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APPLICATION OF LASER BARCODE TECHNOLOGY TO SHEET METAL PARTS IDENTIFICATION

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Purpose: In the development of ideas for Industry 4.0, information about the element production cycle has become more and more important. Knowledge of the subsequent forming processes, determination of the machine on which the process has been carried out and of the type and wear of the tool, leads to smart production management, which plays an increasingly important role in the metal forming industry. To meet the current expectations for these challenges, an advanced technology needs to be introduced for monitoring the manufacturing processes by deploying flexible solutions. This technology must include, but not be limited to, identifying and tracking the product using laser marking.

Design/methodology/approach: Laser marking allows a permanent mark in the form of a barcode to be applied to the sheet metal surface. Commonly used marking methods and the condition of the sheet metal surface can affect the marking contrast. This paper presents a concept for recording individual stages of sheet metal forming and determination of the impact of the laser marking technology on the contrast of the applied barcode. To ensure accurate control of the deformation stages, the bulging process of the spherical dome has been used as an example.

Findings: Analysis of the influence of laser marking method on the barcode recognition accuracy can contribute to the development of smart management of the production process according to the idea of Industry 4.0.

Research limitations/implications: A large plastic deformation has been applied to the sheet metal surface and no limitation in a barcode reading process (using vision scanning technology) was indicated. Also, the geometry deformation (different angle view of the CCD camera) of the barcode image has introduced no additional problems with a barcode reading.

Originality/value: The optimal parameters of a laser marking technique for barcode marking, which are critical for the material that is subjected to metal forming operations that deform it, have been studied. The results shows that traceability is an attractive solution for tracking technological data in the production chain for a single-shaped product.

Keywords: manufacturing control, laser marking, vision analysis, sheet metal forming, barcode quality.

Category of the paper: Technical paper.

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1. Introduction

Numerous manufacturing support systems, including Smart Technology or Flexible Manufacturing, enable the production of different products on the same line, minimizing the unavoidable delays caused for example by tool changes (Peters et al., 2014). The rapid adaptation of the production chain to new purposes can be supported using robotic stations and computer systems to supervise the production. The great interest in improving the production means that software solutions for monitoring the manufacturing process are sought to meet the growing need for flexible solutions. The complexity and diversity of these software solutions to be adapted in production conditions has been noted for a long time. Moreover, the adaptation of algorithms to frequent changes required a systematic approach (Chaar et al., 1993). The important role of production process monitoring methods, which cover a very wide range of tasks, is invariably emphasized (Ho et al., 2003). Such methods make it possible to collect information aimed at determining the current state of a production system, verifying the correct implementation of ongoing operations, and controlling a series of related operations in real time. In practice, detecting and correcting undesirable events that may occur while planned technological operations are underway is the key to achieving more efficient work and better product quality. To this end, a set of methodologies (Lechmann, Kuhn, 2020) can be used to support the development of real-time monitoring techniques. These methodologies directly improve manufacturing processes on production lines. This paper proposes further improvement of manufacturing processes by introducing the optimized barcode marking technique for process monitoring. This solution includes elements of the technology information management strategy that leads to higher quality in obtained products, in accordance with the assumptions of Industry 4.0 (Chozdić, 2015).

In the development of the idea of Industry 4.0, which aims at smart management of the production process, information about the production cycle becomes very important. Knowledge of the technological aspects of manufactured products – such as parameters of all operations, material supplier, type and material properties, type and wear of the tool and determination of the machine on which the process was carried out – plays an increasingly important role, and it also affects the final cost and quality of the product. Identification codes can be affixed to products or printed onto them. There are various methods for collecting such information, the most widespread of which is the use of barcodes, which are currently a primary method of identifying and tracking a product simultaneously (Chowdhury et al., 2019). The popularity of barcodes led to the development of one-dimensional reading technology based on lines of different thickness (barcodes). Later, two-dimensional codes (2D codes) represented by rectangular type objects called matrix codes (QR) were also utilized. The one-dimensional barcode reading method consists in detecting and identifying the sequence of lines. The biggest advantage of barcodes is their low price, as well as widespread knowledge and dissemination of them (Shejwal et al., 2016). While the barcodes can also be affixed to products or printed onto them, they can also be applied on various surfaces using laser marking.

Generally, two principal groups of devices related to the direct part marking technology can be utilized: monochrome and colour laser engravers. The potential application of these engravers is closely related to the capabilities of their implementation, in which the repeatability of results, process stability in the industrial environment, and productivity are the major factors. However, the basic limitation in using the colour laser marking (CLM) method in this area (despite numerous advantages) is low productivity, which may be critical for large production volume. Recently Odintsova (Odintsova et al., 2019), proposed a new approach to increase CLM productivity by up to 40 times, thanks to the use of high pulse rate frequency (up to 1 MHz) fibre laser. Despite this, monochrome technology (YVO4 lasers) continues to be a laser market leader in industrial applications due to the much better performance parameters, with pulse repetition rates of up to hundreds of GHz.

