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## LASER ASSISTED MACHINING OF SHEET MATERIAL

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### Abstract

A system and process for fabricating components from sheet material. Various embodiments of the disclosure combine punching of components from sheet material with a scoring process that outlines the components prior to the punching operation. In addition, a system and process where the scored portion of the sheet material that includes the scored outline is subjected to a high compression flattening process prior to the punching operation is disclosed. Performing the flattening operation prior to the punching operation has the effect of streamlining the process. That is, the sheet material can be easily handled and conveyed from the scoring process, through the flattening process, and to the punching process without need for separate handling of the component.

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**Background/Summary**

RELATED APPLICATIONS [0001] This application is a continuation of U.S. patent application Ser. No. 17/047,153, filed on Oct. 13, 2020, which is a 371 of PCT/US2019/027363, filed Apr. 12, 2019, which claims the benefit of U.S. Provisional Patent Application No. 62/657,242, filed Apr. 13, 2018, the disclosure of which is incorporated by reference herein in its entirety.

**FIELD OF THE DISCLOSURE**

[0002] This application is directed generally to methods and systems for fabricating components from sheet stock, and more specifically laser machining of sheet stock in tool and die fabrication processes and systems.

**BACKGROUND OF THE DISCLOSURE**

[0003] A wide range of sheet metal parts are manufactured by stamping and punching from sheet stock. Conventionally, the gap between the die and punch requires tight clearances, typically 5% to 15% of material thickness. For thin sheet stock, the die and the punch must be machined within tolerances to provide the required fit.

[0004] Furthermore, certain materials are not conducive to stamping or punching. An example of difficult materials to stamp or punch is electrical steels, which, due to normal wear and tear of the stamps and dies, will eventually produce the parts with unsatisfactory edge quality or damage to (cracking of) the sheet itself. Because of the high forces that repeatedly act on the tools, the rate of wear on the tools can be quite high, thus requiring frequent refurbishment or replacement.

[0005] The tight tolerances required for stamping of thin sheets, in addition to the need to frequently refurbish or replace, makes stamping of certain materials untenable. A system and method that addresses these issues would be welcomed.

**SUMMARY OF THE DISCLOSURE**

[0006] Various embodiments of the disclosure describe the process of making components or parts from sheet or coil material by combining cutting, scoring and separation processes with the a flattening process. The cutting process includes cutting a partial outline of the perimeter of the component using high power energy source, such as a laser beam. The cutting process may include cutting of between 20% to 97% of the perimeter of the component. The scoring process includes scoring at least a partial outline of the component perimeter. The component perimeter is scored using high power energy source, such as a laser beam. The scoring process may include scoring of 20% to 100% of the perimeter of the component. The process of separation includes separating the component from sheet or coil, such as by a punching operation, and removing the component with compressed air or with an electromagnetic pulse.

[0007] In addition, a system and process where the scored portion of the sheet material that includes the scored lines is subjected to a flattening process prior to the punching operation is disclosed. Performing the flattening operation prior to the punching operation has the effect of streamlining the process. That is, the sheet material can be easily handled and conveyed from the scoring process and any cutting process, through the flattening process, and to the separation process without need for separate handling of the component. Such streamlining is of particular value when handling thin sheets that, in some cases, resemble foil material. Herein, “sheet

material” is construed broadly to include conventional sheets, ribbons, thin plates, reels, coils and other such forms that may be processed in a stamping or through-punch operation.

[0008] The flattening process acts to return the cut and/or scored portion of the sheet material to substantially the original thickness by flattening proud features that may arise in the cutting or scoring processes, such as dross or beads of molten materials which may form at the corners of the scored grooves. The cut and/or scored portion of the sheet may undergo some degree of bowing or warping due to the temperature gradients that are incurred during the cutting and scoring processes. The flattening process may remove or diminish such bowing or warping and restore the scored portion of the sheet material to a planar state.

[0009] Another aspect of the disclosed systems and processes are that the score line establishes the location of a line of separation between the component and the sheet material during the separation process. If the separation process is conducted with rigid punch and die, tight tolerances between the punch and the die are not required to effect the desired shape of the component. This relaxes the tolerance requirements of the tooling, so that instead of 5% to 15% of the sheet material thickness, the die gaps may be one or two times the thickness of the sheet material or greater. Accordingly, the cost of tooling is reduced, and the tooling can experience greater levels of wear before requiring replacement or refurbishment. Furthermore, the rate of tool wear may be greatly reduced, as the forces required to shear the component at the score line is reduced relative to shearing the full thickness of the sheet material.

[0010] Surprisingly, we have found that, for many applications, the sequence of compressively flattening the cut and/or scored portion of the sheet material before the separation process produces a finished or nearly finished component. The roughness of the edges is, for some applications, within a finished specification. Often, the dross or reformed molten material that was turned down at the corners of the cut and/or scored grooves during the flattening process is pre-stressed and fatigued, and is easily removed by light finishing techniques. The components, even though produced with more generous punch and die clearances, may also retain a satisfactory planarity through the punching process.

