Process Planning and Metallurgical Issues for Laser Assisted Spin Forming of Dual Phase Automotive Steel

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Abstract:

Laser assisted spin forming is used to process a galvanized Dual Phase steel with minimum damage to coating, microstructure and material properties. Effective increase in formability was achieved, but no evidence of recrystalization, neither drop in forming force was detected. The paper discusses the possible mechanism of formability improvement through the analysis by EBDS of laser assisted formed samples and their relation with strain hardening behavior and local plasticity, together with the local thermal history of the part under laser radiation.
Keywords: Spin Forming, Laser Assisted Forming, Advanced High Strength Steel, Work Hardening, EBSD

1. MOTIVATION

Advanced High Strength Steels (AHSS), were developed as a solution to the demands and requisites for weight reduction, safety regulations and improved manufacturing paths in automotive industry. Dual Phase steels (DP) are a specific group of AHSS steels with fine Martensitic-Ferritic structure. This material relies in the balance between the deformable and hard phases for high toughness/weight ratio,. DP steels are easier to weld and cheaper than other AHSS products, so they are widely used in modern vehicle designs.
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, shape inaccuracy and large spring back effect due to the stored elastic energy. There is a growing interest on hot or warm forming for dealing with DP steels to overcome those difficulties and extend their usability.

Progressive and incremental forming is an alternative to stamping for this kind of materials. Efficient local forces allow for lower total energy, tool wear and springback for the same workpiece. Its main drawback is productivity, which can be overcome with

state-of-the-art control and movement equipment, to perform high speed progressive forming. Anyway, when tested with AHSS, the increased strain rate results in limited cracks and defects, due to strain hardening.
Alternative processes had been proposed using lasers to assist mechanical forming [Geiger & Merklein, 2004] by provoking localized yielding. Laser local modification of microstructure [Wesheit et al., 2005] allows controlled formability improvement. Laser heating has been used for warm stamping or bending with laser pre-heating [Schuocker, 2000]. Simultaneous lasing and bending has been demonstrated [Tönhoff et al., 2005].
Several advantages are pursued, with the use of the laser, namely: reduction of forming forces and tool wearing, reduction of residual stresses, beneficial effect on the final mechanical properties and extension of the formability limits. To attain a deep understanding of the laser assisted processing on Dual Phase steels, thermal-mechanical-metallurgical implications are studied with instrumented and controlled tests. Resulting samples are characterized to identify metallurgical transformations. Dynamic recrystallization under high strains is expected to occur when combining high speed forming and high power density heating in the same process.

2. RATIONALE

Cone Power Spinning (or Shear Spinning) is a progressive forming method to produce axisymmetric shapes out from flat sheet with intense thickness reduction. Advantages include low forming forces, high accuracy and excellent surface finish. Forming action is theoretically a pure shearing force, normal to the plane of the original plate, so the projection area keeps constant. This leads to thinning according to a relation known as "Sine Law" [$T_f = T_i \cdot \sin \alpha$], relating initial thickness T_i with final T_f by using cone angle α (Figure 1) [Wong et al, 2003].