The demand for traceability is growing in the manufacturing industry. For example Fraser (Fraser et al., 2016) showed that laser marking seems to be the optimal technology in the forging industry to satisfy hot, dirty and rough conditions as well as large deformations and subsequent surface or heat treatment of aluminium in the temperature range between 25 and 400°C. Generally, laser marking has been carried out on various metals, such as stainless steel, nickel and aluminium alloys, and on titanium coatings. Li (Li et al., 2016) investigated the effects of laser processing variables on the quality of the laser-marked barcodes on the surfaces of aluminium alloys using a diode pumped Nd:YAG laser and found that barcodes with higher surface roughness could be more easily identified. Velotti (Velotti et al., 2016) characterized the laser marking process on aluminium sheet with Cold Spray Deposition Ti coating for aerospace applications. Investigating the influence of the laser marking process parameters on the groove geometry of the marking, the researchers showed that laser marking was governed mainly by the heat input and that the penetration depth was higher than that obtained on solid material. Astarita (Astarita et al., 2016) also studied the maximum penetration depth and width of the marks as well as internal damages induced by the laser marking tests of cold sprayed titanium coatings. To report and discuss the results of the width and depth peaks measurements, both a surface 3D reconstruction and a cross-section presentation of the laser marks were carried out. Leone (Leone et al., 2018) performed laser marking tests on AISI 304 steel, using a diode-pumped Nd:YAG laser to determine the correlation occurring between working parameters and resulting mark visibility. In particular, changing the working parameters such as variation of the pulse frequency significantly altered the appearance of the upper surface of the groove, as demonstrated by the results on the cross-section of the laser marks. Bassoli (Bassoli, 2018) established the relationship between the process variables used in laser marking of Inconel alloy 718 and both the geometrical and the optical characteristics of the mark, and similarly presented all these geometrical features (e. g. width and height of the peaks, depth of the groove and distance between the peaks) on the outline of the sample cross-section. However, another technique has also been reported for engraved surface measurement. Sobotova and Badida (Sobotova, Badida, 2017) evaluated the roughness of aluminium samples to show how different laser variables affect the surface texture and colour change while creating minimal waste as compared with other marking methods.

Laser marking, unlike sticky labels or ink printing, introduces not only geometric but also structural changes in the top layer of the sheet metal. Guk (Guk et al., 2016) reported that the inhomogeneity of the microstructure had no significant effect on mechanical properties, while the induced geometric inhomogeneity markedly influenced material formability. This was determined using the Erichsen cupping test for cold-rolled and zinc-coated dual-phase steel sheets with a thickness of 1 mm. Guk (Guk et al., 2017) showed that these conclusions also concerned multiphase steel sheets with high strength. Fraser (Fraser et al., 2016) claimed that laser marking is usually the only possible technology for permanent marking of die castings to ensure traceability of the component from casting to final assembly and even in the life cycle phase. Li (Li et al., 2016) found that one of the most important factors affecting the effectiveness of the barcode identification is the contrast between the marker and the surface of the sheet. Therefore, since a high contrast laser marking is critical, Penide (Penide et al., 2014) proposed to carry out a colorimetric analysis to compare the resulting marks and their contrast on alumina plates. It was concluded that the atmosphere was the key variable in producing the darkest marks.

As shown above, there are various problems related to the quality and identification of barcodes on various surfaces. Assessing the impact of the marking method on the later possibilities of effective detection of the applied markings on a given surface is very important and especially crucial with regard to industrial requirements and environments. In accordance with such demands, this paper presents some concept of recording individual stages of the sheet metal forming process and determination of the impact of laser marking technology on the contrast of the applied markings. By introducing an appropriate barcode marking technique for process monitoring, manufacturing on production lines can be improved. Hence, this solution also includes some elements of the technology information management strategy intended to increase the quality of obtained products, according to assumptions of Industry 4.0 as presented by Hozdić (Hozdić, 2015).

2. Material identification and traceability

The discussion on launching monitoring systems to collect manufacturing data has been initiated in recent years and has also influenced the creation of numerous marking techniques. One such solution is a system to apply marks using a laser. In particular, the automotive industry has found a wide application for this solution, currently used to designate numerous components, which include mechanical parts (crankshafts, engines and gearboxes, bearings, bolts), equipment parts (plastic buttons, control panels, mirrors), electronic parts (printed circuit boards, electronic circuits), and plastics (wipers). At one time, Świłło (Świłło et al., 2016) suggested a modified method of identifying metal forming tools based on an existing solution of applying laser tags. It is now therefore proposed in this paper to extend the application of permanent marks to car body parts. Moreover, it is proposed to apply patterns before the forming of these parts, but not after any deformation processes. This, however, can lead to great identification difficulties because of the negative impact of sheet metal deformation and curvature of the marked steel sheet surface. In the next part of the paper, the authors will deal with the explanation of these problems.

The growing expectation regarding the final product quality and their tracking within production areas have led to a new concept of material traceability (Krivács et al., 2010). This type of function includes linking the product with the supplier and all the technological parameters within the production process for a single product. The aim of the authors was therefore to propose a general concept of system traceability for a manufactured product using the barcode method and laser technology. Applying recognition marks at the outset of the product manufacturing process considerably extends traditional solutions and provides a wide range of data storage options, creating, among other things, the possibility of combining the quality with the manufacturing history of the product. The proposed concept of recording individual stages of sheet metal forming process is shown on the simplified example (one sequence only) of a car trunk floor-stamping (Figure 1). In this concept, a sheet with a barcode is identified before the production cycle begins (Stage 1). Collected data on the production line (Stage 2) will be assigned to the obtained product after scanning the barcode at the end of the line (Stage 3). This concept could be easily applied to manufacturing processes with a greater number of sequences.

