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Optimization of process parameters for high efficiency laser forming of advanced high strength steels within metallurgical constraints

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Abstract

Laser forming (LF) has been shown to be a viable alternative to form automotive grade advanced high strength steels (AHSS). Due to their high strength, heat sensitivity and low conventional formability show early fractures, larger springback, batch-to-batch inconsistency and high tool wear.
In this paper, optimisation of the LF process parameters has been conducted to further understand the impact of a surface heat treatment on DP1000. A FE numerical simulation has been developed to analyse the dynamic thermo-mechanical effects. This has been verified against empirical data. The goal of the optimisation has been to develop a usable process window for the LF of AHSS within strict metallurgical constraints. Results indicate it is possible to LF this material, however a complex relationship has been found between the generation and maintenance of hardness values in the heated zone. A laser surface hardening effect has been observed that could be beneficial to the efficiency of the process.

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Keywords: Laser forming; laser; optimization; AHSS; micro hardness

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1. Introduction

Advanced high strength steels (AHSS) are an automotive grade of steel which are of a significant interest to manufacturing industries due to their high strength when compared to conventional steels, which leads to a

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reduction in weight and crash risk. This paper is concerned with Dual Phase Steel (DP1000), which is one of the most widely used types of AHSS by car manufacturers (*Kuziak, A. Camoletto*).

Dual phase steel (DP) has a microstructure composed of soft ferrite and 10-40% of hard martensite or martensite-austenite islands (*J .R. Bradley*). The strength of the DP steel microstructure is determined by the amount of martensite which is developed by the transformation of austenite during quenching after hot rolling or annealing (*Kuziak*).

A major disadvantage of dual phase steels is their resistance to deformation and spring back effects in comparison with conventional steels. According to *Neugebauer*, heat treatment of the DP steel leads to an increased formability comparable to conventional mild steels, without spring back. *Neugebauer* recommended a laser heat treatment to improve the formability locally without compromising the whole bulk strength.

Laser forming (LF) is a non-contact process of shaping metallic and non-metallic sheets by inducing thermal stress using a de-focused laser beam without any melting. Laser forming has a potential of the industrial promise of controlled shaping of metallic and non-metallic components for prototyping, correction of design shape or distortion and precision adjustment applications.

The thermal stress can induce permanent plastic strains bending, shortening or buckling the work-piece depending on the geometry, process parameters and the mechanism active.

This work is concerned with the shortening mechanism (Edwardson et al) where a large beam diameter compare with the thickness and slow process speed induces in-plane shrinkage. This is particularly useful for the forming of tubular and box section geometries used in structural component in the automotive industries. Recent work has shown the process can be used to form square section tubes (Sheikholeslami et al).

Laser forming has been shown to be a viable alternative to locally heat and form AHSS despite the sensitivity of material to heat. Griffiths et al. investigated the potential to form heat sensitive dual phase steel by the laser bending process within metallurgical constraints by optimisation of process parameters. Griffiths classified two temperature regimes where the DP 1000 experienced a reduction in hardness. Within a low temperature heating regime a loss of tetragonality in the martensite region resulted in a slight reduction in hardness. Within a higher temperature regime of greater than the upper critical transformation temperature in mild steel of equivalent carbon content (1000-1140 K) a major loss of hardness was observed due to austinization effects.

Further studies presented in this paper on dual phase steel (DP1000) indicate a more complex relationship between the generation and maintenance of hardness values in the heated zone. A laser surface hardening effect has been observed that could be beneficial to the efficiency of the forming process.

Laser surface hardening depends on laser processing variables as well as interaction time to produce a martensitic structure in steel (J.Senthil Selvana et al).They characterised the laser transformation hardening process into three basic steps; An increase in temperature above a critical point of the steel (Ac1) followed by rapid self-quenching into the bulk material. Typically in low carbon steels as the surface temperature is brought to 980–1773K within a short interaction time the original pearlite morphology transforms into a metastable martensite which increases the hardness not only on the surface of the steel but to a depth of 0.2-1 mm. DP1000 is also considered a low carbon steel and so should behave in a similar way.

In this paper, optimisation of the laser forming process parameters has been conducted to further understand the impact of a surface heat treatment on 1.2mm thick DP1000. A FE numerical simulation has been developed to analyse the dynamic thermo-mechanical effects. The goal of the optimisation has been to develop a usable process window for the laser forming of AHSS materials within strict metallurgical constraints.