[0011] Structurally, various embodiments of the disclosure include a scoring-assisted method for punching components from a sheet material, comprising scoring an outer score line on a sheet material with a high energy radiation source, the outer score line defining a shape of an outer perimeter of a component; after the step of scoring, flattening a scored portion of the sheet material with a flattening device, the scored portion of the sheet material including the outer score line; and after the step of flattening, driving a component punch through the sheet material to separate the component from the sheet material, the component punch contacting the sheet material within the outer score line. In some embodiments, the high energy radiation source in the step of scoring an outer score line on the sheet material is a laser.

[0012] The method may include, before the step of flattening, cutting a discard out of the sheet material with the high energy radiation source to separate the discard from the sheet material. Alternatively, in some embodiments, before the step of flattening, the method includes scoring a discard score line on the sheet material with the high energy radiation source, the discard score line defining a shape of an outer perimeter of a discard, the discard score line being surrounded by the outer score line. Before the step of driving the component punch, the method may include driving a discard punch through the sheet material to separate the discard from the sheet material, the discard punch contacting the sheet material within the discard score line. Before the step of driving the discard punch, the method may include aligning the outline with a discard die, the discard die being positioned and configured to receive the discard punch. In some embodiments, the method includes configuring the discard punch to be inserted within the discard die to define a minimum die clearance gap that is at least one and not more than three times a thickness of the sheet material.

[0013] In various embodiments, before the step of driving the component punch, the method includes aligning the outer score line with a component die, the component die being positioned

and configured to receive the component punch. The method may also include configuring the component punch to be inserted within the component die to define a minimum die gap clearance that is at least one and not more than three times a thickness of the sheet material. In some embodiments, the flattening device in the step of flattening is a compressive roller. A roller pressure may be applied by the compressive roller during the step of flattening that is less than a yield strength of said sheet material.

[0014] In some embodiments, the method includes providing the sheet material having a thickness in a range of 20 micrometers to 400 micrometers inclusive. The sheet material may be of a metallic material, and may also be of an amorphous metal, and furthermore of silicone steel. In some embodiments, the step of scoring defines a groove depth that is in a range of not less than 20% and not more than 80% of a thickness of the sheet material. In some embodiments, after the step of scoring and before the step of driving, the method includes removing surface debris from the portion of the sheet material. The step of removing loose material may be performed with compressed air.

[0015] In various embodiments of the disclosure, a scoring-assisted system for manufacturing components from a sheet material is disclosed, comprising a conveyor for conveying a sheet material along a conveyance path, a high energy radiation source for forming an outer score line on the sheet material that defines a shape of an outer perimeter of a component, a flattening device for flattening the sheet material, a component punch for separating a component from the sheet material at the outer score line, and a component die configured to receive the component punch. In some embodiments, the flattening device is disposed between the high energy radiation source and the component punch along the conveyance path. The high energy radiation source may be configured for cutting a discard from within the outer score line to separate the discard from the sheet material.

[0016] Alternatively, the high energy radiation source may be configured for forming a discard score line that is surrounded by the outer score line, the discard score line defining a shape of an outer perimeter of a discard. In such embodiments, the system may include a discard punch for separating the discard from the sheet material at the discard score line, and a discard die configured to receive the discard punch, wherein the discard punch is disposed between the flattening device and the component punch along the conveyance path.

[0017] The scoring-assisted system may be configured to handle a sheet material having a thickness in a range of 20 micrometers to 400 micrometers inclusive. In some embodiments, the high energy radiation source is a laser. In some embodiments, the flattening device is a compressive roller. The compressive roller may be configured to apply a roller pressure on the sheet material that is less than a yield strength of the sheet material. The high energy radiation source may be configured to form a groove depth that is in a range of not less than 20% and not more than 80% of a thickness of the sheet material.

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## Description

### BRIEF DESCRIPTION OF THE DRAWINGS

[0018] FIG. 1 is a partial perspective view of a scoring-assisted system according to an embodiment of the disclosure;

[0019] FIG. 2 is a partial perspective view of a scoring-assisted system including a discard punch and die, according to an embodiment of the disclosure;

[0020] FIG. 3 is an end sectional view of score line grooves before and after flattening, according to an embodiment of the disclosure;

[0021] FIG. 4 is a cutaway view of a scored tab bridging a through-cut according to an embodiment of the disclosure;

[0022] FIG. **5** is a plan view of a perforated score line according to an embodiment of the disclosure;

[0023] FIG. **6** is a side sectional view of the perforated score line of FIG. **5** according to an embodiment of the disclosure;

[0024] FIG. **7** is a side sectional view of an alternative perforated score line according to an embodiment of the disclosure;

[0025] FIG. **8** is a side sectional view of another alternative perforated score line according to an embodiment of the disclosure;

[0026] FIG. **9** is a perspective view of a discard punch and a discard die in alignment with a scored section of a sheet material, according to an embodiment of the disclosure;