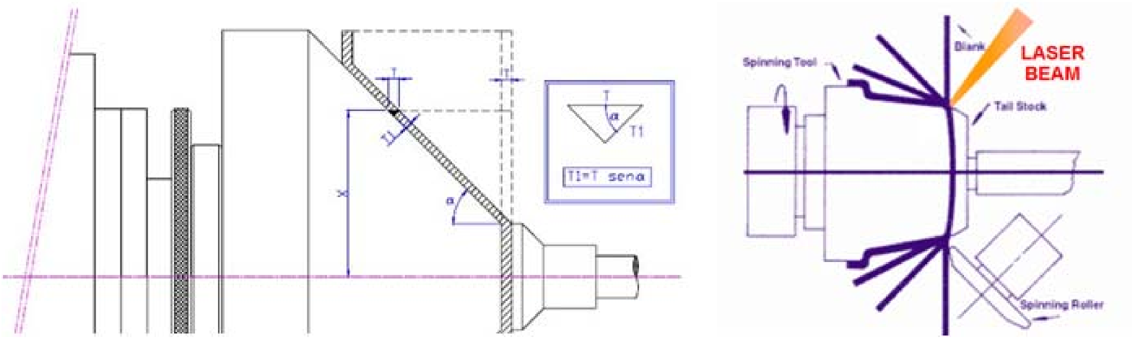


Figure 1: Basic arrangement of conical spinning and concept of laser assistance

This shearing involves severe cold working. Resulting anisotropy and work hardening often demands for thermal treatment of the finished part. Flame and induction heating are used to heat-assist the forming process, and extending the thickness and forming limit of the spun materials, but this technique is difficult to control and incompatible with coated substrates, or dual phase steels.

Laser heating has shown to be compatible with forming of coated DP steels with up to 70% reduction in spring-back in bending or stamping [Romero et al, 2006].
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.

3. EXPERIMENTAL WORK

Laser assisted spin forming experiments were performed in a medium-size industrial spin forming machine (model KENN80 manufactured by DENN). No major modifications were made to the machine or its control. 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 1000 microns optical fibre and laser beam is shaped with a 76/100 mm collimating and focusing optics (Figure 2).

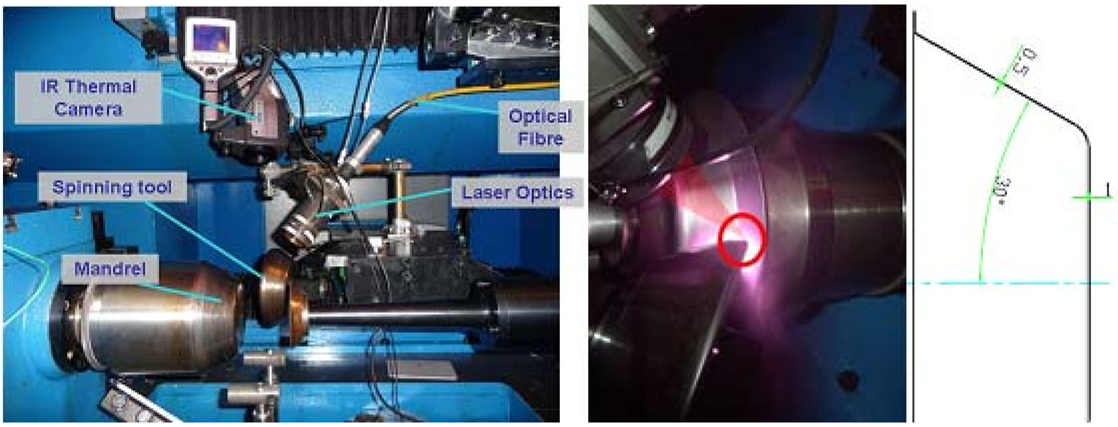


Figure 2: Experimental setup and workpiece design

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 (offset). Laser parameters are power, focal distance, angle and laser spot position. About 40 different parameter combinations were tested (Table 1).

PARAMETER:		Rotation (rpm)	Feed (mm/rev)	Offset (mm)	Power (kW)	Spot (mm)
Range	Max	200	1	0	0	7
	Min	2000	5	4	3.6	15

Table I: Parameter Ranges in the laser assisted spinning tests.

4. RESULTS

1.1. Low feedrate tests

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% (Figure 2).
Most trials resulted in broken parts, 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, 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, (maximum temperatures of 350ºC), shown in Fig 3.