2. Experimental

An initial empirical study was conducted on graphite coated DP 1000 steel sheet with the thickness of 1.2 mm using a 1.5kW CO2 TEM00 laser (operating at a wavelength of 10.6 µm and in continuous wave mode) and an industrial 5 axis gantry. The speed range was from 15 mm/s to 45 mm/s with the beam spot size of 8 mm and laser power of 600 W and 1000 W. The pass numbers were from single to five passes.

To study the effect of the process on the metallurgical properties of the material, a Vickers micro hardness test with the specification HV 0.1/10 with 1 kg load was used to measure the hardness of the samples; the specific sample preparation is described in Sheikholeslami et al.

A FE numerical simulation has been developed in COMSOL Multi-physics vs 4.4 to analyse the dynamic thermo-mechanical effects. The intensity distribution *I* of the incident laser beam was approximated by a Gaussian distributed heat source:

$$I = I0\, e^{-\left(\frac{2r^2}{w0^2}\right)} = \left(\frac{2P}{\pi r^2}\right) \tag{1}$$

Where I0 is the peak intensity (W/m2), P is the average laser power (W), r is radial distance (m) and ω0 is the beam radius (m).

The FEM model has been validated against experimental bend angle Sheikhoelslami et al .The model was conceived based on empirical processing conditions. All defined material properties were empirically found temperature dependent properties of DP1000. The boundary conditions were set for convective and radiative heat loss. The sample has been clamped from one side only along an edge. The generalised alpha solver has been used to develop the model. Figure 1 shows the irritation path with a very fine mesh density.

The global mesh element size was set to coarse and along the irradiation path a suitable maximum element was found to be 0.01 mm, determined by a convergence study.

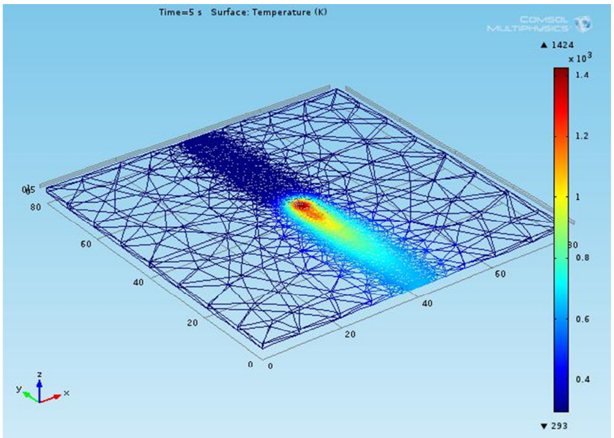


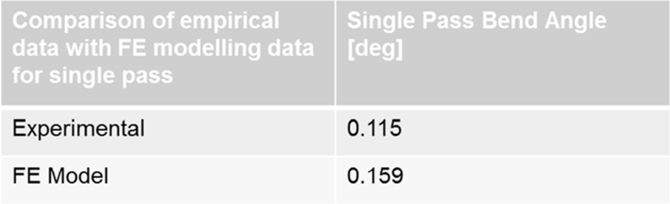
Fig. 1. FE model developed for DP100 showing the direction of a Gaussian beam travelling toward the end of coupon.

3. Results

The numerical model has been developed to analyse the dynamic thermo-mechanical effects during laser foming of 1.2mm thick DP1000 to predict the temperature to further understand the impact of a surface heat treatment.

3.1. Model validation

Validation of empirical results with FE modelling by COMSOL Multi-physics for a single pass using the optimum of power of 600W, 8mm beam diameter and 10mm/s travers speed for EN10305-5 E220 +CR2 tube of 50mm x 50 mm x 1.5 mm(*Sheikhoelslami et al).*



Comparison of empirical data with FE modelling data for single pass	Single Pass Bend Angle [deg]
Experimental	0.115
FE Model	0.159

Fig. 2**.** Validation of empirical results with FE modelling for a single pass using the optimum of 600W, 8mm beam diameter and 10mm/s tubular displacement.

3.2. Effect of speed

Initially, the effect of traverse speed on the micro hardness along the irradiation path throughout the thickness of component was determined. This was conducted by using a constant power and beam spot size whilst varying speed to study the effect of interaction time. It can be seen in Figure 2, that as the speed drops and the interaction time increases, the temperature increases and a subsequent a loss of hardness in the heated zone at the midpoint is observed.