[0027] FIG. **10** is a perspective view of a component punch and a component die in alignment with a scored section of a sheet material with a discard removed, according to an embodiment of the disclosure;

[0028] FIG. **11** is an elevational, partial cutaway view of a punch centered over a sheet material and a die, according to an embodiment of the disclosure;

[0029] FIG. **12** is an enlarged, partial view of the cutaway of FIG. **11** depicting a die clearance gap, according to an embodiment of the disclosure;

[0030] FIG. **13** is an elevational view of a punch inserted through the sheet material and into the die of FIG. **11**, according to an embodiment of the disclosure;

[0031] FIG. **14** is a sectional view at plane A-A of FIG. **13** for a discard punch inserted in a discard die according to an embodiment of the disclosure;

[0032] FIG. **15** is a sectional view at plane A-A of FIG. **13** for a component punch inserted in a component die according to an embodiment of the disclosure;

[0033] FIG. **16** is a graph of a cutting depth of a groove versus a scanning rate for a single pass of a 1 kilowatt Ytterbium single-mode continuous wave cutting laser according to an embodiment of the disclosure; and

[0034] FIG. **17** is a graph of a cutting depth of a groove versus a number of passes for a 1 kilowatt Ytterbium single-mode continuous wave cutting laser at a scanning rate of 20 meters per second according to an embodiment of the disclosure.

#### DETAILED DESCRIPTION OF THE FIGURES

[0035] Referring to FIG. **1**, a scoring-assisted system **30a** for fabricating components **32** from a sheet material **34** is depicted according to an embodiment of the disclosure. In the depicted embodiment, the scoring-assisted system **30a** includes a scanning radiation source **42**, a sheet flattening device **44**, a component punch **48**, and a component die **54**. Also in the depicted embodiment is an air nozzle **56** directed at the sheet material **34**. A discard bin **72** may be configured to receive discards **74** that are removed from the sheet material **34** by scanning radiation source **42**. The discards **74** may be a single continuous piece (depicted) or may be a plurality of pieces (e.g., a plurality of isolated apertures). Likewise, a component bin **75** may be configured to receive components **32** that are removed from the sheet material **34** by the component punch **48**.

[0036] Referring to FIG. **2**, a scoring-assisted system **30b** for fabricating the components **32** from the sheet material **34** is depicted according to an embodiment of the disclosure. The scoring-assisted system **30b** includes many of the same components and attributes as the scoring-assisted system **30a**, which are indicated with same-numbered reference characters. In addition, the scoring-assisted system **30b** includes a discard punch **46** and a discard die **52**. The air nozzle **56** is not depicted in FIG. **2**, but it is contemplated that the air nozzle **56** may be utilized in the scoring-assisted system **30b** as well. For the scoring-assisted system **30b**, the discards **74** are generated by actuation of the discard punch **46**, so the discard bin **72** is positioned and configured to receive the discards **74** from the discard die **52**.

[0037] The scoring-assisted systems **30a** and **30b** are herein referred to generically or collectively as scoring-assisted system(s) **30**. The scoring-assisted systems **30** are configured to convey the

sheet material **34** in a direction **62** along a conveyance path **64** so that a given portion of the sheet material **34** is conveyed under the scanning radiation source **42**, through the sheet flattening device **44**, and between the component punch **48** and component die **54** in sequence.

[0038] The scanning radiation source **42** delivers a concentrated beam of radiation **80** and may be configured to rapidly trace an outline **82** of the component **32** on the sheet material **34**. Examples of rapid moving radiation sources are found, for example, at U.S. Pat. No. 9,649,727 to Kancharla and owned by the owner of the present application, the disclosure of which is hereby incorporated by reference herein in its entirety except for express definitions and patent claims contained therein. The scanning radiation source **42** may be a laser **88**. The laser **88** may be either continuous wave (CW) or pulsed. A non-limiting example of a suitable laser includes a Ytterbium single-mode CW laser, such as the YLR-1000-WC-Y14 manufactured by IPG Photonics. Other single mode lasers of sufficient power, pulses or continuous wave, may be utilized. A beta radiation source (i.e., electron beam) is also contemplated for use as the scanning radiation source **42**. In some embodiments, the radiation source **42** is configured to deliver power within a range of 0.5 kW (kilowatts) to 2 kW inclusive. Herein, a range that is said to be “inclusive” includes the end point values of the range as well as all intermediate values within the range.

[0039] The portion of the sheet material **34** on which the outline **82** is scored is referred to herein as the scored portion **83** of the sheet material **34**. In the depicted embodiment, the outline **82** includes an inner or discard score line **84** and an outer score line **86**. The inner score line **84** traces an outer perimeter **85** of the discard **74**. The outer score line **86** traces an outer perimeter **87** of the component **32**. The inner and outer score lines **84** and **86** combine to define the boundaries of the component **32**. The scanning radiation source **42** may be configured to score the outline **82** to a desired depth within a thickness  $t$  of the sheet material **34** (e.g., FIG. 12) over multiple passes. Non-limiting examples of the desired depth of the score lines **84** and **86** is in a range of 20% to 80% inclusive of the thickness  $t$  of the sheet material **34**. In some embodiments, the thickness  $t$  is in a range of 20  $\mu\text{m}$  (micrometers) to 400  $\mu\text{m}$  inclusive.