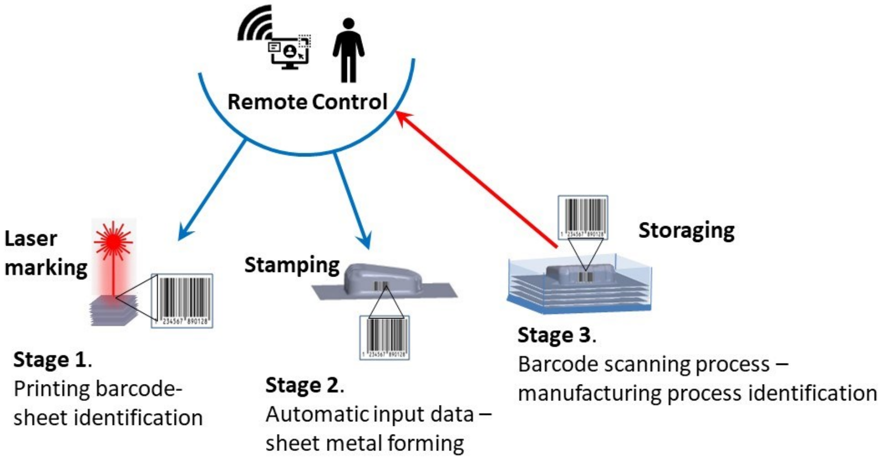

Figure 1. The proposed concept of using laser barcode technology for car body sheets identification and tracking.

Source: own elaboration.

3. Laser processing parameters

The proposed laser marking method is based on a unique solution, taking into account the mutual influence of the three light effects on an object: reflection, aberration, and transmission. The key to applying patterns to an object correctly is to achieve high absorption, which is a function of the temperature increase. Otherwise, the reflection and transmission will be increased, detracting from the beam power needed to make the mark. For this purpose, a special type of hybrid laser Keyence MD-X1500C was used to apply the barcodes, whose operating characteristics differ from the classic solutions. The high power of laser light (peak power) was compensated by short pulse duration, which allowed the intensity (temperature) of the laser beam to be controlled. The solution gives the possibility of choosing the device's operating variables (power, time, speed, beam focus) for any material, which are determined by the calibration pattern.

In this research two parts of the study are foreseen: applying the calibration patterns (reference fields) and applying the appropriate patterns in the form of barcodes on the surface of the deep-drawing DC04 steel sheet (0.017% C, 0.096% Mn, 0.006% P, 0.032% S) with a thickness of 1 mm. Next, it is planned to examine the influence of sheet metal deformation on the quality of patterns (their readability) and the potential decrease in the material formability.

The marking process variables influence the obtained surface geometry structure and the contrast of markers applied to the sheet surface. The contrast between the marked and native surfaces of the sheet metal is crucial for correct detection and recognition of the barcode. It is important, therefore, to examine the impact of laser marking technology on the contrast of created barcodes, which directly affects their correct identification. As part of the research, reference patterns in the form of square fields with selected parameters were applied on flat steel sheet by the laser technology (Figure 2a).

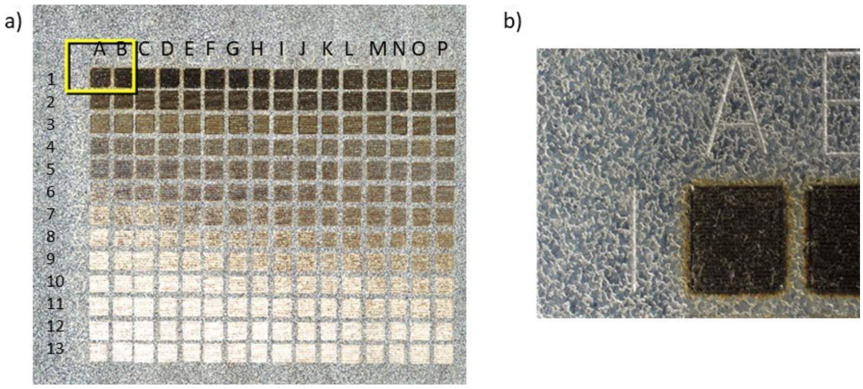

Figure 2. The reference patterns made with selected laser marking parameters (a), and the example of laser burnt field (b), shown by green circle in the reference pattern.

Source: own elaboration.

