Double sided irradiation for laser-assisted shearing of ultra high strength steels with process integrated hardening

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\begin{abstract}
Most small or medium sized parts produced in mass production are made by shearing and forming of sheet metal. This technology is cost effective, but the achievable quality and geometrical complexity are limited when working high and highest strength steel.

Based on the requirements for widening the process limits of conventional sheet metal working the Fraunhofer IPT has developed the laser-assisted sheet metal working technology. With this enhancement it is possible to produce parts made of high and highest strength steel with outstanding quality, high complexity and low tool wear. Additionally laser hardening has been implemented to adjust the mechanical properties of metal parts within the process. Currently the process is limited to lower sheet thicknesses (<2 mm) to maintain short cycle times. To enable this process for larger geometries and higher sheet thicknesses the Fraunhofer IPT developed a system for double sided laser-assisted sheet metal working within progressive dies.
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\begin{keyword}
Hybrid Manufacturing; Sheet Metal Working; Laser-Assisted Machining; Lightweight Construction; Fine Blanking, Inline Heat Treatment, Hardening
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\section{1. Motivation}

Energy and resource efficiency demands made lightweight construction an ubiquitous trend in almost any sector of the producing industry. A very effective and immediately scaling method is to reduce wall thicknesses of product parts. For not to infringe the mechanical stability of the product the use of high and highest strengths steel is a common choice. While solving stability issues new challenges arise with the widespread use of high strength steels for the manufacturer of sheet metal parts. Conventional manufacturing processes like shearing, bending, deep drawing and embossing in progressive die tools reach their limit regarding possible geometries and operations, product quality as well as tool wear. High tensile strength of any material comes with low remaining formability, consequently severely limiting forming processes to very simple operations with a low degree of deformation. That correlation increasingly places sheet metal part manufacturers in a dilemma between customer wishes regarding a light weight product and geometry requirements. Some processes and geometry parameters like small bending radii and high aspect ratio shearing with small holes in bulk material are often not feasible at all and result in immediate tool or

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part failure. But even shearing simple geometries using steels with tensile strengths of higher than 1600 MPa result in considerable tool wear limiting the profitability of an in other respects highly autonomous production process due to frequent tool change cycles. Shearing operations with highest strengths materials that remain feasible at all are generally limited in edge quality with small clear cut ratios and extensive fracture zones.

Those frontiers motivated the development of the laser-assisted sheet metal working at the Fraunhofer IPT. By adding a laser irradiation cycle to the conventional working process, the challenges high strength steels pose to a conventional process could be addressed achieving outstanding edge quality and low tool wear even with difficult shearing operations. Mode of operation of a laser-assisted sheet metal working system is the implementation of an additional irradiation cycle during the working process sequence (cf. figure 1). By the use of laser scan heads a part adapted geometry can be used to heat up precisely the area of operation. When shearing the path of the laser focus spot is usually displaced from the geometry by the laser beams focal radius to irradiate exactly next to the future shearing line into the scrap part. This prevents the product surface from melting under the influence of the high intensity laser beam (cf. figure 2).

![Fig. 1. Concept of double sided irradiation.](image)

The ability to impart thermal energy into the material is limited by laser power and heat conduction within the material. This leads to a significant increase in cycle times when working materials with more than 2 mm thickness. A setup to irradiate both sides simultaneously was developed to counter this challenge. The experiments have been conducted with a real product geometry that cannot be published with this paper.

### 2. Characteristics and limitations of conventional shearing

Conventional shearing is a widespread industry standard process of the utmost economic importance in every branch of the producing industry. It combines a stable and well understood process with a high level of automation and the possibility for extensive autonomous machine operation. Achievable edge quality and geometry complexity is limited to satisfy basic needs, increasingly when working material with the low plasticity of todays high and highest strength steel materials. A conventional shearing process can be devided into five destinct phases of the cut (cf. figure 2).

**Phase 1:** The sheet metal is clamped between the sheet metal holder and the cutting die prior to contact of the stamp to the material surface (cf. figure 2 - a).

**Phase 2:** The cutting stamp gets in contact with the material. A moment of force is created within the plane of the material depending on the size of the cutting gap, thickness of the material and the size of the cutting stamp. The material undergoes elastic deformation between stamp and die (cf. figure 2 - b).
Phase 3: When the forces rise above the elastic threshold of the material shear stresses induce plastic flow of the material. The stamp penetrates the surface of the material initiating the actual cutting process (cf. figure 2 - c). The plastic flow of material at the cut causes a draw in of the upper side of the material. A corresponding deformation occurs at the other side at the slug. Increasing penetration of the stamp into the material forms a clear cut area. During this phase the material is capable of internal stress relief by plastic flow. The magnitude of this cylindrical cut is fundamentally depending on the plasticity of the material and the cutting gap.

Phase 4: Cracks start to form when the ability of the material for plastic deformation is depleted. The cracks initiate at the working edges of the both cutting tools and propagate from both sides inclined out of the axis of the clear cut into the strain hardened material (cf. figure 2 - d).

