Laser Assisted Conical Spin Forming of Dual Phase Automotive Steel. Experimental demonstration of Work Hardening Reduction and Forming Limit Extension

P. Romero\textsuperscript{a,*}, N. Otero\textsuperscript{a}, J.M. Cabrera\textsuperscript{b}, D. Masagué\textsuperscript{c}

\textsuperscript{a}AIMEN, Laser Apps. Centre, Relva 27A, 36700 Porriño (Pontevedra), Spain
\textsuperscript{b}UPC, Dept. of Mat. Sci. and Met. Eng., Diagonal 647, Barcelona, Spain
\textsuperscript{c}Industrias Piugjaner – DENN, Pintor Vila Cinca 5, Polinyà del Vallès, Barcelona, Spain

Abstract

Laser Assisted Spin Forming is investigated for improving the poor formability of Advanced High Strength Steel DP-800 and Aeronautic Grade Titanium alloy, with minor or no change in microstructure, final properties improvements and no damage to coating, thanks to controlled energy input and fast thermal cycles. IR imaging and force-torque monitoring are used to characterise the forming process. Residual stress measurement, microstructure, microhardness and EBSD are used to study the formed parts under the combined action of laser and mechanical force. A micromechanism of laser assisted spinning is proposed, as well as advantages and limitations of the technique.

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1. Introduction

Advanced High Strengh Metals (AHSS) are a relatively new family of materials arisen from the needs of the Automotive Sector, driven by the ULSAB (Ultra Light Steel Auto-Body) concepts and requisites for weight reduction, safety regulations and improved manufacturing paths. AHSS are a key factor to new vehicle concepts, which display an excellent performance in lightweight structures, due to their outstanding mechanical properties.

Dual Phase steels (DP) are a specific group of AHSS steels with very fine Martensitic-Ferritic microstructure. This material relies in the balance between the deformable and hard phases to provide high toughness/weight ratio, which allow light structures with improved crashworthiness based on a wide elastoplastic field. DP steels are easier to weld and cheaper than other AHSS products, so are widely used in modern vehicle designs, alone or as part of Tailored Welded Blanks.

* Corresponding author. Tel.: +34-986-344-000.
E-mail address: promero@aimen.es.
The main drawback of using these materials is that the extended elastic field brings difficulties in forming: high loads are required and result in tool wearing and shape inaccuracies. Besides, a large amount of elastic energy is stored in the sheet while being formed, and is partially released in shape recovery (spring-back effect) and partially remaining as residual stresses. There is a growing interest on hot or warm forming for dealing with DP steels to overcome those difficulties and extend their usability, but as most AHSS steels, it relays on the balance of metastable phases and fine grain structure, so its physical properties are very sensitive to thermal history.

Laser has demonstrated to be able to help mechanical forming of metals. Laser local modification of microstructure [1] allows controlled formability improvement. Laser heating has been used for warm forming, by stamping or bending right after laser pre-heating [2]. Finally, simultaneous lasing and mechanical processing (bending and hydroforming) has been demonstrated [3]. The present paper is part of a research in which a simultaneous laser-mechanical forming concept is applied in two different progressive spin forming techniques; conical spin forming (power spinning) and cylindrical spin forming (progressive reverse tube drawing). Several advantages are pursued, with the use of the laser, namely:

- Higher shape certainty of finished parts.
- Reduction of forming forces and tool wearing.
- Reduction of final residual stresses.
- Minimal or beneficial effect on the final mechanical properties.
- Extension of the formability limits when processing AHSS steels.

To attain a deep understanding of the laser assisted processing on Dual Phase steels, thermal-mechanical-metallurgical implications had been studied. Tests were run under instrumented and controlled conditions and resulting samples were characterized to identify metallurgical transformations and mechanical behavior. Dynamic recrystallization under high strains is expected to happen in this case.