This can be attributed to tempering due to austinization. It can be also been seen in figure 3 that at the speed of 15 mm/s there appears to be some recovery of the micro hardness value. Figure 4 shows the corresponding temperatures from the model output for the midpoint of the sample.

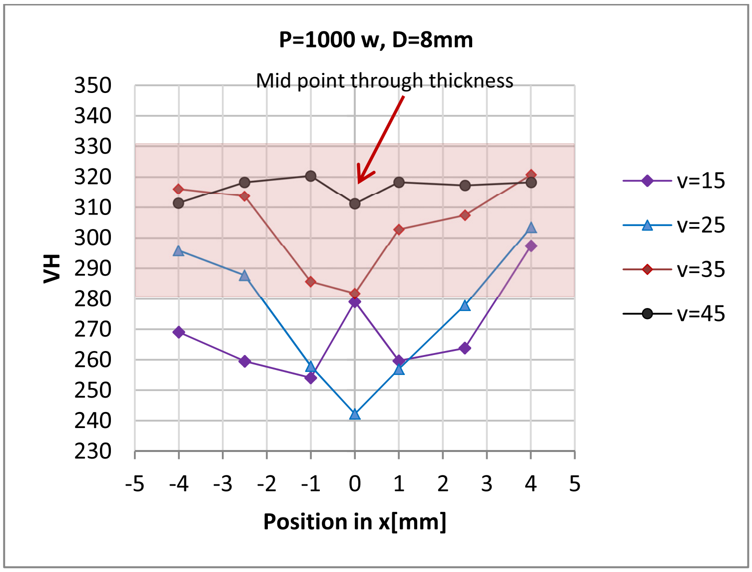


Fig. 3. The effect of varying speed on hardness of DP1000, 1.2mm thickness. The highlighted area shows the hardness of DP1000 as received without any heat treatment.

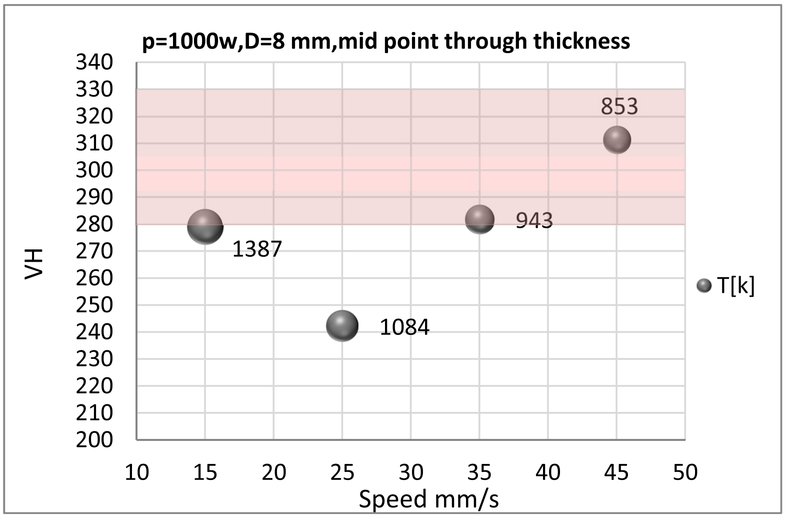


Fig. 4. Variation of VH with increasing traverse speed from 15 mm/s to 45 mm/s with the power of 1000 w and beam diameter of 8 mm. Temperatures have been obtained by FE model. The highlighted area shows the hardness of DP1000 as received without any heat treatment.

It can be seen that at the speeds of 25 mm/s and 15 mm/s the temperature has exceeded the critical austinization temperature of approximately 1000 K. However at 15 mm/s the temperature is higher again and the time at temperature is longer therefore a laser surface hardening effect is possible. The through section temperature distribution at the mid plane of the sample can be seen in figure5.

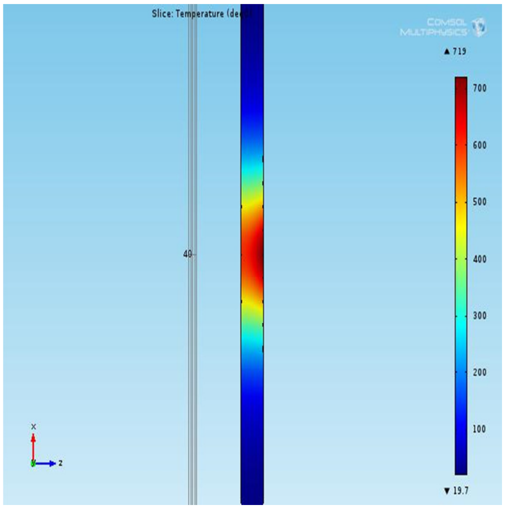


Fig. 5. Temperature distribution through thicknes. The process parameters are ; power of 600w, beam spot size of 8mm, the traverse speed of 20mms and 1.5 second.