Phase 5: Separation occurs when the cracks formed at the working edges of the tools meet inside the material (cf. figure 2 - e). The machine frame experienced elastic deformation under the work load of the process and immediately recoils when the load suddenly collapses. The discharge of the energy stored within the elastically deformed machine frame excites intense vibration of the frame and the environment of the machine. The slug is removed out of the machine through the canal inside the die.

3. State of the art of laser-assisted sheet metal working

The approach of the laser-assisted sheet metal working technology is to extend the phase of plastic deformation during the cutting process (cf. figure 2 - c) due to increased plasticity by selective warming of the shearing zone Michael Emonts (2010). Several metallurgical effects can contribute to increase the plasticity of the material in the shearing zone, depending on the material, existing heat treatments and strain hardening effects as well as the parameters of the irradiation. Precise control of laser power and time of irradiation ensures repeatability of irradiation strategies adjusted to the process needs. Material properties can be changed exactly to the amount needed for the process. Tempered materials can undergo a locally confined annealing process in the shearing zone with the base material maintaining original properties. Strain hardened materials can be heated to regenerate the crystal structure to allow for right the amount of formability needed without affecting the base materials properties. Increasing heat input can induce a full scale recrystallization if desired. Standard soft materials profit from disabling strain hardening effects by heating of the shearing zone, thus allowing for plastic flow up to the complete shearing process depending of the heat induced.
Figure 3 presents the fundamental differences between several conventional sheet metal working processes and their laser-assisted counterparts focused on the results. The first column of pictures shows shearing of 2 mm thick stainless steel material and the different edge qualities achieved. While conventional working results in a large fractured area, laser-assisted shearing enables a clear cut ratio of more than 90%, increasing dynamic yield strengths of the product significantly.

Bending operations with high yield spring steels are limited to considerable high bending radii. The spring steel 1.4310 depicted in figure 3 in its cold rolled delivery status is limited to a minimal bending radius for crack free bending of 2.5 to 9.5 times the material thickness - Material Data Sheet (2014). The exact value depends on the degree of strain hardening by cold rolling and the alignment of the bend relative to the rolling direction and varies slightly with supplier datasheets. In a laser-assisted bending operation a bend with an inner radius of 0.25 mm without crack initiation or damaging base material properties after work was demonstrated.

Drawing depth without crack initiation has been more than doubled. The benefit of laser-assisted embossing could not be quantified as conventional embossing of high strength steel results in immediate tool damage and is not possible at all.

3.1. Industrial prototype used in production

Upon successful development of the laser-assisted sheet metal working technology an industrial prototype hyPRESS operating inside progressive dies has been launched and has been in service since. The process integration of that prototype is shown in figure 4. The industrial prototype features a laser chassis integrated control compartment and interface panel. The press mounted platform has been vibration isolated from the machine frame to ensure undisturbed operation of the optomechanical systems in the platform. The whole system has been CE certified to guarantee laser class 1 operation.

3.2. Test system at Fraunhofer IPT

To conduct experiments a hydraulic C-frame punching press has been used since the development of the laser assisted sheet metal technology. This test system has been modified numerous times to account for the various experimental tasks. A direct linear drive motor has been implemented to simulate the characteristic progressive die feed cycle into a small scale test system. Direct diode lasers supplied by Laserline GmbH are used as energy sources to heat up the material. Their fundamental properties are shown in table 1. For irradiation of the sheet metal in the feed area of the machine two 3D adjustable suspensions for a scan head have been designed (cf. figure 5). Both
scan heads are individually controlled by real time controller cards. User-defined geometries can be imported from CAD models into the controllers by a variety of vector based data formats. Both beams are focussed to a spot size of approximately 2 mm diameter by a plane-field f-theta lens. Process force measurements are derived from a strain gauge on the machine frame of the press.

Table 1. Fundamental properties of the direct diode lasers used in the test system.

| Laser model | Maximum Laser power | Nominal beam quality | Wavelengths employed                |
|-------------|---------------------|----------------------|-------------------------------------|
| LDF 3000-40 | 3300 W              | 40 mm · mrad         | 910nm 940nm 980nm (± 10nm)          |
| LDF 4000-30 | 4400 W              | 30 mm · mrad         | 940nm 980nm 1020nm 1060nm (± 10nm)  |

4. Double sided irradiation of press hardening steels

Press-hardening steels have gained significance in the automotive sector within the last years due to their high formability while hot forming combined with their high tensile strength and a considerably high remaining plasticity when hardened. These excellent mechanical properties drove the impulse to explore new applications with that specific group of steel alloys together with the R&D department of Johnson Controls Inc. The major alloying elements of press-hardening steels are manganese and a small amount of ≈5 ppm of boron. The most common press-hardening steel in current use is the alloy 22MnB5. Within a pilot survey to select the most beneficial material for the intended task the non-standard alloy 34MnB5 has been selected due to the higher strength of the material after hardening. This survey also showed that long times of irradiation are needed to thoroughly heat up the material to the desired temperature throughout the material thickness of 4 mm. To counter that effect a setup was implemented to irradiate both sides of the sheet metal simultaneously thus reducing the distance that needs to be heated by heat conduction by half. The higher overall laser power of both beam sources combined will further speed up the process, to aim for a high output series production in the future.