2. Laser assisted forming techniques

Laser has been used for years in forming of metal plates, taking advantage from the large attainable thermal gradients. Laser Thermal Forming is a non-contact forming technique which can attain very high shape accuracy with no Spring-Back. It is a thermal-gradient driven process; a moving focused beam scanned along a line causes thermal expansion, strong constrained distortion and result in permanent plastic distortion. Laser thermal forming does not fit the high productivity demands of automotive industry. Alternative processes had been proposed in previous works [4], where laser is not the driving force for the forming, but a way to get localized weakening, which is exploited by external mechanical forces to provoke restricted yielding, thus concentrated plastic strain with low energy demands. This combination of mechanical action and laser local heating has been reported with different names, like “hybrid forming process”, “laser augmented forming” or “laser assisted mechanical forming”.

Simultaneous processing is proven to be the most effective way to use laser for assisting mechanical forming when compared to , but also the most technically complex and intrusive in the existent manufacturing facilities. Several laser assisted forming processes can be seen in Figure 1, all of them considered in the Forma-0 Spanish research project.
Fig. 1. Different forming processes combining laser and mechanical action, in growing order of complexity

3. Laser assisted spin forming

Conical Power Spinning (Shear Spin Forming) is a progressive forming technique to produce axisymmetric shapes out from flat sheet, resulting in intense thickness reduction of the formed plate. Some advantages of the technique are low forming forces, high shape accuracy and excellent surface finishing. Anyway, power spinning is a severe coldworking operation with strong effect on the metallurgy and mechanical properties of the work metal. Severe directional anisotropy and work hardening usually results in the need for thermal treatment of the finished part. Actually, the technology failed to fulfill the requirements of certain automotive parts because of excessive work hardening in the final piece which affected to its elongation to fracture. In conical spin forming the action is theoretically pure shearing of the plate, normal to the plane of the original plate, so the projection area keeps a constant value. This leads to a thinning of the plate according to the relation known as “Sine Law” \[ T_f = T_i \sin \alpha \], relating the initial thickness \( T_i \) with the final \( T_f \) by means of the angle of the formed part \( \alpha \). Optimal deformation mode is pure shearing.

Similar results are obtained in cylindrical spin forming. Cylindrical spin forming (tube flow forming) is a tube forming technology in which a tubular preform with a given wall thickness and length, is rolled against a cylindrical mandrel to produce a thinner and longer tube, with either constant or variable wall thickness. This is accomplished by applying large pressure with several rollers radially set around the tube, which traverse the mandrel while this is rotating. For open tubes, reverse spin forming is used, in which the force applied by the rollers pushes the material against a ring at the end of the tube. As the rollers compress and extrude the material against the ring, the material flows under, in opposite direction of the rollers, so the resulting process is a combination of rolling and reverse extrusion. The length of the rolled part is a function of the thickness reduction (constant volume), for constant wall it would be \[ L_f = L_0 \left( \frac{D_t^2 t_0^2 + t_0^2}{D_f^2 t_f^2 + t_f^2} \right) \]. Large thickness reduction mean the possibility of making long seamless tubes from easy to produce machined preforms, which is one of the most interesting applications of cylindrical spin forming. The final tube thickness, \( t_f \), is determined by the roller-to-mandrel spacing, and each roller in the machine (usually 3 to 6) allow to perform large thickness reductions per pass.
This results in very precise dimensional control of the final shape, but also significant cold working.

![Different forming processes combining laser and mechanical action, in growing order of complexity](image)

In some cases, this cold working is a desired feature of the formed part, given its higher ultimate strength and hardness. In automotive applications, however, cylindrical spin forming is usually an intermediate step in the hydroformed tube manufacturing path, that allow to produce weld-free variable tube preform for hydroforming (tailored tubes). Cold working rate reduces the formability of the elongated tube (by reducing the elongation to break of the material), so further deformation by hydroforming easily leads to failure of the component.