3.3. Effect of multiple passes

Multiple passes were studied to investigate the effect of time at temperature on the loss mechanism. The results indicate that in a single pass there is a significant loss of hardness for some conditions. However for multi-pass conditions there is a recovery of hardness likely due to a laser hardening effect (figure 6).

Multiple passes include five passes with two different dwell times, 30 seconds and 12 seconds, with the power of 600 W, a beam spot size of 8 mm and a traverse speed of 10 mm/s. This was to further understand the effect of interaction time as well.

The FE model was used to predict the temperature at the top surface the mid-point of the thickness (at 0.6 mm) and at the bottom of the coupon. This was the same position of the micro hardness tests, figure 7.

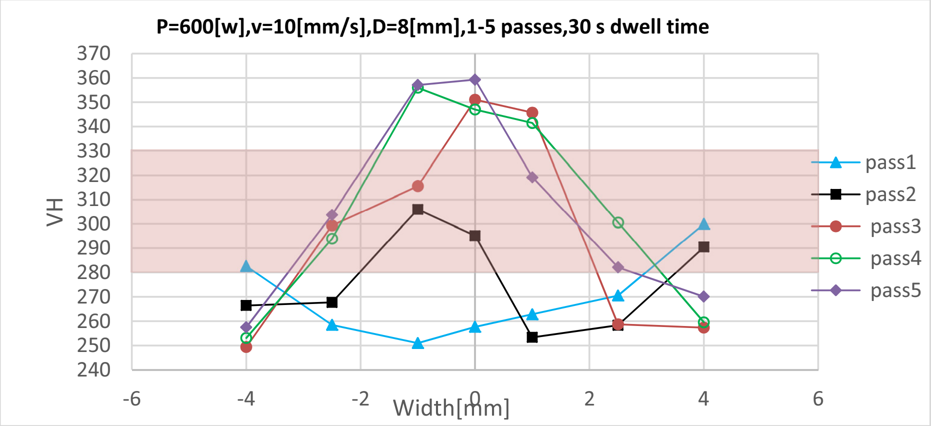


Fig. 6. Vickers micro hardness at seven different points through the middle of thickness 0.6 mm with increasing number of passes with dwell time of 30 s. Parameters used were power of 600 W , travers speed of 10 mm/s and the beam spot size of 8 mm up to 5 number of passes. The highlighted area shows the hardness of DP1000 as received without any heat treatment.

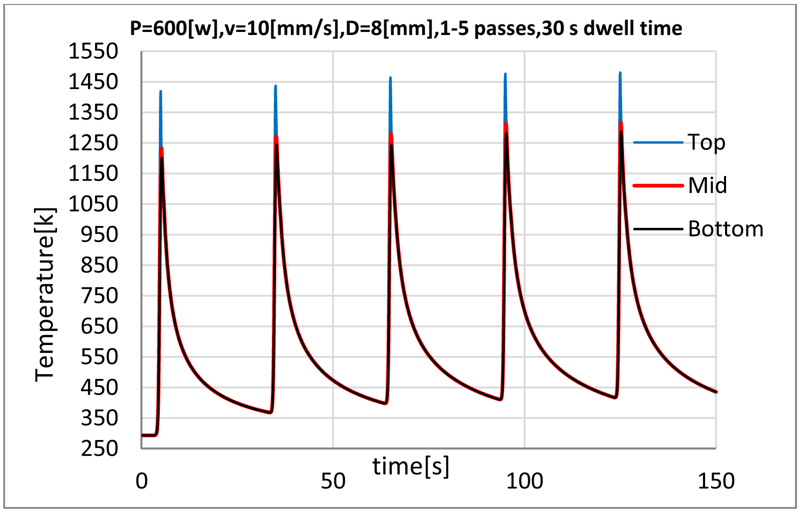


Fig. 7. Temperature for 5 passes obtained by FE model for three different points through the 1.2 mm thickness of DP1000.It can be seen that there is not much difference in temperature between the mid-point and the bottom. Parameters used was power of 600 W , travers speed of 10 mm/s and the beam spot size of 8 mm.