The reference patterns were used to determine the effect of the laser frequency *f* and the beam speed *v* on the sheet surface contrast. The beam focus s was set to the maximum value. Table 1 shows laser marking parameters corresponding to the reference fields presented in Figure 2a. There are two values, *f/v*, in the table cells: the frequency *f* and the speed *v*. The black lines of the common barcode should have the darkest tonal value. This tonal value can be quantified by recording these images using vision system. Then, the tonal value – also called the shade or brightness of the pixel of the image – is recorded. To achieve the highest contrast in relation to the sheet surface, the difference in tonal values between the background and the black lines of the code should be as large as possible. At the beginning, a preliminary qualitative assessment of the reference patterns was carried out. Visual assessment showed that the darkest fields were plotted at low speeds *v* and high laser frequencies *f*. At the same time, it was noted that laser burns appeared at the lowest laser beam speed, *v* = 100 mm/s, as shown at the left-hand side boundary of the reference pattern area. The sample pattern with a burn (Figure 2b) is marked with a green circle in Figure 2a; i.e., for *v* = 100 mm/s and *f* =140 kHz. Visible burns can cause problems when detecting and identifying barcodes.

Table 1.

Parameters of reference patterns for the set shown in Figure 2a

		beam speed v [mm/s]															
		A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
laser frequency f [kHz]	1	80/100	84/100	88/100	92/100	96/100	100/100	104/100	108/100	112/100	116/100	120/100	124/100	128/100	132/100	136/100	140/100
	2	80/200	84/200	88/200	92/200	96/200	100/200	104/200	108/200	112/200	116/200	120/200	124/200	128/200	132/200	136/200	140/200
	3	80/300	84/300	88/300	92/300	96/300	100/300	104/300	108/300	112/300	116/300	120/300	124/300	128/300	132/300	136/300	140/300
	4	80/400	84/400	88/400	92/400	96/400	100/400	104/400	108/400	112/400	116/400	120/400	124/400	128/400	132/400	136/400	140/400
	5	80/500	84/500	88/500	92/500	96/500	100/500	104/500	108/500	112/500	116/500	120/500	124/500	128/500	132/500	136/500	140/500
	6	80/600	84/600	88/600	92/600	96/600	100/600	104/600	108/600	112/600	116/600	120/600	124/600	128/600	132/600	136/600	140/600
	7	80/700	84/700	88/700	92/700	96/700	100/700	104/700	108/700	112/700	116/700	120/700	124/700	128/700	132/700	136/700	140/700
	8	80/800	84/800	88/800	92/800	96/800	100/800	104/800	108/800	112/800	116/800	120/800	124/800	128/800	132/800	136/800	140/800
	9	80/900	84/900	88/900	92/900	96/900	100/900	104/900	108/900	112/900	116/900	120/900	124/900	128/900	132/900	136/900	140/900
	10	80/1000	84/1000	88/1000	92/1000	96/1000	100/1000	104/1000	108/1000	112/1000	116/1000	120/1000	124/1000	128/1000	132/1000	136/1000	140/1000
	11	80/1100	84/1100	88/1100	92/1100	96/1100	100/1100	104/1100	108/1100	112/1100	116/1100	120/1100	124/1100	128/1100	132/1100	136/1100	140/1100
	12	80/1200	84/1200	88/1200	92/1200	96/1200	100/1200	104/1200	108/1200	112/1200	116/1200	120/1200	124/1200	128/1200	132/1200	136/1200	140/1200
	13	80/1300	84/1300	88/1300	92/1300	96/1300	100/1300	104/1300	108/1300	112/1300	116/1300	120/1300	124/1300	128/1300	132/1300	136/1300	140/1300

Source: own elaboration.

4. 3D microscopy measurement of the calibration pattern

In the next stage of experimental investigation, the authors intended to verify the concept of laser overheating, which results in a low surface quality. Therefore, a topography measurement for selected reference patterns with an extreme range of parameters using advanced scanning technology has been proposed. In this experimental investigation, a recently developed confocal microscope VK-X Series (Figure 3a) was utilized, equipped with two type of light sources: laser light and white light. To satisfy all the measurement requirements, both options – a 3D high-speed laser light together with high-accuracy scanning – were chosen to measure selected surfaces areas with references patterns before deformation.

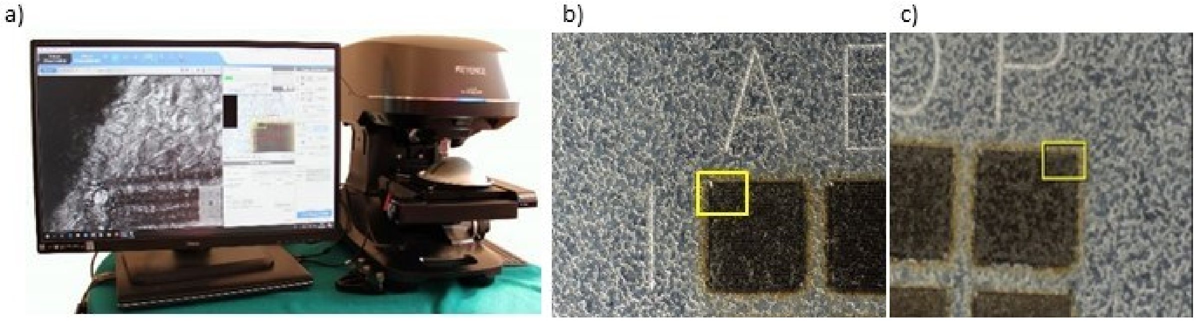

Figure 3. Topography measurement using advanced scanning technology: 3D laser confocal microscope. Type: VK-X Series (a), selected and zoomed reference patterns subject to measurement (b, c).

