibit a much greater shear stress. It is unclear at this stage whether the serrated is more beneficial as an interface due to the larger surface area, or whether the edges will act as crack initiators. However, what is apparent is that no obvious defects are forming in either areas.

Confidence in the strength of the interface is further supported through the EDX line scan (Figure 4a). Both Cr and Ni have diffused readily across the boundary, where a minimum of around 3 µm of cross diffusion can be detected. This is even more for the Cr, where depletion is seen on the stainless 304 side for around 3 µm and around 2 µm into the 42CrMo4 side. Micrographs such as Figure 3 and diffusion profiles such Figure 4a are comparable to friction welded components that have been shown to see just 1-2 µm cross diffusion between 42CrMo and a nickel superalloy [6].

The simulation system using Dictra MOBFe5 database was setup using the 10 µm length from Figure 4a, and an interface position of 5.3 µm. As the cooling rate of the component inside the die is unknown, although due to the martensitic transformation of the 42CrMo4 steel then it is assumed to be >10 C/s [7]. A simple 1D single phase model approach has been applied as the Stainless 304 remains austenitic to room temperature, and the 42CrMo4 steel transforms to martensite and therefore no solute partitioning is likely as with ferrite/pearlite structures. A range of cooling rates were then applied within Dictra. Figure 4b shows the measured EDX compositional traces for Cr and Ni compared with a Dictra simulation with a cooling rate of 12.5 °C/s down to 850 °C. Excellent agreement can be seen for both elements. This tool will be important moving this technology forward using different alloys, applying different cooling parameters to the moulds, or hold times during the forming process.

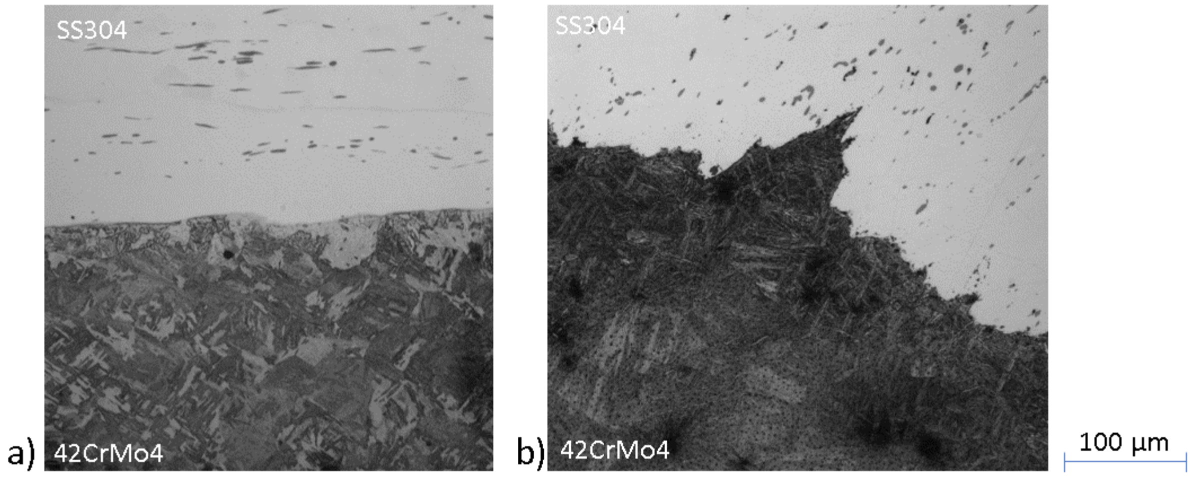

Figure 3: SEM micrographs for the coforged component taken from a) Region 1 and b) Region 2.

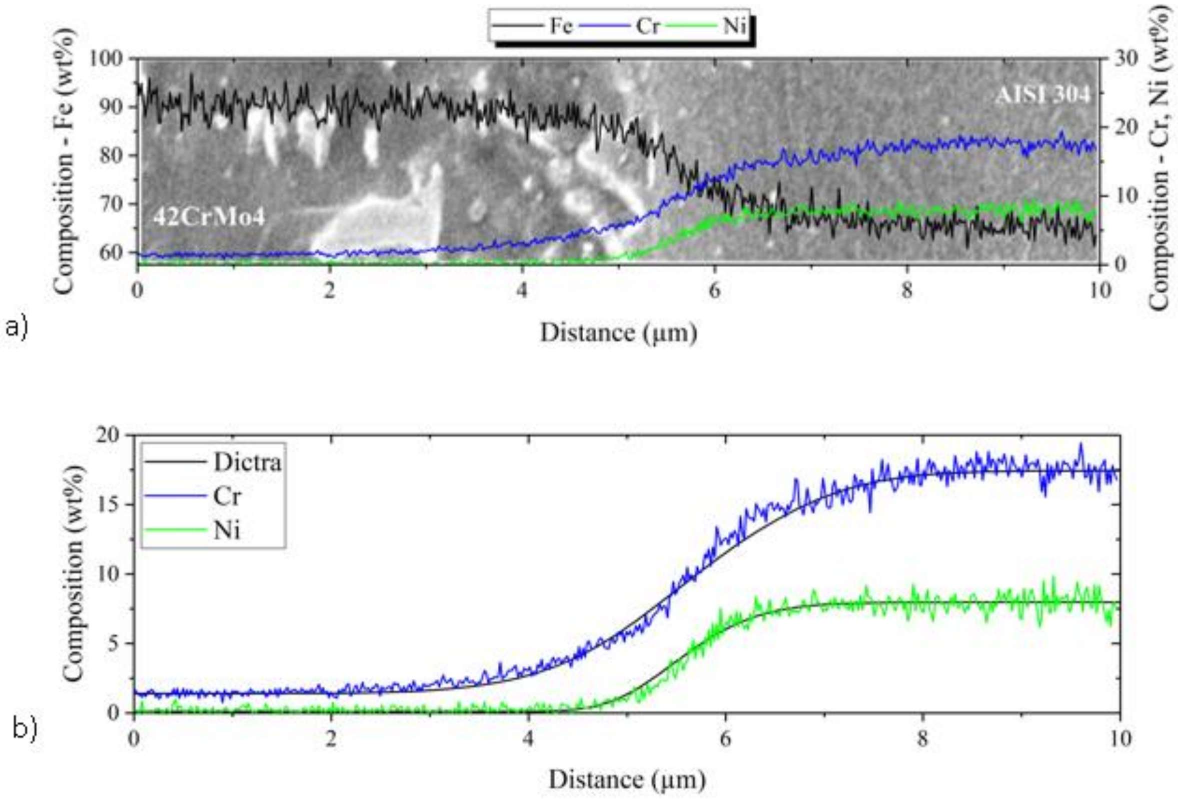

Figure 4:a) EDX line scan across the interface between the 42CrMo4 and Stainless Steel 304 in the coforged component, b) Measured (EDX) and predicted (Dictra) compositional profile curves for Ni and Cr after coforging assuming a 12.5 C/s cooling rate.

4. Conclusions

This research has used the NSF technique to successfully coforge two steels such that expensive stainless steel fully encapsulates a core of 42CroMo4 steel into the form of a complex automotive spindle. Although the process parameters such as temperature, relative amounts of each material and strain rate have not been optimised. There is experimental evidence to show the promise that this technique has, opening possibilities that were previously unobtainable through conventional forging processes.

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