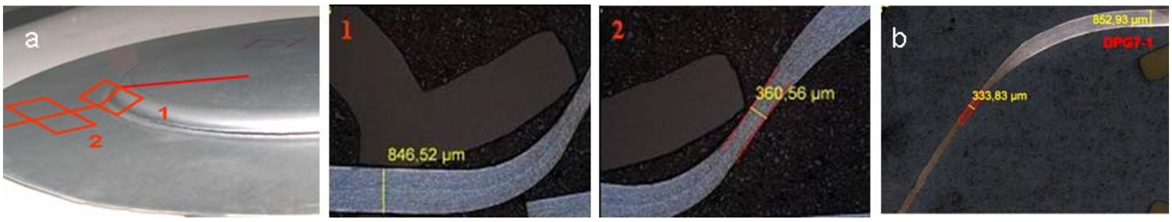


Figure 3: (a) Broken part from a laser test with metallographic details. (b) Successfully formed part with large thickness reduction (70% reduction in thickness).

According to the observations, 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. Laser could help to endure the excessive strains only when the spot was large enough to induce plastific flow in the strained 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. Microstructural observations of the formed parts did not provide any explanation for this improvement in formability.

1.2. High feedrate tests

By placing the laser focus closer to the maximum strain area, better results were attained. Non lased samples failed to be formed at higher speeds, but could be successfully formed with laser at cycle times under 1.5 seconds. The success appears to be related with the right positioning of the laser in relation with the maximum of the strain field induced by the forming tool, being the misfit between both the cause of the previous failures (as shown in Figure 4). 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.

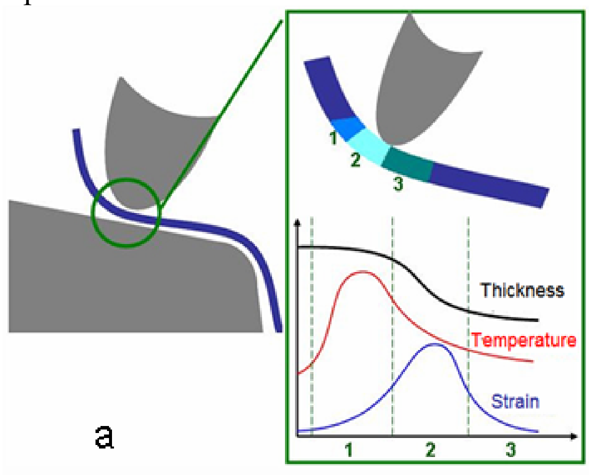


Figure 4: Schematic of the strain-temperature field shift that causes the process to be less effective.

PARAMETER	SAMPLE			
	F18	F19	F20	F21
Rotation (rpm)	2000	2000	2000	2500
Feed (mm/rev)	0.8	0.8	0.8	1
Offset (mm)	0.15	0.15	0.15	0.15
Power (kW)	3.6	0	0	3.6
Spot (mm)	10	-	-	10
Success	✓	✗	✗	✓

Table II: Parameters of selected samples.

Thermal field analysis of high speed trials (Figure 5), 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 6), as evidence of the plastic collapse mechanism absorbing part of the permanent strain induced to the piece.

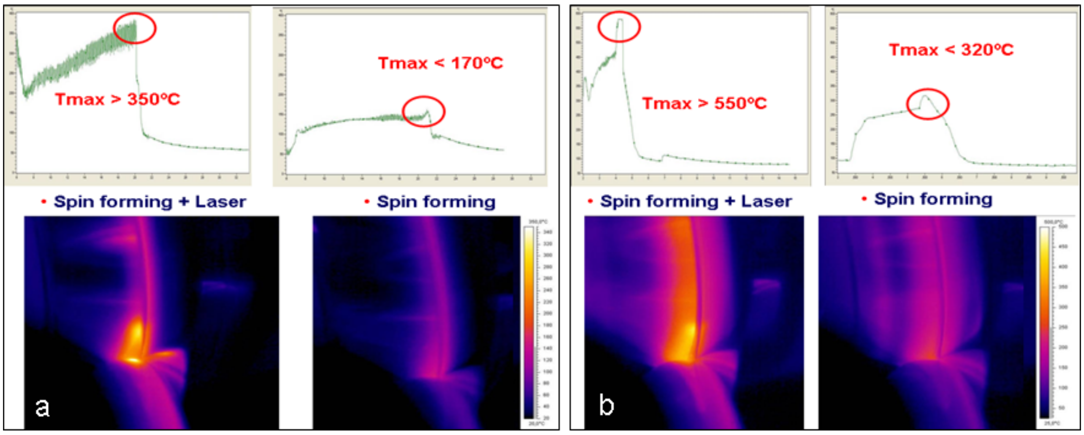
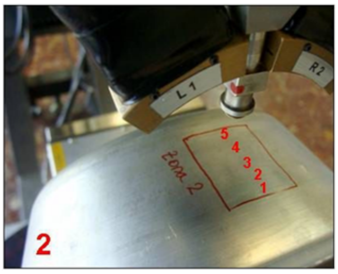