[0040] The air nozzle **56** may be stationed to between the sheet flattening device **44** and the component punch **48** (depicted). Alternatively, the air nozzle **56** may be stationed between the scanning radiation source **42** and the sheet flattening device **44**. In some embodiments, an additional air nozzle is incorporated so that an air nozzle is stationed on both sides of the sheet flattening device **44**. The air nozzle **56** may be configured to deliver an air jet in a manner that sweeps laterally across the sheet material **34** (depicted). In some embodiments, the air nozzle **56** is configured to trace over the outline **82** at close proximity to the sheet material **34**. In some embodiments, the score lines **84**, **86** may be cleaned of surface debris by devices and techniques other than air nozzles **56**, such as brushes, air knife, or water rinse. The cleaning of surface debris may occur before the flattening process, after the flattening process, or both.

[0041] Referring to FIG. 3, the effect performing multiple passes with the scanning radiation source **42** to form the score lines **84** and **86** is depicted according to an embodiment of the disclosure. The score lines **84** and **86** define a groove **96** having a depth  $d$  within the thickness  $t$  of the sheet material **34**, with a web portion **98** that bridges the sides of the groove **96**. The scoring of the sheet material **34** with the concentrated beam of radiation **80** causes some reformed molten and dross material **102** to collect at corners **104** of the groove **96** and to extend proud of a surface **106** of the sheet material **34**. In the depicted embodiment, some of the sheet material **34** is removed from the groove **96** by vaporization, so that the volume and mass of the reformed material **102** is only a fraction of the total of the sheet material **34** that is removed from the groove **96**.

[0042] In some embodiments, the scanning radiation source **42** is configured to scan the outline **82** at a rate that is in a range from 5 m/s (meters per second) to 30 m/s inclusive. In some embodiments, the scanning radiation source **42** delivers radiation in a range of 0.1 kW to 2 kW inclusive. The depicted cross section of the groove **96** of FIG. 2 is a non-limiting rendering of a photograph taken of a cross-section of a sheet material **34** of mild steel of 97  $\mu\text{m}$  nominal thickness

that was scanned with a 1 kW laser a total of four times at a scanning rate of 20 m/s. Results for the same scoring parameters on a sheet of silicon steel were similar. For both mild steel and silicon steel, under the stated scoring conditions, the thickness of material removed from the groove **96** for each pass of the scanning radiation source **42** has been observed to be in the range of 15  $\mu\text{m}$  to 35  $\mu\text{m}$  inclusive, with a nominal thickness of removed material to be 16  $\mu\text{m}$  to 20  $\mu\text{m}$  inclusive. Data for a cutting depth of mild steel and silicone steel at varying scan rates and numbers of passes are presented below at FIGS. **16** and **17**.

[0043] Functionally, by forming the score lines **84** and **86** over multiple passes, the heat affected zone of the sheet material **34** is reduced relative to that of a single pass that dwells long enough to form the groove **96**. Also, because less of the energy delivered by the concentrated radiation beam **80** is absorbed by the sheet material **34**, the amount of material vaporized during the successive passes may be increased relative to a single pass formation of a groove of similar depth. Also, irregularities that may be formed on the sides of the groove **96** (e.g., by reformation of dross) during initial passes may tend to be ablated away in successive passes to form a cleaner, better defined groove **96**.

[0044] In some embodiments, one contour line may be completely through-cut while another contour line may be scored. Such an arrangement is depicted in scoring-assisted system **30a**, where the discard **74** is completely through-cut by the scanning radiation source **42**, while the outer score line **86** remains. This arrangement negates the need for the discard punch process, while leaving the component **32** attached to the sheet material **34** for conveyance along the conveyance path **62** through the sheet flattening device **44** and onto the component die **54**.

[0045] Referring to FIG. **4**, a scored tab configuration **100** is depicted according to an embodiment of the disclosure. In this embodiment, scoring is combined with through-cutting so that a portion of the contour line of the component **32** is cut through the thickness  $t$  of the sheet material **34** while material remains along another portion of the contour line. For example, one or both of the perimeters **85**, **87** may include a through-cut portion **91** and a tab portion **93**, the tab portion **93** bridging the through-cut portion **91**. In some embodiments, the tab portion **93** is scored with the groove **96** in the manner depicted in FIG. **3**. In some embodiments, a plurality of such tab portions **93** are formed along the perimeter(s) **85**, **87**. In some embodiments, a ratio of a sum of the tangential lengths **95** of the tabs **93** to a total length of the corresponding perimeter **85**, **87** is in a range of 50% to 97% inclusive; in some embodiments, the ratio is in a range of 75% to 95%; in some embodiments, the ratio is in a range of 85% to 95%.