Hybrid forming philosophy can be implemented in spin forming process, where laser could provide advantages like extended formability for high strength materials, higher thickness reduction per pass or better further formability of spin-formed parts, particularly the DP steel roll formed tailored tubes for hydroforming. Anyway, close control of the thermomechanical history and understanding of the forming mechanisms is needed, as Dual Phase steel take their properties from very peculiar microstructure and fine grain size, attained by a complex thermomechanical treatment. Excessive heating or too fast cooling can lead to an important drop in strength or toughness. Some laser-assisted techniques display excellent results with aluminum and stainless steel, but can’t be used with advanced steels because of grain grow effects or alteration in the phase distribution of the steel.

The idea underlying the proposed method is to get advantage of the very local and progressive mechanical action of the tooling in Spin Forming, and applying a laser beam on a fixed position relative to the tool. The position of the irradiated area in relation to the strain field induced by the tool is a key factor to get advantage of laser heating.

4. Previous work

4.1. Tests with U-Shaped plates

To study the effect of laser action on pre-stressed steel samples, U-shaped specimens were prepared as follows: rectangular samples were bent with a 30 mm radius up to 180°, then allowed to relax, and Spring-Back angle was measured. Samples were clamped again so they are bent back to 180 °. Laser was scanned on the upper line of the bent sample, on the tension side, and the new angle of the sample was measured after the clamping was removed.

This simple experiment was used to measure a reduction in Spring-Back angle due to plastic collapse in the heated region of the plate. The stress level of the tension side of the sample is very close to the yield stress of the material at room temperature and its released when laser heating. Up to 61% Spring-Back reduction was recorded [5], yet having diverse effects on microstructure depending on scanning speed and laser energy distribution on the sample surface. It was shown that Gaussian energy distribution was far more energy-effective than top-hat, as isotherms could reach deeper in the material for the same average energy density, so same forming results can be achieved with lower metallurgical effect on the steel. This information and thermomechanical FEM models were
used to select beam shaping optics for a 3.3 kW diode laser for better results, which allowed to achieve 35% reductions in Spring-Back at speeds up to 300 mm/s.

This optical path was chosen according to the results of a 2D thermomechanical model which included temperature-dependent surface absorptivity and temperature dependent elasto-plastic mechanical behavior [5].

Rotating plate test:

A simple experimental set-up was designed to test how the high rotation speeds of the spin forming process affect the laser heating. A steel plate is rotated with a variable speed motor and a fibre-coupled diode laser is focused on its surface while scanned in a radius. Scanning speed correspond to the feed speed of the tool, between 0.1 and 0.5 mm/rev. Rotating speed range between 200 rpm and 1200 rpm. This way, the heating ability of laser power is tested against the angular speed and distance to the centre (working point in the conical spin forming, tube diameter in cylindrical forming).

The tests are recorded with IR thermal camera to check the temperature distribution and thermal history, showing that the behavior is quite complex and influenced by all the parameters: feed speed, rotation speed and laser power distribution. At high speeds (over 800 rpm) a ring-shaped virtual spot is formed (figure 4), so the effective power density is inversely proportional to the distance of the spot to the rotation centre. At low rotation speeds, strong local thermal gradient have been detected, and the ring-like heating is less important. In both cases there is a marked dependence of the maximum temperature with the distance to the centre.

The limit of rotation speed for the shift of heating mechanism is also strongly dependent on the plate thickness and thermal properties of the material under study, as well as the spot size and power density. It is mostly independent on the feed speed.

From the rotating plate heating tests, the feasibility of using laser for heating a rotating plate at high revolutions was shown. Small spots are required to provide enough power density (over 2 kW/cm²) to heat up to 400 C. Zinc coating provides smoother temperature distributions and homogeneous ring heating, but requiring higher laser power. This experiment does not account the effect of the tooling on the temperature distribution, but is enough to dimension the kind of laser to be used in the tests.