Figure 5: Thermal field and temperature history of: (a) low rotation speed samples (under 400 rpm) and (b) high rotation speed samples (2000 rpm and above)



Residual Stress (MPa)	Non Lased Sample	Lased Sample
# 1	-164'64 ± 8'39	-117'46 ± 10'58
# 2	-177'69 ± 6'79	-100'18 ± 10'26
# 3	-157'22 ± 11'01	-111'01 ± 11'47
Average	-166'52 ± 8'73	-109'55 ± 10'77

Figure 6: XRD measurement of residual stresses on a formed part, and comparative results of surface compressive stresses for lased and non lased samples.

About 15 to 20% less mechanical power is needed to finish the forming at low rotation speeds. Over 1000 rpm no advantage is detected in power consumption, but some other advantages are recorded; avoidance of breakage, lower residual stresses, and higher forming speeds. Even if there is no change in grain size or phase distribution, some kind of internal activation mechanism is expected to help the forming process.

5. EBSD ANALYSIS

Samples were prepared out from workpieces formed under four different conditions (Table III), to compare the effect of the governing parameters of the process on the results at metallurgical scale. Evidences of dynamic recrystalization were intended to be found by means of EBSD analysis. Optical microscopy revealed no change in the phase nature or distribution of the microstructure in neither case, being the only change a slight grain refinement (Figure 7). No difference was detected between lased and non-lased samples. Martensite keeps in the range of 24±6%, independent of the process. Microhardness measurements confirm the previous observations (Figure 8). Work hardening is detected in all formed samples (increase of over 90 HV1), but little or no effect of the laser is seen. There seem to be a slight increase of hardness in the case of lased samples, but its value is within the error range of the measuring technique. It is interesting to note that lased samples were submitted to larger deformation (larger work hardening), so a larger hardness could be expected, but the actual measurements contradict this assumption.

Condition Identification	Machine Parameters			Laser parameters	
	Feed (mm/rev)	Rotation (rpm)	Feed (mm/rev)	Power (W)	Spot (mm)
NL-1	0.8	2000	0.15	0	-
L-1	0.8	2000	0.15	3600	10
NL-2	1	2500	0.15	0	-
L-2	1	2500	0.15	3600	10

Table III:Parameters of selected samples

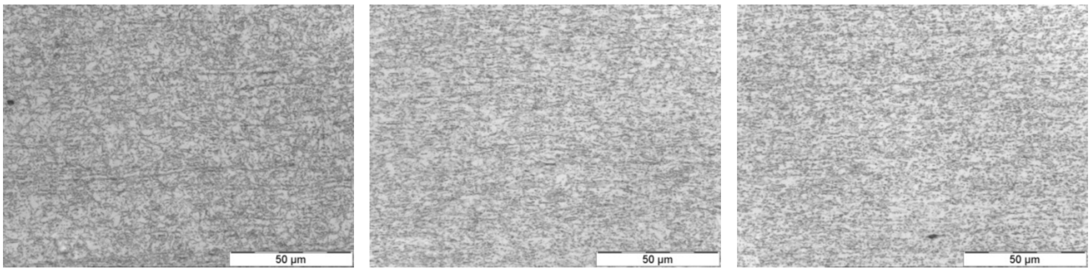


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Figure 7: Metalographic sections, observation plane perpendicular to transverse direction. a) undeformed b) deformed without laser c) deformed with laser