[0046] Functionally, the tabs **93** maintain coupling between the component **32** and the sheet material **34** or between the coupling **32** and discard **74** and the sheet material **34**, enabling the component **32** or the combined component **32** and discard **74** to be stably conveyed along the conveyance path **64** with the sheet material **34**, for positioning over the component die **54** or both the discard die **52** and the component die **54** in sequence. The reduced bridging between the discard **74** and component **32** and between the component **32** and sheet material **34** relative to a conventional stamping process reduces the required separation forces. In embodiments where the tab portions **93** are scored, the forces are further reduced and the line of separation may be predictable within a tighter tolerance than with tab portions **93** that are not scored.

[0047] In the depicted embodiment, the sheet flattening device **44** is a roller assembly **90** that includes opposed rollers **92**, **94** on opposing sides of the sheet material **34**. The opposed rollers **92**, **94** may be coupled to roller mounts **89** that are configured to limit separation of the rollers **92**, **94** at a maximum predetermined distance. In some embodiments, the maximum separation of the rollers **92**, **94** is set to be at least the nominal thickness  $t$  of the sheet material and no greater than 1  $\mu\text{m}$  more than the nominal thickness  $t$ . In some embodiments, the roller mounts **89** are configured to provide rigid separation of the rollers **92**, **94**. Contact of each roller **92**, **94** with the sheet material **34** may be established by an electrical contact measurement. In some embodiments, the rollers **92**, **94** are of a hard metallic material. In some embodiments, the rollers **92** and **94** operate at different

electrical potentials, thereby causing a current to flow through the sheet material **34** during conveyance through the roller assembly **90**.

[0048] Functionally, limiting the separation between the rollers **92**, **94** to a maximum dimension at the nominal thickness  $t$  or rigidly maintaining the separation at the nominal thickness  $t$  of the sheet material **34** enables the roller assembly **90** to perform the flattening function without exerting substantial stresses on the core of the sheet material. As the scored portion **83** of the sheet material passes through the roller assembly **90**, only the proud features relative to the surface **106**, such as the reformed molten and dross material **102** at the corners **104** (FIG. 3), exceed the nominal thickness  $t$  of the sheet material **34** and come into compressive contact with the rollers **92**, **94**.

Because the separation between the rollers **92**, **94** do not exceed or are held constantly at the nominal thickness  $t$ , the reformed molten and dross material **102** will yield locally to the rollers **92**, **94**, resulting in plastic deformation that turns these features down.

[0049] Accordingly, the scored portions **83** of the sheet material are flattened without generating substantial Hertzian contact stresses. Hertzian contact theory characterizes the stresses generated by the contact of curved stresses, and is described, for example, at Xiaoyin Zhu, "Tutorial on Hertz Contact Stress", available at <https://wp.optics.arizona.edu/optomech/wp-content/uploads/sites/53/2016/10/OPTI-521-Tutorial-on-Hertz-contact-stress-Xiaoyin-Zhu.pdf>, last visited on Mar. 27, 2018, the disclosure of which is incorporated by reference herein in its entirety except for express definitions contained therein. Excessive Hertzian contact stresses are known, for example, to adversely affect the magnetic properties of materials.

[0050] Alternatively, the roller assembly **90** may be a compressive roller configured to compress the sheet material **34** therebetween using a predetermined force as the sheet material **34** is conveyed through the roller assembly **90**. Compression between the rollers **92**, **94** may be accomplished, for example, with hydraulic actuators (not depicted). The predetermined force generated by the roller assembly **90** may be tailored to deliver stresses on the sheet material **34** that do not exceed the yield strength of the material. Because the reformed molten and dross material **102** stands proud relative to the surface **106** of the sheet material **34** and constitutes a small fraction of the total line contact of the roller assembly **90**, the local stresses on the reformed molten and dross material **102** will far exceed the average stress on the sheet material **34**, thereby preventing deformation of the core of the sheet material **34** while still providing flattening (plastic deformation) of the reformed molten and dross material **102**. In some embodiments, the roller assembly **90** is configured to apply a compressive force on the sheet material **34** only when the sheet material **34** is moving through the roller assembly **90**. Alternatively, the flattening device **44** may include a flat stamping plate (not depicted), a rocking press (not depicted), or other devices and techniques for flattening sheet material available to the artisan.

[0051] The effect of flattening the sheet material **34** after scoring but prior to punching is also depicted in FIG. 3 according to an embodiment of the disclosure. The sheet material **34** is advanced through the roller assembly **90** so that the reformed material **102** is flattened (i.e., made substantially planar with the surface **106**). For some materials, such as mild steel and amorphous silicon steel, the reformed material **102** is relatively ductile, so that the reformed material is turned down at the corners **104**. Also, some reformed material that is tenuously attached to the corners **104** may be pre-stressed and fatigued or fractured and detached during the flattening process. Operating the rollers **92**, **94** at different potentials may provide local heating of the sheet material **34** to augment the flattening process. The electrical current also interacts with the core of the component **32** to augment plastic deformation desirable in the flattening process.