Figure 8 shows the same conditions as in figure 6 but changing the dwell time between passes. As the loss of hardness is linked with temperature, with the shorter dwell time there is a definite loss mechanism without significant recovery. This could be due to a loss of quench rate as the bulk heats up. This can be seen in figure 9.

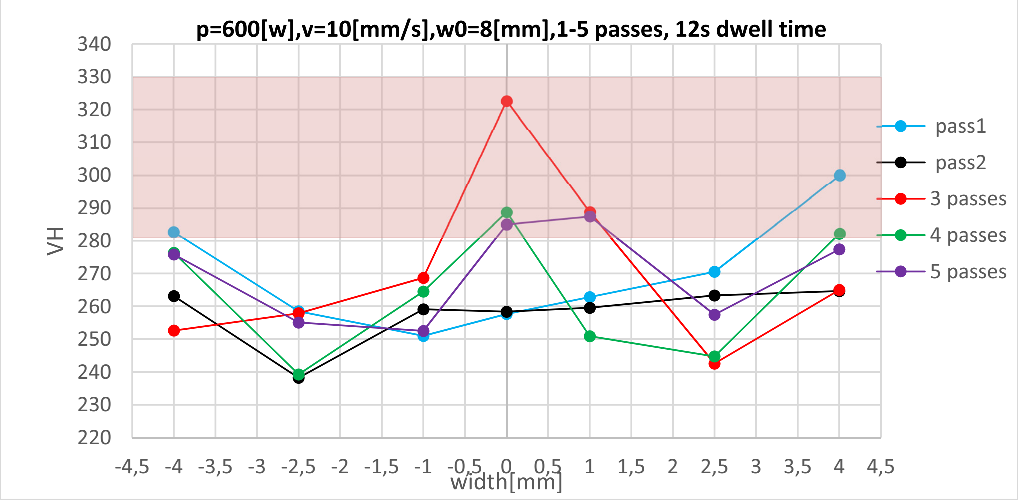


Fig. 8.Vickers micro hardness at seven different points through the middle of thickness 0.6 mm with increasing number of passes with dual time of 12 s. Parameters used waere power of 600 W , travers speed of 10 mm/s and the beam spot size of 8 mm uptp 5 number of passes.

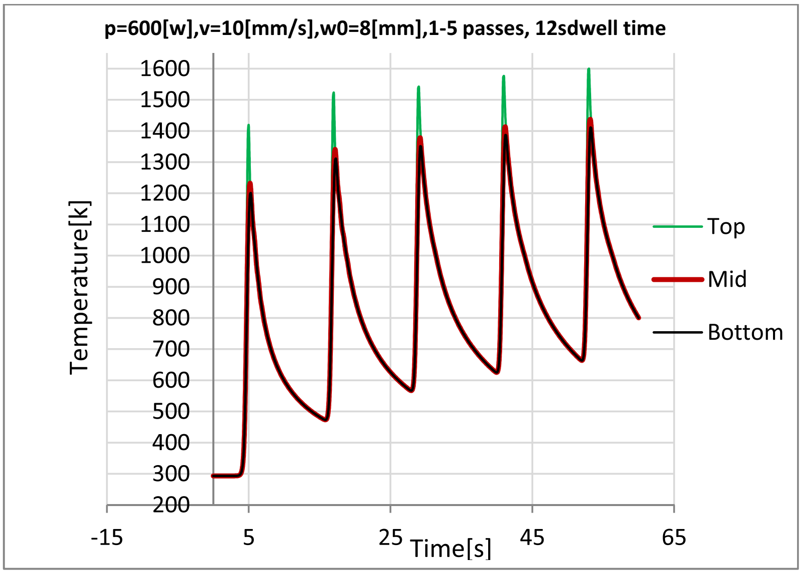


Fig. 9. Temperature in time for 5 passes for three different points through the 1.2 mm thickness of DP100.As the graph shows there is not much difference of temperature between mid-point and bottom. Parameters used was power of 600 W , travers speed of 10 mm/s and the beam spot size of 8 mm.

The figures 10 and 11 indicate the effect of dwell time in the mid-point through thickness (at 0.6mm).