5. Experimental work

The laser assisted spin forming is intended to be demonstrated at an industrial scale. An actual production spin forming machine (model KENN80 from the Spanish manufacturer Industrias Puigjaner, DENN) is used for the shear forming trials. No major modification is needed in the mechanical set-up or the control of the machine to perform the laser assisted tests, which are made in the workshop where the machine is installed. The tests are intended to
evaluate the technical feasibility of the concept, the problems that would arise in practice and to quantify the effect of laser assistance in the product and the process itself, to quantify the benefits and drawbacks of the technique.

For the cylindrical spin forming tests, a medium range industrial machine model RL-150 CNC by DENN was used. It comprises a conventional cylindrical spin forming machine with three spinning rollers at 120°, with the particular ability of high spindle rotation speed, up to 3000 rpm.

A high power diode laser source (Laserline LDL160 with 3.6 kW maximum power) is used to assist the process. The laser power is delivered to the workpiece by means of a 1500 microns optical fibre and laser beam is shaped with a 76/100 mm collimating + focusing optics (Figure 5).

![Laser setup](image)

Fig. 4. (a) Rotating plate test concept draw and (b) experimental setup. (c) Temperature-time graphic for 600 rpm, 0.4 mm/rev feed rate, and 2 kW laser power on a 6 mm Gaussian spot

There are several parameters influencing the process. Machine-related parameters comprise: rotation speed, feed speed of the forming tool, and roller-mandrel distance during the forming (pressing of the sheet, this parameter is usually known as Offset, in the workshop jargon). Laser-related parameters are power, focal distance, angle and laser spot position. About 40 different parameter combinations were tested, within the ranges shown in Table 1.

| PARAMETER | CONICAL | CYLINDRICAL |
|-----------|---------|-------------|
| Rotation (rpm) | 200 2000 | 300 1000 |
| Feed (mm/rev) | 1 5 | 2 4 |
| Offset (mm) | 0 4 | 1 18 |
| Power (kW) | 0 36 | 0 36 |
| Spot (mm) | 7 15 | 7 15 |
6. Results and Discussion

Conical Spin Forming:

Trials consist of spin forming a conical shape out from a 235 mm diameter disk of 0.9 mm thick zinc coated DP780 Dual Phase steel. Cone angle is 30 degrees, so the theoretical thickness reduction by pure shearing (sine law) is 50%, as shown in figure 2.

Most of the first trials resulted in broken parts, so the rotation speed had to be kept as low as 300 rpm and the feed speed as low as 0.2 mm/rev to get a successful result. This led to cycle times of 50 to 70 seconds per part. This cycle time is too large to be competitive.

Some specific parameter combinations led to broken parts without laser, but could be completely formed with laser assistance at maximum power, with maximum surface temperatures of about 350ºC. This case was analyzed in more depth, to reveal the cause of the failure.

By observing and measuring the deformed part, it can be easily derived that the pure shearing deformation mode that allows large plastic deformation was not kept during the process, as the sine law was violated and theoretical thickness reduction was surpassed in more than 20%. There are evidences of strong strain field gradient in the thickness and the ultimate cause of failure is excessive tensile strain, over the elongation limit of the material (Dual Phase Steels have limited elongation to fracture, and pure tensile deformation components must be avoided). Actually, the pieces that survived the forming process with the help of laser heating also violated the sine law by the same amount, as shown in figure 6. It was derived that laser could help to endure the forming excessive strains only when the spot was large enough to have temperature-induced plastification in the large strain area. This explains the need for low rotation speeds (larger heat diffusion) for having good results, and opened the possibility for process optimization based on proper placing of the laser spot on the workpiece, instead of lowering the rotation speed.
placing the laser focus closer to the maximum strain area, better results were attained. Best results are shown in Table 2. Samples 19 and 20 failed during the tests.