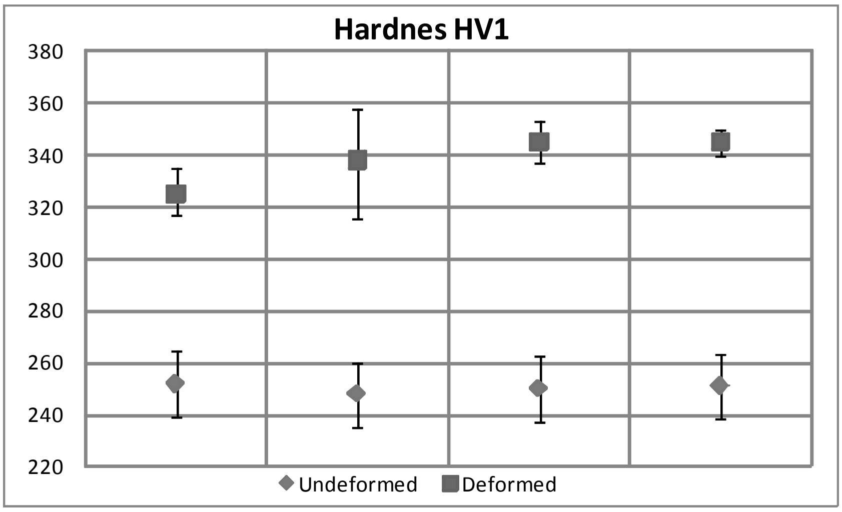
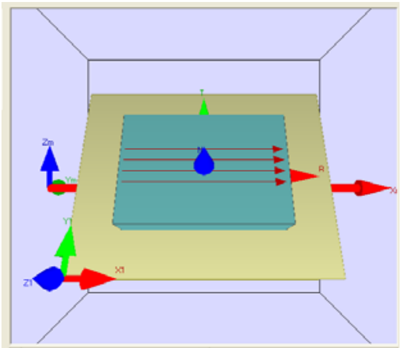


Figure 8: Micro-hardness values for the analyzed specimens

To provide a further insight to the material evolution, all samples were submitted to SEM observation. The parallel arrows in Figure 9 correspond to the deformation flow direction. Band Contrast maps were taken to qualify the suitability of the specimen orientation and response for EBSD analysis. BC maps shown good contrast for each Kikuchi pattern, but there are no remarkable difference between all different samples.



Parameter	Value
WD	12.5mm
Acc. Voltage	20 kV
Magnif.	3000x
Raster	300x250
Step Size	0.1 microns
# Points	75000

Figure 9: Specimen position in the SEM chamber for EBSD, and testing conditions

Figure 10 shows an overlay of Band Contrast Map and the calculated Grain and Phase boundary map. For the discrimination of grain and sub-grain boundaries, a misorientation threshold of 15º was applied. Grain boundary is represented in black (misorientation over 15º) and subgrain boundary in white (misorientation between 2º and 15º) Phase boundaries are marked in grey.
All deformed samples have a rich and well developed sub-grain structure, regardless the use of laser heating. The data was used to perform an analysis of grain and subgrain size in the different conditions.