[0052] Accordingly, to "flatten" the sheet material **34** is to compress or return the reformed molten and dross material **102** to be substantially at or within the original thickness  $t$  of the sheet material **34**, and to mitigate bowing and warping of the sheet material. That is, the sheet material **34** will still define the outline **82** after the flattening process. The flattening process does not compress the sheet material **34** to the point of eliminating the score lines **82** and **84**.



[0053] In some embodiments, the compressive force is applied by the roller **90** only when the sheet material **34** is advanced therethrough. By applying the compressive force with the roller assembly **90** only when the sheet material **34** is passing through the roller assembly **90**, the system avoids dimpling of the sheet material **34** that may otherwise occur as the material dwells momentarily within the rollers **92, 94**.

[0054] Referring to FIGS. **5** through **8**, a perforated score line **108** is depicted in an embodiment of the disclosure. The perforated score line **108** is characterized as having perforations **110** formed along the length of the web portion **98** within the groove **96**. In some embodiments, at least a portion of one or both of the discard score line **84** and the outer score line **86** of the score outline **82** is formed with such perforated score lines **108**. The perforated score line **108** may be formed over multiple passes as discussed above. In FIGS. **5** and **6**, the score outline **82** is initially formed as being continuous and of substantially uniform depth, followed by bursts of radiation energy at discrete points along the length of the groove **96** to form the perforations **110**. In some embodiments, only the perforations are formed by the scanning radiation source **42** (FIG. **7**). That is, the scoring-assisted systems **30** are configured so that the scanning radiation source **42** delivers bursts of radiation only at the desired locations of the perforations **110** to form a discontinuous scoring outline **82**. In some embodiments, the scan rate is undulated so that the concentrated radiation beam **80** dwells or passes more slowly over the regions where the perforations **110** are to be formed (FIG. **8**). After formation of the perforated score line **108**, the sheet material **34** with score lines **82** and **84** thus formed may be compressively flattened as described above.

[0055] Functionally, the perforations **110** serve to reduce the forces required to separate the components **32** or the discards **74** or both from the sheet material **34**. Any dross material that may be formed along the boundaries of the perforations **110** may be flattened or removed by the flattening device **44** in the same manner as the corners **104** described above. The perforations **110** may also serve to limit the effect of tearing or ripping along the lines of separation and to keep the lines of separation centered along the web portion **98**, so that the nominal peripheries of the components **32** are substantially uniform.

[0056] Referring to FIG. **9**, the discard punch **46** and discard die **52** are depicted according to an embodiment of the disclosure. The discard punch **46** and discard die **52** are so-named because they function to remove the discards **74** from the sheet material **34** that is not part of the finished component **32**. The discard punch **46** may define a footprint **112** that approximates but is within the inner or discard score line **84** of the discards **74**. The discard die **52**, when utilized, is configured to receive the discard punch **46** and may define a footprint **114** that approximates but is within the discard score line **84** of the outline **82**.

[0057] Referring to FIG. **10**, the component punch **48** and component die **54** are depicted according to an embodiment of the disclosure. The component punch **48** and component die **54** are so-named because they function to remove the components **32** from the sheet material **34**. The component punch **48** may define a footprint **142** that approximates but is within the outer score line **86** of the components **32**. The component die **54**, when utilized, is configured to receive the component punch **48** and may define a footprint **144** that approximates but is outside the outer score line **86** of the outline **82**. In the depicted embodiment, the outer score line **86**, and therefore a receptacle **146** of the component die **54**, are circular.

[0058] In some embodiments, the punches **46** and **48** and the dies **52** and **54** are made of a rigid material (e.g., tooling steel) that contacts the sheet material **34**. In some embodiments, some or all of the punches **46** and **48** and the dies **52** and **54** include a semi-rigid or a flexible material that contacts the sheet material **34**, such as polyurethane or rubber-like materials. The semi-rigid or flexible material may be disposed on or integrated with the discard punch **46** or discard die **52**, for example, in an overmolding process.

[0059] Referring to FIGS. **11** through **15**, operation of the discard punch **46** and discard die **52** and of the component punch **48** and component die **54** are depicted according to an embodiment of the

disclosure. As operation of the discard punch **46** and discard die **52** is similar to the operation of the component punch **48** and component die **54**, FIGS. **11** through **13** are annotated to depict the operation of both of these punch and die combinations. After the component **32** has been scored with the scanning radiation source **42**, the inner or discard score line **84** of the outline **82** of the component **32** is aligned over the discard die **52** to define a die clearance gap **122** between the discard punch **46** and the discard die **52** (FIGS. **11** and **12**). The scoring-assisted systems **30** may be configured so that the score lines **82** and **84** are in the same rotational orientation as the discard punch **46** and discard die **52**, such that the discard score line **84** is positioned over the die clearance gap **122** by translating the outline **82** over the discard die **52**. When the component outline **82** is aligned with the discard die **52**, the discard score line **84** traces over the die clearance gap **122**. [0060] The discard punch **46**, which aligns within the discard score line **84**, is then thrust through the sheet material **34** to separate the discard **74** from the sheet material **34** (FIG. **13**) at the discard score line **84**. During the separation of the discard **74**, the discard punch **46** is inserted at least partially into the discard die **52**. A cross-sectional view of the discard punch **46** within the discard die **52** is presented at FIG. **14**, depicting a discard punch cross-section **124** and a discard die cross section **126**. In some embodiments, the die clearance gap **122** is defined laterally between the discard punch **46** and the discard die **52** when the discard punch **46** is inserted into the discard die **52**. In some embodiments, a minimum dimension **128** for the die clearance gap **122** is at least one and not more than three times the thickness  $t$  of said sheet material **34**.