Source: own elaboration.

The results show that both the measured topography and the surface quality are varied. The largest elevation (height) for both selected reference patterns (Figure 3b, 3c) however, is approximately 50 µm (Figure 4). This can be accepted as a limit at which surface quality decreases as a result of increasing the burn depth. The deterioration of the surface quality understood in terms of light reflected from the barcode scanning device may be due to changes in the properties of the surface layer under the influence of high temperature. The presented methodological approach and the detailed results for the topography measurement have been used for a precise determination of an optimal burn size.

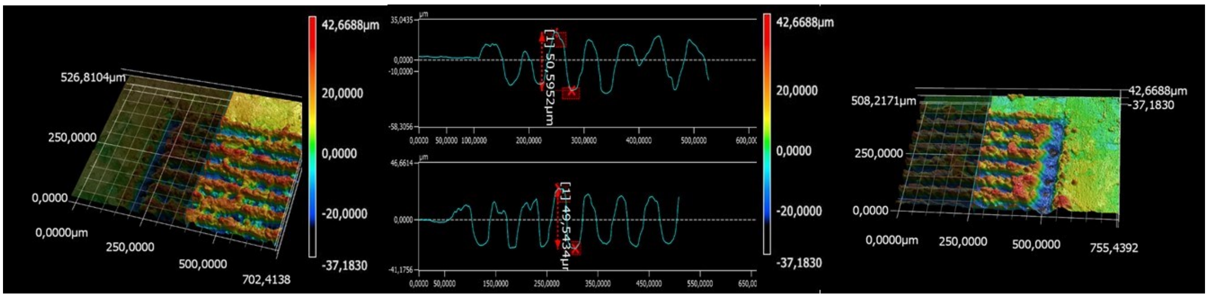

Figure 4. Surface topography and height for selected and zoomed area as shown on Figure 3(a, b).

Source: own elaboration.

5. Measurement of the contrast for the calibration pattern

One of the most important factors affecting the effectiveness of laser mark identification is the contrast. Contrast is the difference in tonal value (brightness of pixels) between neighbouring objects, e.g., barcode lines. The higher the contrast value, the easier it is to detect and read the barcode. To check the impact of laser marking variables on the tonal value, the images obtained from the experimental vision system set-up were used (Figure 3a).

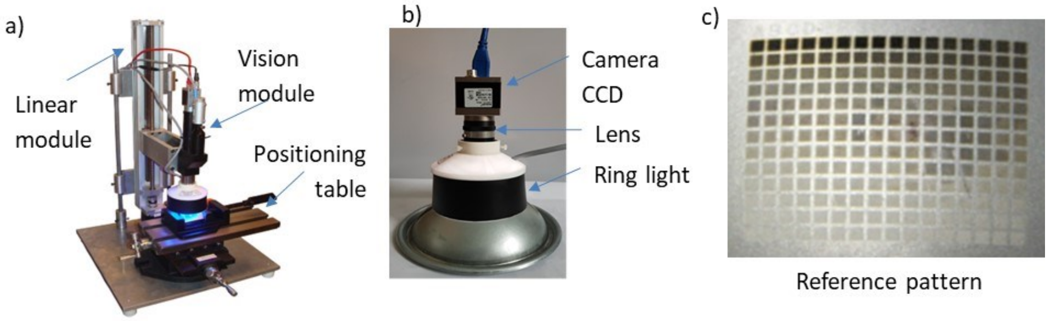

Figure 3. Experimental set-up (a), vision unit (b), measured area of the reference pattern (c).

Source: own elaboration.

The vision system consists of a CCD camera with a resolution of 4096 x 3000 px, lens with 25 mm focal length, 5 mm extension ring, and a specially prepared ring lamp. The extension ring reduces the minimum working distance of the lens, thus enabling marker registration at close range. Specimens shown in Figure 3a and Figure 4b were obtained by hydraulic bulging of flat circular blanks (Figure 4a). A detailed description of the bulging process was presented by (Świłło, 2013). More recently, however, (Kocańda, Jasiński, 2016) extended the evaluation of the similar Erichsen cupping test by laser speckle imaging. The resulting dome shape can cause an uneven distribution of light on the specimen surface without a specialized arrangement of lighting. The ring light ensures an even distribution of illumination in the recorded area of the specimen shown in Figure 3b and Figure 4b.

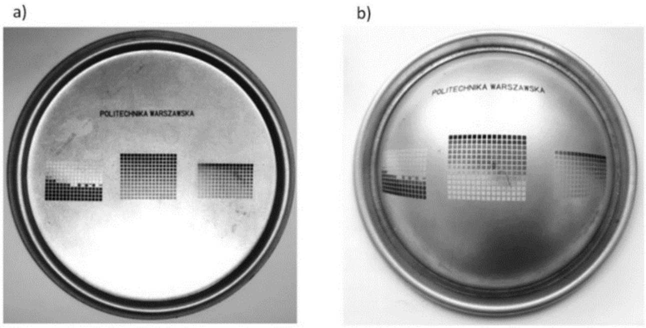

Figure 4. Sheet metal samples with the applied reference patterns before (a), and after the hydraulic bulging (deformation) process (b).