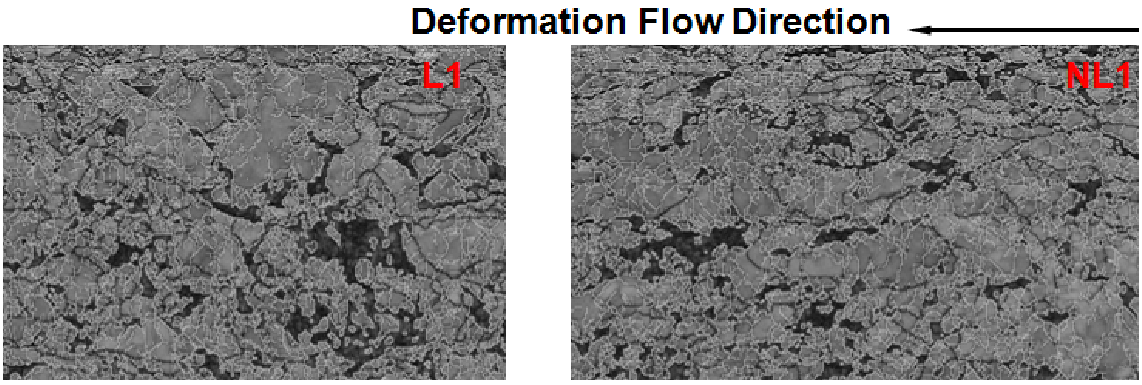


Figure 10: Sub-grain structure in lased (L1) and non lased (NL1) samples (3000X)

There is little or no correlation between process and sub-grain size. Grains are in average a little over one micron in size, and sub-grains average size is about 320 nanometers, while the variation among samples is in the same order of the dispersion in size within every sample (about ±40 nm). It is remarkable that, even when peak temperatures of 600ºC had been recorded for lased samples, the expected growth in the

grain or subgrain size is not verified when comparing L and NL samples. Observations do not suggest any heat induced recrystallization, against the initial hypothesis.
The orientation mapping shows misorientation within each grain for both lased and nonlased samples, see Figure 11. Again, this fact is incompatible with the heat induced recrystalization of the formed microstructure under the action of the laser radiation.

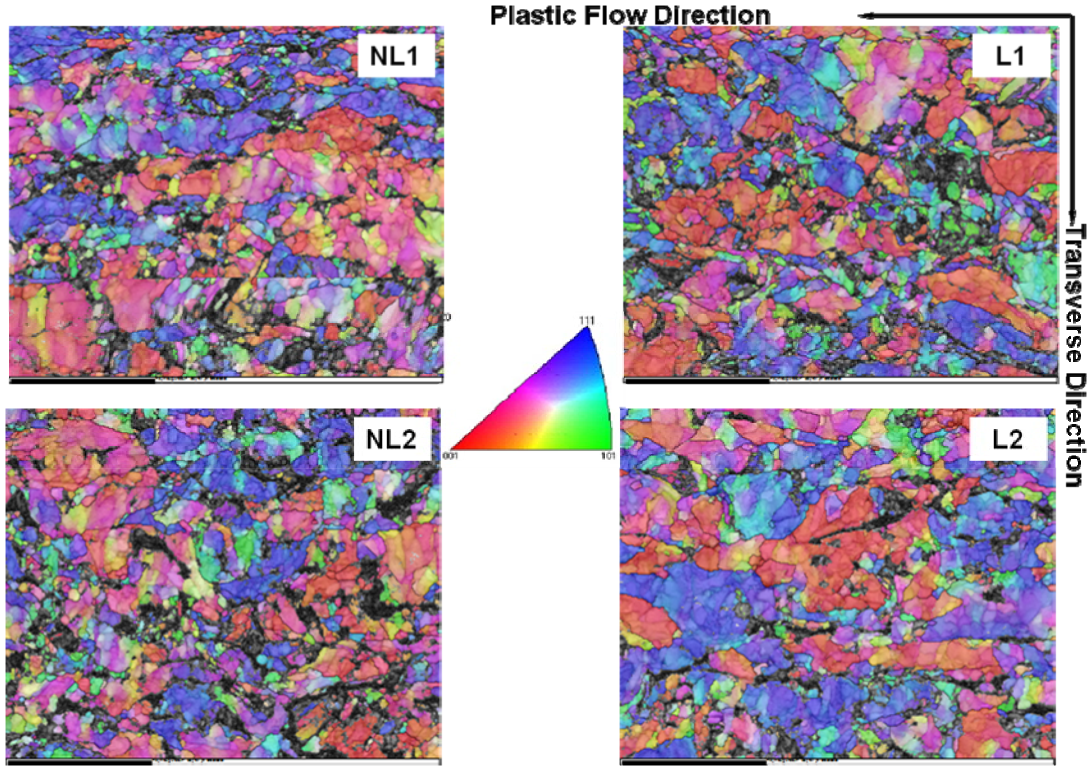


Figure 11: Inverse Pole Figure maps for selected samples (3000X)