[0061] After the discard **74** has been removed from the sheet material **34**, the outer score line **86** of the outline **82** is aligned over the component die **54**, the component **32** being radially suspended at the outer score line **86**. When in alignment, the component punch **48** and the component die **54** define a die clearance gap **162**, over which the outer score line **86** is positioned (FIGS. **11** and **12**). The component punch **48** is then thrust through the sheet material **34** to separate the component **32** from the sheet material **34** (FIG. **13**) at the outer score line **86**, so that the component **32** drops into the component bin **75**. During the separation of the component **32**, the component punch **48** is inserted at least partially into the component die **54**. A cross-sectional view of the component punch **48** within the component die **54** is presented at FIG. **15**, depicting a component punch cross-section **162** and a component die cross section **164**. A continuous, die clearance gap **166** is defined between the component punch **48** and the component die **54**. In some embodiments, a minimum dimension **168** for the die clearance gap **16** is at least one and not more than three times a thickness  $t$  of the sheet material **34**.

[0062] Functionally, the score outline **82** controls the line of separation in both the discard **74** and component **32** punching processes in the scoring-assisted system **30b**, and controls the line of separation of the component **32** in the scoring-assisted system **30a**. This is in contrast to a conventional stamping process, where the line of separation is controlled by tight tolerances between tool and die. Accordingly, the tolerances between the component punch **48** and the component die **54** and, when utilized, between the discard punch **46** and the discard die **52** may be more generous. Because of the compressive rolling process that occurs after scoring and any cutting process but before the punching operation(s), at least the flatness of the component **32** is in a finished state upon separation from the sheet material **34**. The edges of the components **32** may then be finished to final specifications, for example by sand blasting, turning, milling, grinding, honing, electrical erosion, or other finishing processes available to the artisan.

[0063] Referring to FIG. **16**, a graph **170** of data characterizing a cutting depth parameter **172** of a groove versus scanning rate (cutting speed) **174** of a laser is presented according to an embodiment of the disclosure. The data were obtained in an experimental setup using an IPG Photonics YLR-1000-WC-Y14 Ytterbium single-mode CW laser at a power level 1000 Watts utilizing a fiber diameter of 14  $\mu\text{m}$ . The laser was scanned with an IPG 2D High Power Scanner with a 200 mm collimator and a 254 mm focus lens. The focus spot diameter was calculated at 18  $\mu\text{m}$ . The tests were performed at an ABB IRB2400 robot work station in a stationary scanner set up. The tests

were performed on a vacuum honeycomb cutting table with an air knife purge directed on the process area. The tests were performed on mild steel sheet stock and silicon steel sheet stock of 100  $\mu\text{m}$  nominal thickness. Mild steel data **176** and silicon steel data **178** are presented in the graph **170**.

[0064] Data were taken for a single pass of the cutting laser at scanning rates of 7.0, 8.0, 10.0, 15.0, and 20.0 m/s. The graph **170** demonstrates that cutting depth is reduced as the scanning rate is increased, and that results were substantially similar for mild steel and silicon steel. It was also observed that less dross material was formed along the boundaries at higher scanning rates.

[0065] Referring to FIG. **17**, a graph **180** of data characterizing a cutting depth parameter **182** of a groove versus the number of passes **184** of a laser is presented according to an embodiment of the disclosure. The data were obtained in an experimental setup using an IPG Photonics YLR-1000-WC-Y14 Ytterbium single-mode CW laser at a power level 1000 Watts utilizing a fiber diameter of 14  $\mu\text{m}$ . The laser was scanned with an IPG 2D High Power Scanner with a 200 mm collimator and a 254 mm focus lens. The focus spot diameter was calculated at 18  $\mu\text{m}$ . The tests were performed at an ABB IRB2400 robot work station in a stationary scanner set up. The tests were performed on a vacuum honeycomb cutting table with an air knife purge directed on the process area. The tests were performed on mild steel sheet stock and silicon steel sheet stock of 100  $\mu\text{m}$  nominal thickness. Mild steel data **186** and silicon steel data **188** are presented in the graph **180**.

[0066] Data were taken at a scanning rate of 20 m/s for the cutting laser at with the number of passes ranging from 1 to 5 inclusive. The graph **180** demonstrates that increasing the number of passes also increases the cutting depth, and that results were substantially similar for mild steel and silicon steel. It was also observed that complete cut through of the stock material was achieved at 5 passes at the 20 m/s scanning rate.