Source: own elaboration.

Before the bulging process, three sets of patterns were applied to the flat surface of the circular blank of sheet metal. All tests were performed at the same exposure time and light intensity. Additionally, it was decided to verify the effect of sheet metal deformation on the obtained results. For this purpose, the measurement of the mean tonal value on the specimen surface was performed by experimental set-up before (Figure 4a) and after the hydraulic bulging process (Figure 4b). Among the three reference patterns shown in Figure 4a, only the middle one (subjected to the highest deformation) was chosen for further research, which corresponds to the parameters shown in Table 1.

Figure 5 shows the effect of the laser frequency *f* and the beam speed *v* on the pixel brightness before (Figure 5a) and after (Figure 5b) bulging process. The main purpose of the tonal value measurement was to indicate the marking variables that will ensure the darkest and lightest areas possible on the surface of the sheet and the highest barcode contrast. The graphs obtained show that decreasing the speed *v* considerably reduces the brightness of marks in the recorded image. On the other hand, increasing the frequency *f* of the laser beam also reduces brightness of marks but to a much smaller extent. To sum up, the correct marking technology for 1 mm thick DC04 sheets that ensure the darkest marks without burns were obtained for $v = 300$ mm/s and the highest frequency f=140 kHz. To obtain the brightest surface, the highest speed and the lowest laser frequency indicated in Table 1 were used. The original average tonal value of the sheet surface was 129. Applying black lines on a bright background increases the contrast tonal values to 135. The maximum contrast that is possible to obtain in a camera with a dynamic range of 8 bit is 255, but this contrast could be obtained only theoretically due to problems related to noise on the camera matrix or to changes in lighting. In any case, obtaining more than half of the maximum contrast is a very good result, which ensures the correct reading of the barcode.

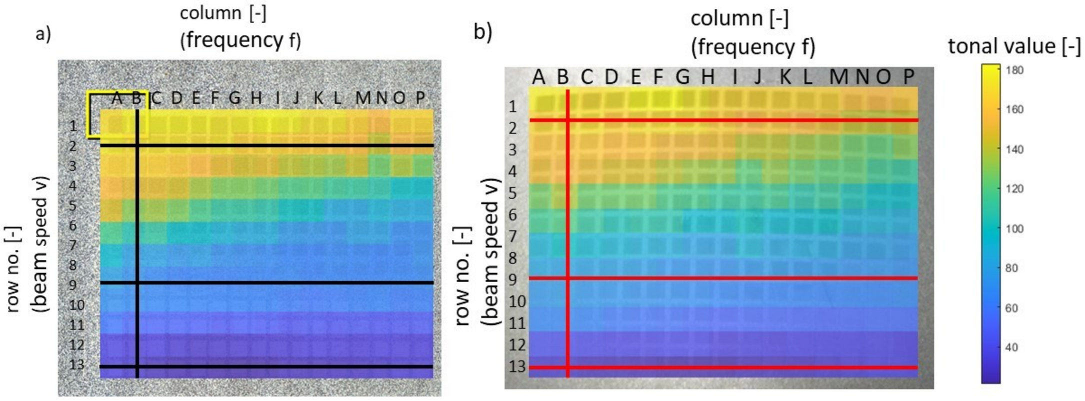

Figure 5. Effect of laser frequency *f* and beam speed *v* (as related to rows and columns in Table 1, on the pixel brightness before (a), and after the bulging process (b).

Source: own elaboration.

Figure 6 shows the markers' tonal values before and after the process for column "B" (Figure 6a) and row 2,9 and 13 (Figure 6b) with the approximation. The study showed that the level of brightness of the surface of the analysed reference pattern did not change noticeably after the deformation of the sheet. The differences were within tonal values of around 5%, which corresponded to the measurement error.

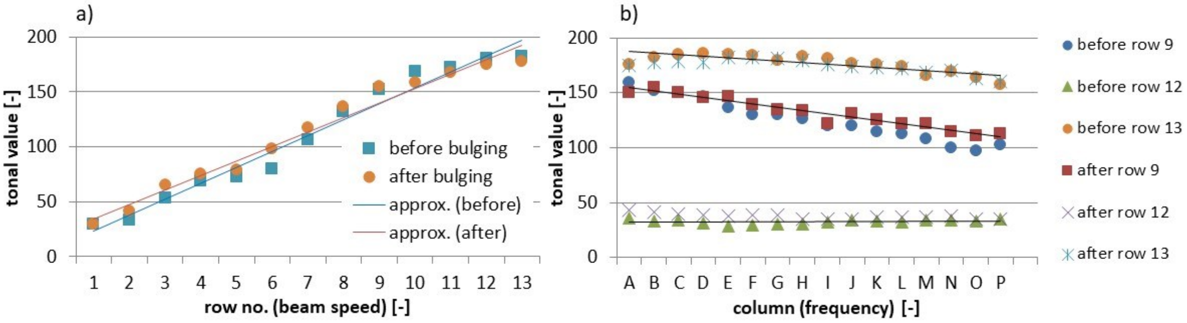

Figure 6. Tonal values before and after the bulging process for column "B" (a), and row 2,9 and 13 (b) from Table 1.