A new hypothesis can be proposed, supported by the evidences, that the energy of laser impacts the material at a more intimate level, not affecting the grain growth but working at the level of dislocations mobility, favoring the internal reorientation of the microstructure. The higher dislocation mobility would explain the extended formability even with no change in the final properties. To validate this hypothesis, more insight analysis was performed on the distribution of the misorientation angles within each sample.
Correlated misorientations did not show any difference between samples. Anyway, non-correlated misorientation distribution was graphed together with McKenzie theoretical distribution for a random misorientation. In the case of non lased samples, a deviation is detected from the McKenzie distribution; with larger fraction of misorientation angles in the 10-30º range (Figure 12). When forming with laser assistance in the same conditions the distribution is closer to the theoretical.

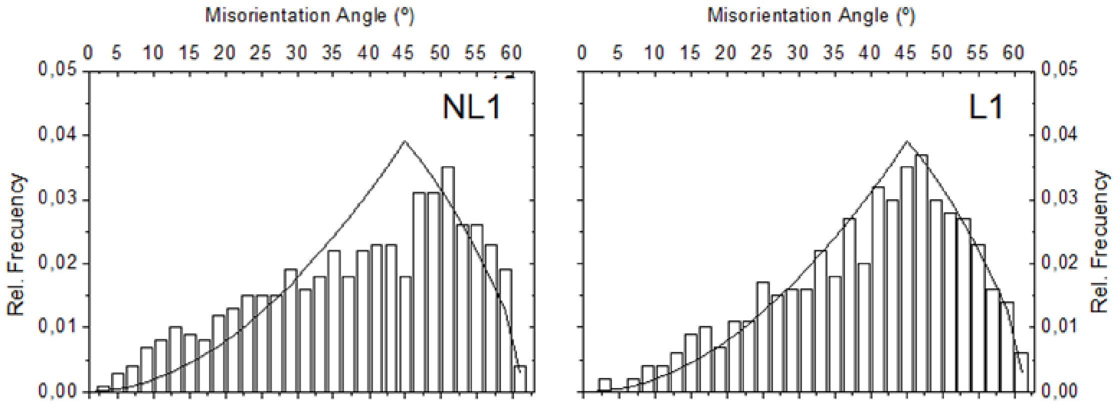


Figure 12: Misorientation distribution in lased (L1) and non lased (NL1) samples

The effect of laser has a clear impact in the Orientation Distribution Function(ODF), which provides a complete description of the texture in each sample beyond the IPF map. Figure 14 shows a 2D representation of the ODF for samples deformed under two different mechanical conditions, with or without laser.