The intended effects of using laser in spin forming are: Reduction of forming forces and total energy usage, reduction of work hardening on the final part, reduction of residual stresses on the final part, improving the shape accuracy on the final part, enable new formable geometries and materials, enable faster and more productive process. All those effects have to come with no negative effect on final microstructure or mechanical properties. The analysis of the formed parts was oriented to study how much those intended effects could be attained with the proposed setup.

Thermal field analysis of high speed trials (figure 8), when compared with the low rotation speed, reveal large heat generation from the forming itself. This results in higher surface and body temperatures that help coupling the laser power to the workpiece, and explain that high temperatures are reached despite the results of the rotating plate heating tests. Thanks to this higher initial temperature, and the body heat generation within the plate, it is easier for the laser to induce a ring-like heating line. This more homogeneous thermal field is responsible for the proper yielding of the material within the high strain area. This effect is revealed by the residual stresses stored in the finished workpiece, measured with XRD. Stress levels are less negative (compressive) at the lased sample (Figure 7c), as evidence of the plastic collapse mechanism absorbing part of the permanent strain induced to the piece.

Fig. 7. (a) Schematic of the strain-temperature field shift that causes the process to be less effective. (b) Parameters of selected samples. (c) Residual stresses in two samples spun at 1500 rpm

Fig. 8. Thermal field and temperature history of: (a) low rotation speed samples (400 rpm) and (b) high rotation speed samples (2000 rpm)

Anyway, there is no beneficial effect of laser assistance to the piece in the total forming energy or forming forces needed in the process, when using the laser at high rotation speeds. With low rotational Speed certain effect on forming forces can be detected. About 15 to 20% less mechanical power is needed to finish the forming. With high rotational speed no advantage is detected in power consumption, but some other advantages are recorded; avoidance of breakage under high tensile components, lower residual stresses, and higher forming speeds. In summary, redesign of the optical-to-mechanical coupling avoided high tensile components, and improved the thermal to strain...
field relation. Even if there is no change in grain size or phase distribution, dynamic recovery appears to happen: no new grains are formed (low recrystallization), nor the grain size is refined or grown, but TEM images of deformed ferritic grains show a cleaner structure in lased samples, with less dislocation density and lower sub-cell formation.

![Fig. 9. Registered tailstock torque during the forming process, for low speed and high speed forming](image)

EBDS investigation on laser assisted shear formed Dual Phase steel, show a considerable occurrence of recrystallized ferrite grains (about 60%) in the laser irradiated and deformed area, in contrast with the cold formed parts, with larger count of substructured and deformed grains. The result of both EBSD and TEM imaging suggest that laser heating is enough to activate a dynamic recrystallization while forming, allowing dislocation mobility and reducing both subgrain formation and grain distortion. This explains the larger formability, better mechanical properties of formed part (better ring-hoop tests on formed cylinders) of laser assisted mechanical forming.

**Cylindrical Spin Forming:**

Trials were run on DP600 and DP780 dual phase steel tubular preforms, with initial thickness of 3.5 and 2 mm respectively. The laser heating is located between the first and second roller, to get advantage of softening the deformed material prior to a further deformation, theoretically reducing the spinning power requirements.

Over 40 different trials were run to test this configuration. Metallographic analysis were performed on the formed samples including microhardness measurement, and several formed and unformed tubes were also mechanically tested to study the influence of laser assisted forming on the final mechanical properties of the tubes.

Metallographic analysis reveals the same elongated ferritic-martensitic structure in lased and non-lased samples. No evident effect of laser on microstructure is displayed (figure 11). Hardness values seem to be linked to the plastic
deformation (thickness reduction), and not to temperature-induced phase transformations; 50% thickness reduction comes with rising of average hardness from 250 to 300 HV, both with laser or without it.

Mechanical properties of formed tubes were evaluated by means of a ring hoop test, performed with an universal tensile machine and specific tooling (figure 12). The sample is gradually expanded until the fracture is localized in the reduced section.