Source: own elaboration.

The results of measuring the tonal values have shown that as the frequency increases and the speed decreases, the tonal value of the markers decreases. The beam speed has a greater impact on the tonal value than the frequency (Figure 5, 6). At high values of the beam speed and low frequency, tonal values of the mark that are higher than those of the sheet surface are obtained, which can be used to create a background for a barcode. Creating a light background for the barcode significantly increases the contrast, which allows easier detection and analysis of the barcode. A background with high tonal value gives a higher contrast than black lines directly applied to the sheet surface. There were no clear differences in tonal values of the patterns before and after their deformation, which permits the assumption that the contrast of the barcode before and after the metal forming process will be preserved.

6. Experimental measurement of barcode distortion

Barcode distortion in sheet metal forming could be a result of both material deformation and changes in geometry. These two phenomena change the barcode dimensions recorded by the CCD camera sensor before (for the flat sheet metal blank) and after the bulging process. These dimensions depend on both the measurement location and camera orientation. The schematic presentation of the measurement method is shown in Figure 7.

In the bulging process, the sheet metal deformation leads to the permanent barcode distortion. The 25 mm barcode applied initially to the sheet metal surface therefore experiences a complex strain state in three directions (two of them on the surface and one in the thickness). To recognize the barcodes and to investigate the results of a scanning process, the authors of this paper have been using the CCD-equipped camera and a specially developed scanning application written by (Pavlidis et al., 1990) in the Matlab/Simulink programming language. The application was designed to scan and present the results in real time, as shown in Figure 7. To determine the readability of the scanning method, three barcode locations with numbers 1, 2 and 3 were chosen (Figure 7c). The camera was then perpendicularly oriented to the surface to consider only a plastic deformation of the barcodes and their displacement. To estimate the barcode deformation, the equivalent strain of specimen was calculated after bulging by using a specially patterned specimen. Additionally, to take into account the camera orientation, several tilt angles were chosen (0°, 25° and 45° degrees), as shown in Figure 8.

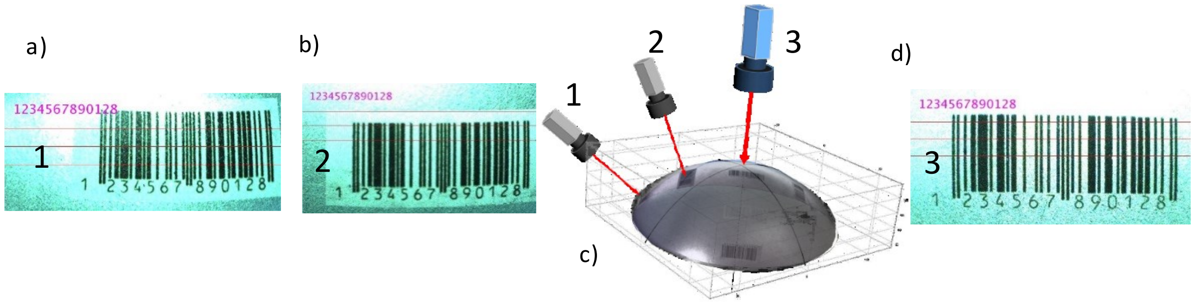

Figure 7. Schematic presentation of the scanning process for three barcode locations, as described (c): location 1 (a), for location 2 (b), and location 3 (d).

Source: own elaboration.

For the first group of measurements, three barcode locations (Figure 7c) perpendicular to the specimen surface were selected. The results for the scanning of selected barcodes using machine vision technology were displayed online during the measurement (the pink number above the scanning lines), as shown in Figure 7 a, b, d. The identifications were correct for all the barcodes.

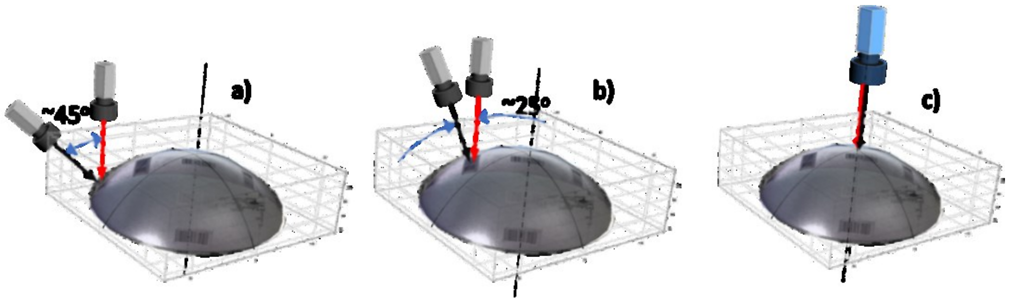

Figure 8. Schematic presentation of the barcode identification with different camera tilt angles: tilt angle 45° degree (a), tilt angle 25° degree (b), tilt angle 0° degree (c).

Source: own elaboration.

