Tailored boron steel sheet component properties by selective laser heat treatment

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Abstract. This investigation is focused on the stamping behaviour of boron steel, the properties of which are modified by selective laser heat treatment. Both CO₂ and fibre lasers are tested. By using different laser processing parameters, the hardening depth in the 1 mm thick boron steel sheet Boloc 02 is varied. Four routes are tested and verified. The forming operation (in which a so-called flexrail beam is produced) in all four routes is conducted at ambient (room) temperature. The Reference route comprises stamping of the sheet. The GridBlank route starts with selective laser heat treatment of the blank, after which the blank is allowed to cool down, moved to a hydraulic press and stamped. In the GridTube route, the blank is first stamped, after which the part is moved to a laser cell and selectively laser heat treated. The fourth route, the RapidLaser route, is similar to the GridBlank route, but a higher laser speed is used to promote higher total productivity. The GridBlank route results in the highest hardness values and the best shape accuracy. The initial sheet material exhibits a hardness of 200 HV, while the parts produced in the GridBlank route exhibit a hardness of 700 HV.

1. Introduction
The automotive industry has constantly sought new technology solutions to meet increasingly stringent emission norms, provide greater passenger safety & incessantly drive down the cost per vehicle produced. In Sweden, too, there is a consensus that the transportation sector must continue to deliver value to society & industry, with minimal environmental impact & fewer traffic injuries/fatalities, while remaining globally competitive. To achieve the above, the industry must enhance productivity, augment part performance & durability, accommodate greater volume flexibility with existing production systems as well as continue vehicle light-weighting efforts by inducting high-strength steels & light alloys (of Al, Mg & Ti). This demands use of new, cost-effective, adaptable & flexible process technologies capable of handling new materials & higher customer adaption/product individualization.

The present investigation is driven by the established ability of a laser to selectively heat treat materials to locally modify properties. When applied to sheet materials, the above approach can provide a rapid & cost effective pathway to locally tailor properties in a pre-determined manner to either aid forming operations during component manufacture or enhance overall performance of formed sheet metal parts by imparting superior properties in select locations as demanded by the operating
environment. Due to the immense flexibility of present day lasers, this approach will be of significant interest to adopt in production and will generate, in turn, higher customer adaption/product individualization both in supplier-OEM relationship & OEM-market segments’ differentiation. Compared to for instance hot stamping, the present approach requires much smaller investments, is much less process and type bound, and is more flexible both in in-house production and in cases where supplier integration should be considered.

1.1. The technical concept
High power lasers find widespread use in the automotive industry for many manufacturing operations spanning cutting, welding & surface modification. However, their application for sheet metal parts has been restricted largely to cutting & welding (e.g., tailor welded blanks) & their utility in sheet metal part fabrication steps such as forming or in augmenting performance of sheet components remains largely unexplored. Selective heat treatment with a laser involves heating the sheet material according to a predetermined specific pattern, in the form of discrete localized areas of certain shape/size, continuous “lines” of a particular width, pattern of such “lines” to generate a grid pattern or other desired contours. The heat treatment may also be followed by cooling. An appropriate heat treatment protocol, & an optimum treatment pattern, promises to yield local sheet metal formability improvements &/or realize local strengthening/reinforcement in sheet material.

As an example, consider a sheet of boron steel. During selective heat treatment, the boron steel can be converted into austenite by heat treatment, after which cooling can be employed to promote conversion of austenite into martensite selectively in treated regions, for the martensite to act as the reinforcing structure & impart strength to the sheet material component either before or after forming. Similarly, selective heat treatment can also be utilized to improve formability during stamping, although the window of properties required to be realized in the sheet metal can be entirely different in this case. Illustrative examples of grid patterns or portions of grid patterns that can be investigated to assist forming or to tailor the component properties are depicted in Figure 1.

![Figure 1. Illustrative examples of some selective heating grid patterns.](image)

It may be appreciated that the specific heat treatment pattern to be followed, including its exact shape & precise location, needs to be designed (based on reverse engineering or detailed simulations) & later realized based on identified requirements. One such potential selective heat treatment grid is illustrated in Figure 2. Here, the forming may be executed immediately after selective heat treatment, such that parts of the sheet material, in particular the martensite grid pattern, are already at a temperature higher than the ambient. On the other hand, the objective might be to improve the component properties/performance by reinforcement, the selective heat treatment being conducted either before or after sheet material shaping.

1.2. Objective
Given the above, the overall objective is to investigate selective laser heat treatment of sheet metals from a new knowledge generation perspective by comprehensively determining processing-structure-property relationships, ascertaining influence of selective treatment on subsequent forming operation, testing/optimizing part behaviour for different applications/requirements & eventually demonstrating proof of tailored sheet metal formability concept on a couple of actual components. The present paper
is focused on the stamping behaviour of boron steel sheet selectively laser heat-treated in accordance to four (4) different routes.