Figure 12 show the averaged tensile test results for ring hoop tests, depending on the forming conditions, for the different material tested, all with the same overall thickness reduction of 50%. In both materials a beneficial effect of laser assistance is displayed in the formed tube mechanical performance, increasing the ultimate strength and elongation, but only when spinning conditions are moderate (low rotation speeds). These results agree with the shear spin forming results for registered forming forces. From the thermal analysis on these samples, it can be derived that at high rotation speeds the temperature is risen by the deformation-driven volumetric heat generation, so laser heating is not easily dissipated and the desired temperature gradient is somehow lost. This helps to explain why the laser assistance is not effective under high spindle turning speeds.

Fig. 11. Microscopic observation of DP780 steel samples deformed under different conditions

Fig. 12. Ring hoop sample and setup. Averaged values for ultimate strength of deformed samples.
When spindle rotation is moderate, anyway, thermal cycling is fast and localized, corresponding to better effect of laser assistance. Also, this effect is more evident on DP780 steel, thanks to a higher amount of metastable phases. Even when Ring-hoop tests are not conclusive enough to evaluate the precise behavior of formed parts under severe plastic deformation, the previous results are valuable, as they support the thermographical observations and the thesis that the autogenous heat generation dilutes the laser effect, so good thermal management would be beneficial for the process performance. Under low spindle speeds, otherwise, the laser processing helps to get restoring effect on microstructure and better mechanical properties, with up to 20% improvement on elongation and ultimate strength in the ring expansion deformation mode.

7. Conclusions

Industrial Feasibility of Laser assisted Spin Forming of Dual Phase Steel was demonstrated in this work. High Speed Scanning of the laser on the workpiece, thanks to the rotation, creates a ring-like power distribution on the surface of the Zinc Coated AHSS Steel. Local plastic collapse mechanism was detected, helping to lower the residual stresses and failure risk at high strain rates. No detrimental effect on coating, microstructure or performance results from the use of laser. The set-up needed for the process is quite complex and difficult to optimise, due to the large amount of variables involved, and the need for accurately place the laser heating spot within the high strain area. Nonetheless, the use of laser results in a robust, industrial and repeatable process. Laser heating has shown compatible with both cylindrical (reverse extrusion) and conical (shear) spin forming of Dual Phase steels, even in galvanised condition. Interactions between thermal and strain fields, and their effect on the forming mechanism, are complex and difficult to analyse, but when laser is placed in the correct place in relation with the forming forces, the beneficial results shown are remarkable. In shear forming, laser assistance on DP steels allow a large extension of the formability and the process window, allowing extreme forming speeds without failure. In cylindrical forming, laser assistance result in improved mechanical properties of the formed parts, which make them more suitable for further hydroforming.

Results are very promising with this general purpose equipment. There is room for improvement by using tailored laser heating system instead.

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References

A. Wesheit, G. Vitr, K. Wissenbach, J. Zajac, H. Thoors: “Local Heat Treatment of Ultra High Strenght Steels to Improve Formability”, in F. Vollersten, T. Seefeld (Ed.), 1th Intl Workshop on Thermal Forming IWOTE 05, Bremen, Germany, 14-16 April 2005, 63-81.
D. Schuocker: “Laser Assisted Forming”, in Philips (Ed): Proc. Of SPIE, Vol. 4065, 2000, 117-127
H. Tönshoff, J. Bunte, O. Meier, L. Engelbrecht: “Deformation Behaviour of Sheet Materials in Laser Assisted Hydroforming Processes”, Advanced Materials Research, Vol 8 (2005) 361-368
M. Geiger, M. Merklein: “Laser Forming Technology, an idea and the way of implementation”, Journal of Materials Processing Technology, Vol. 151, 2004.
P. Romero, G. Rodriguez, J. Arias, J. Vázquez: “Spring-Back Control in Laser Assisted Mechanical Forming of Dual Phase Steels”, Proc. of 25th ICALEO, 2006