In the second group of measurements, the barcode was read with different tilt angles of CCD camera orientation (Figure 8a, b, c). As before, identifications were correct for all the barcodes. To quantify the process of the sheet metal deformation, a specially designed stereovision system was utilized (Figure 9a). A laser marking method was used to create a circle grid pattern on the surface of sheet metal blank for the bulging process. Next, a complex measurement based on image processing and data analysis was performed. In this case, image acquisition data was used to capture the real shape of specimens from two different points of view (Figure 9b, c) and then to proceed to a 3D reconstruction of the object (Figure 9d).

To calculate the true strain values, a mathematical model based on the directional derivative of the material surface displacement has been utilized. A numerical solution of the presented method developed and published by (Świłło, 2001) was adapted in this research for measurements of the grid before and after deformation. True strain reached the highest value of 0.6 (Figure 9d) for a barcode placed on the top of the specimen surface. As for the next two locations of barcodes, the true strains were 0.5 and less than 0.3, respectively.

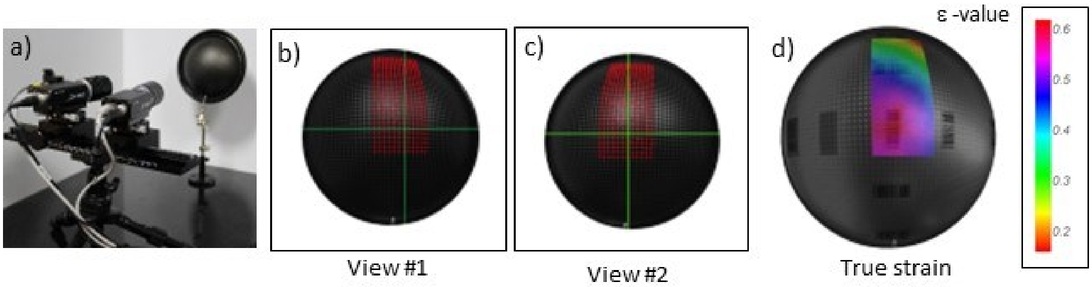

Figure 9. Experimental set-up with stereovision camera, deformed specimen, and video display (a), and results of surface strain measurement (b, c, d).

Source: own elaboration.

In the final investigation of the scanning process readability, the effects of barcode deformation were considered simultaneously, i.e., sheet metal surface displacement and changes in geometry (Figure 10c). Also, under these extreme conditions the results have proved that the final quality of barcode marked by the proposed method would not be a limitation for its recognition, as shown in Figure 10 a,b,d.

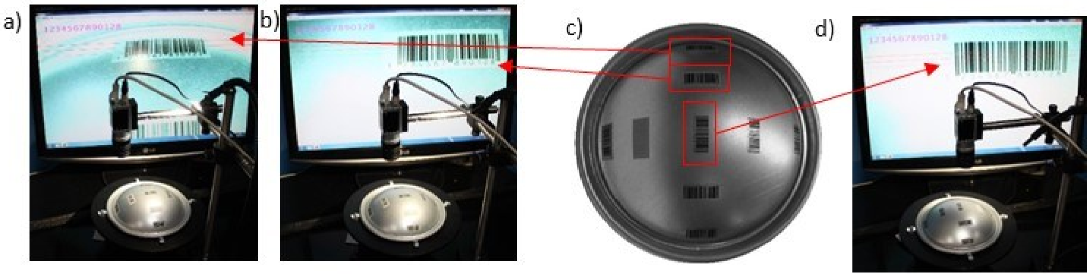

Figure 10. Scanning processes for the selected barcodes subjected to extreme conditions due to sheet metal surface displacement and changes in geometry (a, b, and d), for fixed camera orientation as shown (c).

Source: own elaboration.

7. Conclusions

This paper presents the results of potential influence of a laser marking method on sheet metal surface quality. Two aspects of surface quality were considered in relation to the sheet metal formability and barcode recognition. For these purposes, specially applied barcodes and calibration patterns were generated on the specimen surface using advanced laser technology, and the specimen was exposed to a large deformation through a hydraulic bulging process. Finally, several measurements were performed for both barcodes and calibration patterns. The results can be summarized as follows:

- The proposed method of applying appropriate laser marks at the initial phase of the product manufacturing process considerably extends traditional solutions and provides a wide range of data storage options.
- Laser beam speed v significantly affects the tonal values of the marked surfaces of the DC04 sheet metal.
- By selecting the appropriate laser beam, tonal values of the marked surface that are even higher than those of the native sheet metal surface can be obtained, allowing a truly high contrast between a white background and black marks when identifying barcodes.
- Differences in these high tonal values of the marked sheet metal surface before and after the bulging process are negligible.
- A barcode reading process was successfully accomplished by using vision scanning technology for the sheet metal surface subjected to large deformation (true strain within the range of 0.3-0.6).
- Additionally, the distortion of the barcode image caused by large sheet metal deformation was also successfully verified by tilting the camera around the optical axis in a range of 0 to 45 degrees.
- Laser marking of barcodes on a sheet metal surface introduced no problems with sheet metal formability in the applied bulging process with relatively large plastic strains.
- The presented application of barcode marking technique should be regarded as a very helpful solution for the technology information and the flexible manufacturing management strategy that can lead to an increase in the quality of obtained products, in accordance with the assumptions of Industry 4.0.

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