[0067] Each of the additional figures and methods disclosed herein can be used separately, or in conjunction with other features and methods, to provide improved devices and methods for making and using the same. Therefore, combinations of features and methods disclosed herein may not be necessary to practice the disclosure in its broadest sense and are instead disclosed merely to particularly describe representative and preferred embodiments.

[0068] Various modifications to the embodiments may be apparent to one of skill in the art upon reading this disclosure. For example, persons of ordinary skill in the relevant arts will recognize that the various features described for the different embodiments can be suitably combined, uncombined, and re-combined with other features, alone, or in different combinations. Likewise, the various features described above should all be regarded as example embodiments, rather than limitations to the scope or spirit of the disclosure.

[0069] Persons of ordinary skill in the relevant arts will recognize that various embodiments can comprise fewer features than illustrated in any individual embodiment described above. The embodiments described herein are not meant to be an exhaustive presentation of the ways in which the various features may be combined. Accordingly, the embodiments are not mutually exclusive combinations of features; rather, the claims can comprise a combination of different individual features selected from different individual embodiments, as understood by persons of ordinary skill in the art.

[0070] Any incorporation by reference of documents above is limited such that no subject matter is incorporated that is contrary to the explicit disclosure herein. Any incorporation by reference of documents above is further limited such that no claims included in the documents are incorporated by reference herein. Any incorporation by reference of documents above is yet further limited such that any definitions provided in the documents are not incorporated by reference herein unless expressly included herein.

[0071] Unless indicated otherwise, references to “embodiment(s)”, “disclosure”, “present disclosure”, “embodiment(s) of the disclosure”, “disclosed embodiment(s)”, and the like contained herein refer to the specification (text, including the claims, and figures) of this patent application

that are not admitted prior art.

[0072] For purposes of interpreting the claims, it is expressly intended that the provisions of 35 U.S.C. 112 (f) are not to be invoked unless the specific terms “means for” or “step for” are recited in the respective claim.

## Claims

1. A scoring-assisted method for punching components from a sheet material, comprising: scoring at least part of an outer score line on a sheet material with a high energy radiation source, said outer score line defining a shape of an outer perimeter of a component; after the step of scoring, flattening a scored portion of said sheet material with a flattening device, said scored portion of said sheet material including said outer score line; and after the step of flattening, driving a component punch through said sheet material to separate said component from said sheet material, said component punch contacting said sheet material within said outer score line.
2. The scoring-assisted method of claim 1, comprising: before the step of flattening, cutting a discard out of said sheet material with said high energy radiation source to separate said discard from said sheet material.
3. The scoring-assisted method of claim 1, comprising: before the step of flattening, scoring at least part of a discard score line on said sheet material with said high energy radiation source, said discard score line defining a shape of an outer perimeter of a discard, said discard score line being surrounded by said outer score line; before the step of driving said component punch, driving a discard punch through said sheet material to separate said discard from said sheet material, said discard punch contacting said sheet material within said discard score line.
4. The scoring-assisted method of claim 3, comprising: before the step of driving said discard punch, aligning an outline of said component with a discard die, said discard die being positioned and configured to receive said discard punch.
5. The scoring-assisted method of claim 4, comprising: configuring said discard punch to be inserted within said discard die to define a minimum die clearance gap that is at least one and not more than three times a thickness of said sheet material.
6. The scoring-assisted method of claim 1, comprising: before the step of driving said component punch, aligning said outer score line with a component die, said component die being positioned and configured to receive said component punch.
7. The scoring-assisted method of claim 6, comprising: configuring said component punch to be inserted within said component die to define a minimum die gap clearance that is at least one and not more than three times a thickness of said sheet material.
8. The scoring-assisted method of claim 1, wherein said flattening device in the step of flattening is a roller assembly including two rollers.
9. The scoring-assisted method of claim 8, comprising maintaining a separation between said two rollers that is not less than a nominal thickness of said sheet material and not greater than one micrometer more than said nominal thickness.
10. The scoring-assisted method of claim 9, wherein a roller pressure is applied during the step of flattening, said roller pressure being less than a yield strength of said sheet material.
11. The scoring-assisted method of claim 1, comprising providing said sheet material having a thickness in a range of 20 micrometers to 400 micrometers inclusive.
12. The scoring-assisted method of claim 1, comprising providing said sheet material of a metallic material.
13. The scoring-assisted method of claim 1, comprising providing said sheet material of an amorphous metal.
14. The scoring-assisted method of claim 1, wherein the step of scoring defines a groove depth that is in a range of not less than 20% and not more than 95% of a thickness of said sheet material.

- 15.** The scoring-assisted method of claim 1, wherein said high energy radiation source in the step of scoring an outer score line on said sheet material is a laser.
- 16.** The scoring-assisted method of claim 1, comprising: after the step of scoring and before the step of driving, removing surface debris from said portion of said sheet material.
- 17.** The scoring-assisted method of claim 16, wherein the step of removing loose material is performed with compressed air.
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