1.3. State of the art
Various laser-based operations have been considered for sheet metal processing, including shock processing, shearing, bending, forming etc. & also widely employed in the manufacture of tailor welded blanks [1-5]. Incidentally, the term “tailored blanks” initially referred to joining of sheets of similar or dissimilar materials &/or with identical or different thickness. More recently, “tailor heat treated blanks” involving material properties adjusted by local heat treatment, have also been pursued [6]. The use of high strength steels or various light alloys for body-in-white applications has been limited by their inherent low formability [7]. Selective heat treatment can potentially improve the forming behaviour of these materials by modifying sheet material properties at specific locations in a predetermined manner to facilitate high drawing depth, sharp edges etc. A laser provides a promising pathway for the above, although deciding an appropriate heat treatment layout to accomplish the above can be challenging [8]. Vollertsen & Hofmann used a CO₂-Laser to demonstrate enhancement of formability in several 6000 series aluminium alloys [9]. Later, Geiger et al. used a lower wavelength Nd:YAG laser to allow for more efficient coupling, thereby eliminating need for a graphite layer [10]. There have been subsequent studies devoted to investigating the efficacy of local laser heat treatment on sheet metal forming [11]. These have dealt with Aluminium alloys [12-14], Magnesium alloys [15] as well as ultra-high strength steels widely used in the automotive industry [16]. However, notwithstanding its acknowledged potential, comprehensive investigations on the subject remain scarce. Particularly in Sweden, research efforts in this direction are yet to be initiated despite the fact that the technology, once developed, has the capability to be relevant to various other industries beyond the automotive.

1.4. Pilot study
A pilot study was conducted to demonstrate that sheet material properties can be modified in a controlled manner by manipulating the laser processing parameters. These have involved the following:

- CO₂ & fiber laser processing
- Fixed laser spot size (ϕ6.24 mm for CO₂ & ϕ5.50 mm for fiber)
- Different laser powers & scan speeds
- Heat treatment of 1.0 mm thick boron steel Boloc 02 sheet material

Figure 3 reveals cross-sectional micrographs of a 1 mm thick Boloc 02 steel sheet CO₂ laser treated under two different conditions (laser power = 650 W, scan speed = 500 mm/min and case depth = 0.6 mm in Figure 3 (a) and laser power = 2300 W, scan speed = 5000 mm/min and case depth = 0.17 mm in Figure 3 (b)) & the results are both educative & relevant. At the outset, they reveal that it is possible to manipulate & optimize the laser heat treatment process to achieve the desired impact (in this case, an enhanced hardness of 470 HV compared to initial sheet hardness of 220 HV). Furthermore, they also demonstrate that the desired surface hardness can be obtained under varied operating conditions & with controllable case depths, thereby suggesting that the process can be optimized to achieve faster processing speeds, offering an opportunity to generate varied properties.
Figure 3. Typical cross-sectional micrographs of a 1.0 mm thick boron steel Boloc 02 laser heat treated with a CO$_2$ laser at (a) power = 650 W & (b) power = 2300 W.

Figure 4. Typical cross-sectional micrographs of a 1.0 mm thick boron steel Boloc 02 laser heat treated with a fiber laser at 670 W and with a scan speed of (a) 1320 mm/min & (b) 1500 mm/min.

Figure 5. Vertical (90°) bending tests of selectively laser heat treated blanks (Figure 3).

Results of similar trials were conducted using a fiber laser, with the Boloc 02 sheet material graphitized for better coupling, are depicted in Figure 4.

Vertical (90°) bending tests were conducted on the selectively laser heat treated blanks of 1 mm thick boron sheet steel Boloc 02 shown in Figure 3. Bending was conducted so that the inner bend radius was located on both the burned side and the unburned side of the sheet. Inner bending radius was 4.5 mm in all cases and all tests were successful (no cracks or other defects were detected), Figure 5.

2. Materials
In this investigation, 1.0 mm thick boron steel sheet Boloc 02 was used. Table 1 displays the chemical composition of this material. The mechanical properties of 1 mm thick Boloc 02 are shown in Table 2,
Table 1. Chemical composition of Boloc 02.

| Material | C (%) min-max | Si (%) min-max | Mn (%) min-max | P (%) max | S (%) max | Cr (%) min-max | B (%) min-max |
|----------|---------------|----------------|----------------|----------|-----------|---------------|-------------|
| Boloc 02 | 0.20-0.25     | 0.20-0.35      | 1.00-1.30      | 0.030    | 0.010     | 0.140-0.260   | 0.0015-0.0050 |

in which $R_e$ is the yield strength, $R_m$ the ultimate tensile strength and $A_{80}$ is the fracture elongation in tensile testing.