Due to shorter times of irradiation the loss of heat into the width of the material is significantly lower as there is less time available for heat conduction until the working step of the machine. Out of theoretical consideration the ideal local temperature inside the sheet metal directly depends on the local degree of deformation the material undergoes.

Fig. 4. Prototype integration into customer machine.
during working. When shearing the zone of plastic deformation is a narrow band aligned perpendicularly to the sheet plane (cf. figure 2). An ideal temperature distribution for a laser-assisted shearing process would therefore be a narrow uniformly heated shearing zone with exact the right temperature to allow for the amount of plastic formability needed for the process without local overheating (cf. figure 6). That exemplary temperature distribution cannot be created in reality and can only be approximated by heat conduction effected temperature distributions. As shown in figure 6 the temperature distribution created by a double-sided irradiation resembles that ideal temperature distribution closer than it could be created with a single-sided irradiation setup.

![Fig. 5. Test system at Fraunhofer IPT with adjustable scan head suspensions.](image)

![Fig. 6. Temperature distribution within a sheet metal cross section after irradiation - darker means warmer.](image)
5. Process results

5.1. Reduction of the process forces

With heating of the material significant force reductions can be achieved. The total process forces can be reduced from 183.4 kN to 114.9 kN. As the experimental part is only partially irradiated, the force reductions can only be realized in the irradiated parts of the geometry. 46% of the geometry has been irradiated while 54% are used to close the geometry and create a reasonable sized experimental part without being irradiated. The measured absolute force reductions underestimate the achieved process force significantly. The absolute force reduction can thus be referenced to the irradiated part of the geometry under the assumption that the force difference only derives from the irradiated part. That leads to a net force reduction of up to 81% by laser-assisted shearing.

![Diagram of process force readings](image_url)

Fig. 7. Process force readings: Double-sided laser-assisted shearing.

The diagram in figure 7 depicts process forces over time. As the flow rate of the hydraulic pump – and the movement speed of the stamp with it – depends on the oil pressure the forces do not relate to a certain position of the stamp. Lower forces generally result in higher speed of the stamp. The plateau-phase in the beginning of the diagram derives from a gear shift operation within the hydraulic pump of the stamping machine used in the test system. After that the forces rise to the process maximum and induce material separation in the shearing zone.

5.2. Increase in edge quality

Heat induction into the shearing zone by laser radiation increases the plasticity of the material and allows for prolonging the period of plastic flow (cf. figure 2 - c). The clear cut of the resulting edge is created during that period of the shearing. Figure 8 shows the change in edge quality of the series related to the force measurements depicted in figure 7. Starting with the unirradiated conventional shearing on the left side with increasing irradiation times to the right at a laser power of 3 kW per side.
5.3. Inline hardening of the cut surface

The steel alloy 34MnB5 is capable of transformation hardening. Requirements to create a hardening effect are sufficient temperature and time to create an austenitic crystal structure during a heating cycle and a fast enough quenching to enforce the martensitic transformation of the crystal structure (cf. figure 9). Depending on the process parameters of the irradiation the created edges of the shearings are well heated by the laser. With shearing the heat reservoir is removed instantaneously that has been induced directly next to the shearing line (cf. figures 2 and 6). This results in only a small amount of heat remaining in the part and supports a high cooling rate. To ensure martensitic
transformation with these experiments the parts were quenched in a water bath. If that additional cooling effort is needed at all is subject of further exploration.

The laser-assisted shearing process with integrated hardening of the product leads to a hardness distribution shown in figure 10. The origin represents the shearing line and higher values along the x-axis correspond to an increasing distance from the shearing line. One objective of this experimental task was to examine the maximum hardness depth that can be achieved away from the shearing line. As a result a uniformly high hardness level around 620 HV1 was created up to 3.5 mm away from the shearing line. A loss of mechanical properties due to a heat influenced zone in the base material has not been detectable.

Fig. 10. Hardness distribution of the experimental part shown in figure 9.

6. Summary and Outlook

Three major beneficial effects on the process and its results have been demonstrated by using double-sided laser irradiation to assist a conventional shearing operation. The process forces needed to shear the irradiated parts of the geometry have been reduced by up to 81 %. The edge quality has been significantly increased. The fracture characteristic of the conventional shearing process without laser irradiation is complex with a low clear cut ratio and a large fracture zone. With a laser-assisted working process a clear cut ratio of up to 93 % has been achieved. An uniform and repeatable in-situ heat treatment within a progressive die compatible process has been successfully demonstrated.

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