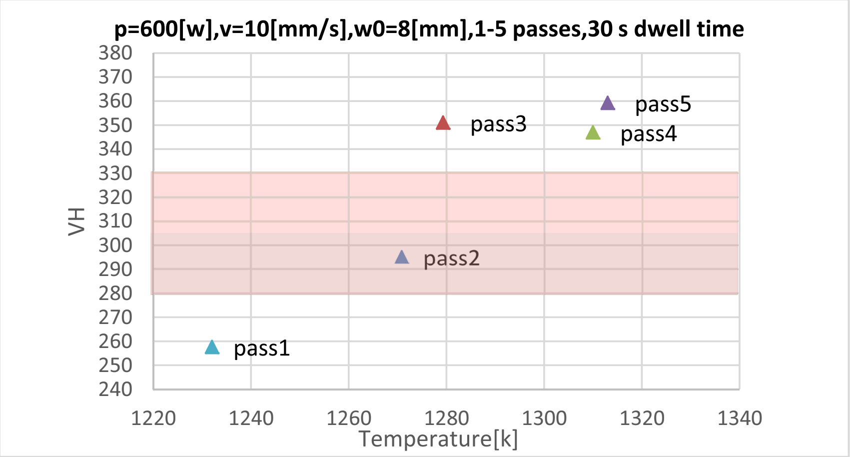


Fig. 10. Variation of VH with temperature for 5 passes with 30 s dwell time for mid-point through thickness. Parameters used were power of 600 W, Travers speed of 10 mm/s and the beam spot size of 8 mm and temperature obtained from FE model. The highlighted area shows the hardness of DP1000 as received without any heat treatment.

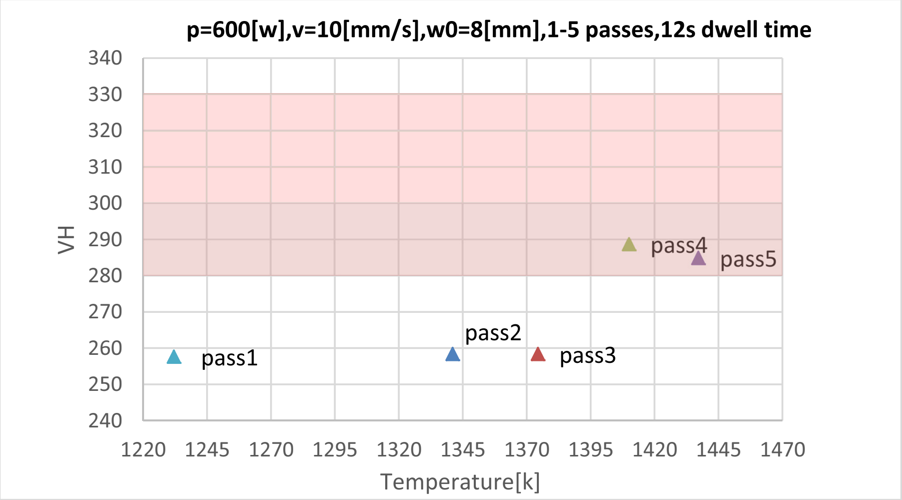


Fig. 11. Variation of VH with temperature for 5 passes with 12 s dwell time for mid-point through thickness. Parameters used were power of 600 W, Travers speed of 10 mm/s and the beam spot size of 8 mm and temperature obtained from FE model. The highlighted area shows the hardness of DP1000 as received without any heat treatment.

As can be seen dwell time has a significant effect on laser hardening and therefore the regeneration of martensite to recover the hardness loss.

From Figures 9 and 10, show that a shorter dwell time produces higher temperatures during multi-pass laser forming but no significant recovery in hardness. As we are observing a single point in the middle of the sample this could mask a more complex interaction and further work is required to confirm this.

4. Conclusion

A FE numerical simulation has been developed to analyses the dynamic thermo-mechanical effects. The main conclusions of this work on laser heat treatment of ultra-high strength steels are: In-process laser heat treatments have the potential to improve the formability of ultra-high strength steels. Laser forming of DP 1000 can cause a reduction in post-forming hardness for certain conditions. The effect is likely due to tempering of martensite. This is not desirable as this could cause a stress concentration feature and a potential failure point for a structural component. A lower speed and higher realised temperatures appears to recover the post-forming hardness loss, this is likely due to a laser hardening effect. As the velocity is low enough to raise temperature sufficiently high enough and the interaction time is sufficiently long enough, followed by a self-quenching a regeneration of the martensite appears to occur. Whilst a re-hardening is not useful for conventional formability, for LF it is a useful post-forming heat treatment effect to mask any unwanted side effects. With the recovery of hardness being the goal of the optimization, a wider process window for the laser forming of AHSS materials within strict metallurgical constraints may therefore be possible.

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