Table 2. Mechanical properties of 1 mm thick Boloc 02.

| Material | Thickness (mm) | $R_e$ (MPa) | $R_m$ (MPa) | $A_{80}$ (%) |
|----------|----------------|-------------|-------------|--------------|
| Boloc 02 | 1.0            | ca 340      | ca 480      | 28           |

3. Experimental procedure
To prove the concept, the flexrail shown in Figure 6 was selected as the demonstration component. The stamping tool set used to form this flexrail is displayed in Figure 7.

Figure 6. The flexrail produced in accordance to the four production routes (shown in Figure 8) in this investigation,

Figure 7. The stamping tool set used to form the flexrails.
These four (4) production routes were followed in this investigation.

Four (4) different production routes were used to make the flexrail mentioned above. These four production routes are depicted in Figure 8. The blank size and shape used in all four routes are displayed in Figure 9.

The four production routes exhibited in Figure 8 comprise:
- **Reference** route: In this route, 1 mm thick blanks of Boloc 02 (Figure 9) were produced in City 1, transported to City 2 and stamped at ambient (room) temperature in the tool set displayed in Figure 7 in City 2.
- **GridBlank** and **RapidLaser** routes: In these routes, 1 mm thick blanks of Boloc 02 (Figure 9) were produced in City 1, selectively laser heat treated in City 1 in such a fashion that the heat treatment grid pattern constituted the network depicted in Figure 10, allowed to cool down (still air cooling) in City 1, transported to City 2 where they were stamped at ambient (room) temperature in the tool set displayed in Figure 7. In the **GridBlank** route, the laser processing parameters in Figure 4(a) were used. For **RapidLaser** blanks, the laser processing parameters in Figure 4(b) were applied.
- **GridTube** route: In this route, 1 mm thick blanks of Boloc 02 (Figure 9) were produced in City 1, transported to City 2, where they were stamped at ambient (room) temperature in the tool set displayed in Figure 7 in City 2. After stamping, the stamped flexrails were moved to a fibre laser cell in City 2, where they were selectively laser heat treated in such a fashion that the grid pattern constituted a network with a quadratic side length of 20 mm (such as that shown in Figure 10).
To selectively laser heat treat the flexrails stamped in the *GridTube* route (Figure 8), the laser robot path must be generated based on the scanned shape of the *GridTube* flexrail (Figure 11). Since another laser cell (located in City 2) was used and the selective laser heat treatment must be conducted on stamped flexrails, the laser processing parameters needed to be found and optimized. After 12 test run, the following parameters yielding a hardness of 550 HV were selected: spot size \& shape = $\phi5$ mm, laser speed = 25 mm/s, temperature = 1500-1530 °C, the flexrail was graphitized before selective laser heat treatment, no cooling used at any time (except still air). Figure 12 depicts the cross-sectional micrograph of this twelfth (12th) test run.

**Figure 10.** The selective laser heat treatment pattern used in the production routes *GridBlank* and *RapidLaser*.

**Figure 11.** The scanned shape of the *GridTube* flexrail was used to generate the laser robot path.

**Figure 12.** The cross-sectional micrograph of the sheet laser heat treated in accordance to the parameters set after 12 test runs.
To produce comparable flexrails, the process parameters during stamping needed to be kept constant regardless of the production route. From a formability perspective, the GridBlank option (Figure 8) is the toughest case. The GridBlank blanks are selectively hardened in such a fashion that the hardening case is almost as large (0.95 mm) as the sheet thickness (1.00 mm) and the laser heat treatment pattern constitutes a network, Figures 4(a) and 10. Therefore, the stamping try-outs started with the GridBlank option lubricated with 1.5 g/m² Aral Ropa 4332. Stamping with a binder pressure of 100 bar resulted in a crack. Reducing the binder pressure in combination with trimming a portion of the initial blank and finally shimming corresponding to the sheet thickness (1 mm) resulted in an approved flexrail, Figure 13.

These process parameters, i.e. trimmed initial blank, a binder pressure of 90 bar, shimming corresponding to 1 mm, and using 1.5 g/m² Aral Ropa 4332 as lubricant, were used in all stamping operations regardless of the selected production route (Figure 8). In other words, all flexrails in this study were stamped with these parameters regardless of the production route.

**Figure 13.** Stamping try-outs with the GridBlank option to find the stamping process parameters that should be and were kept constant regardless of the production route.

### 4. Results

The flexrails, the side members or beams, manufactured in accordance to the production routes described in Figure 8, *Reference, GridBlank, GridTube and RapidLaser*, are shown in Figure 14. Note in this figure that the GridTube flexrail is displayed during selective laser heat treatment.