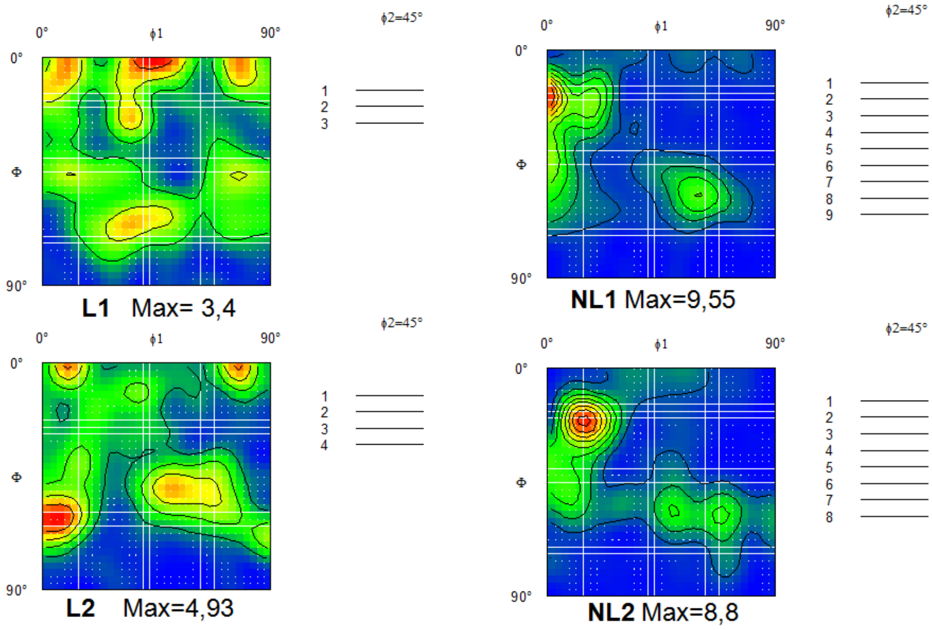


Figure 13: The φ_2 section of the ODFs obtained for the different samples

Samples formed without the assistance of laser radiation show a high frequency on orientations corresponding to the α-fibre {001}, typical behaviour of cold working of BCC, and typically associated with a reduction in the forming limit [Davison, 1974; Lewis & Pickering, 1983]. Laser assisted deformation yield, instead, a more homogeneous orientation distribution with smaller peaks. This is closer to a random distribution as suggested by the misorientation distribution analysis against the McKenzie theory. The trend of the material is to have a large amount of grains with its {111} planes oriented parallel to the sheet plane, texture known as γ-fibre (the ideal relaxed texture of BCC materials), and in the directions of the cube. This is related with the behavior of BCC materials under recrystallization [Lewis & Pickering, 1983] but this process probably could not fully develop, probably due to the very fast heating and cooling rates and very high strain rates.

It can be easily concluded that, while no effective recrystallization was detected in any sample, laser heating has an effect in the texture of the resulting micro-structure. The grain or subgrain size or shape is not affected by the laser, neither is the misorientation within each subgrain. The effect can be detected as a relaxation of the fibrated texture derived from the plastic deformation, and as a result, in a more random orientation of the texture.

What is relevant to the laser assisted process is that laser heating affects the capability of subgrains to relax their orientation energy and produces restored microstructures that suggest a higher dislocation mobility, which has a moderate impact on the mechanical properties of the part, but improves the forming limit while this mobility is active.

6. CONCLUSIONS

Industrial feasibility of Laser assisted Spin Forming of Dual Phase Steel was demonstrated, and the benefits were shown in terms of extended formability and improve in working window and productivity. High Speed Scanning of the laser on the rotating workpiece creates a ring-like power distribution on the surface. 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 optimize, 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. Interactions between thermal and strain fields, and their effect on the forming mechanism, are complex and difficult to analyze, but when laser is placed in the correct place in relation with the forming forces, the beneficial results shown are remarkable, allowing extreme forming speeds (close to 3000 rpm in the current work) without failure, and without any detrimental effect on the mechanical properties of the steel.

The action of the laser left no visible mark in the microstructure, coating or on the mechanical properties of the formed parts, and it was difficult to understand the mechanism which allowed the extension of formability. EBSD analysis showed a larger trend to orientation through the gamma-fibre than through the alpha-fibre, which was the preferred in the cold-formed samples. Even when the alpha-fibre is associated with lower formability, this fact alone does not explain the results, as no recrystallization evidence was found. Anyway, the analysis of uncorrelated misorientation distribution and the lower frequencies of the peaks in the ODF, allows concluding that the

microstructure has better chance to move and reorganize during the laser assisted process, producing a dynamic restoration with no effect in grain size, thanks to high heating, cooling and strain rates.
Results suggest the possibility to apply the same principle to a wider range of processes of high forming speeds. There is room for improvement by using tailored heating systems which simplify the setup and help in the proper positioning.

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