The blanks made for the GridBlank and RapidLaser routes, Figure 8, were selectively laser heat treated and allowed to cool down in City 1, and transported to City 2, where they were stamped at ambient (room) temperature in the tool set displayed in Figure 7. These blanks, particularly the select-
Figure 14. The flexrails manufactured in accordance to the production routes described in Figure 8: Reference, GridBlank, GridTube and RapidLaser. Note that the GridTube flexrail is displayed during selective laser heat treatment.

Iively heat treated blanks in the GridBlank route, were not flat/not plane before stamping. This type of blank positioned on the die prior to stamping is displayed in Figure 15. The blank is however stretched out during the stamping and the stamped flexrail is not “buckled”. See the GridBlank flexrail, top right photograph in Figure 14.

The punch force was registered, as the blanks were stamped (or the flexrails were formed). Figure 16 displays the maximum punch force (during stamping) for the different production routes (Figure 8). As shown in Figure 16, 20% and 41% higher maximum punch forces were required for the RapidLaser and GridBlank routes respectively compared to the reference route.

Figure 15. The selectively laser heat treated blank positioned on the die prior to stamping a flexrail according to the GridBlank route in Figure 8.
The flexrails produced in accordance with the production routes shown in Figure 8 were scanned. These flexrails were then compared in three sections, A-A, B-B and C-C, with respect to shape accuracy, Figure 17. The scanned shapes of the produced flexrails are displayed at the above-mentioned 3 sections in Figure 18. As shown in Figure 18, the GridBlank route displays the smallest springback (or the best shape accuracy) in all three studied sections.

The surface hardness was measured (on the flexrails produced in accordance to the four tested routes in Figure 8) in the longitudinal and transverse directions and positions indicated in Figure 19. The results of these hardness measurements are depicted in Figure 20. As shown in this figure, the flexrail produced in accordance to the:

- **Reference** route displays an even hardness of 200 HV in both the longitudinal and transverse directions.
- **GridBlank** route exhibits the highest hardness, approximately 700 HV, in the laser heat treated tracks and in both longitudinal and transverse directions.
GridTube route shows a hardness of approximately 500-530 HV in the left hand track & somewhat lower hardness in the right hand track in both the longitudinal and transverse directions. RapidLaser route displays a hardness of approximately 275-280 HV in the left hand track and somewhat higher hardness in the right hand track in both the longitudinal and transverse directions.

5. Discussion
The present paper is an account of the results obtained so far in an ongoing investigation. The following domains are scheduled for further studies.
Flexrails produced in accordance to the four production routes displayed in Figure 8 will be subject to further tests, such as 3- and 4-point flexure tests and crash tests.
The pattern generated by selective laser heat treatment will be predicted and optimized by simulations.
Based on the intended component behaviour in use, the laser heat treatment pattern, including its exact shape & precise location, will be designed by reverse engineering and simulations and tested in practice.
Several business cases comprising different large production volume scenarios will be generated and evaluated.
The results of the above-mentioned studies will be accounted for, as soon as they are conducted/completed.

Figure 18. Flexrail shape accuracy/springback in three sections (see also Figure 17) for the four tested production routes (Figure 8).
Figure 19. The surface hardness was measured in the indicated longitudinal and transverse positions.

Figure 20. The results of the surface hardness measurements (Figure 19) on the flexrails produced according to the four tested routes (Figure 8).
However, the results accounted for in this paper indicate that the GridBlank and RapidLaser routes can be considered as the most efficient and flexible routes for large volume production. They are the most efficient and flexible routes for large volume production, since the selective laser heat treatment can be conducted at the material supplier or at a supplier between the material supplier and the stamping plant or at the stamping plant. The existing press/stamping lines can be used as usual. “No difference” needs to be taken into consideration, since the sheet material in combination with the selective heat treatment pattern and “normal” stamping generate the intended components with the required properties.

6. Conclusions
The chief conclusions drawn from this investigation are as follows:

It is possible to tailor boron steel sheet component properties by selective laser heat treatment. This selected laser heat treatment can be conducted on the blanks prior to stamping at ambient (room) temperature or on the component after stamping at ambient (room) temperature. The selective laser heat treatment accomplishes conversion into austenite and still air cooling results in the conversion of austenite into martensite.

The GridBlank production route, in which 1 mm thick blanks of Boloc 02 (Figure 9) was selectively laser heat treated, allowed to cool down (still air cooling), transported to the stamping plant where it was stamped at ambient (room) temperature, yields the best component (flexrail) shape accuracy and the best hardness (700 HV) but required 41% higher maximum press force than the none laser heat treated Boloc 02.

The selective laser heat treatment of the sheet material (the blank) before stamping yields the most efficient and flexible route for large volume production.

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