Laser-assisted metal spinning for an efficient and flexible processing of challenging materials

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Abstract. The demand for components made from high performance materials like titanium or nickel-based alloys as well as strain-hardening stainless steel is steadily increasing. However, conventional forming operations conducted on these materials are generally very laborious and time-consuming. This is where the limitations of metal spinning also become apparent. Using a laser to apply heat localized to the forming zone during metal spinning facilitates to enhance the formability of a material. In order to analyse the potential of the new manufacturing process, experimental investigations on laser-assisted shear forming and multi-pass metal spinning have been performed with austenitic stainless steel X5CrNi18-10, nickel-based alloy Inconel 718 and titanium grade 2. It could be demonstrated that the formability of these materials can be enhanced by laser-assistance. Besides the resulting enhancement of forming limits for metal spinning of challenging materials, the forming forces were reduced and the product quality was improved significantly.

1. Introduction

1.1. Motivation and state-of-the-art of metal spinning

The demand for highly stressed components for the use in several industrial sectors is forcing manufacturers to use more innovative materials. The call for reduction in fuel consumption in automotive industry led to an increased demand for thin sectioned parts with reduced weight and improved corrosion resistance. Titanium with a density of 60% of steel while maintaining a high specific strength (i.e. ultimate tensile strength UTS divided by density) has gained in importance in production [1]. Consequently, commercially pure titanium grade 2 (3.7034) was used as a representative for this class of materials for the investigations presented in this work and will be denominated as "Ti grade 2" throughout the rest of this work. For high-temperature applications nickel-based alloys are frequently used. Nickel-based alloys provide a high corrosion resistance and maintain a high material strength at elevated temperatures [2]. As prominent representative of Ni-based alloys, Inconel 718 (2.4668) has been investigated in this work. Inconel 718 is used in gas turbines, aircraft engines, spacecraft, nuclear reactors, pumps, and tooling [3]. Because of the high costs of titanium and nickel-based alloys, stainless steel still is the most common material if the
demands of the application can be met with such a material. A prominent representative is the widely used austenitic steel X5CrNi18-10 (1.4301) and has thus been investigated in this work.

Due to their outstanding mechanical properties, materials like titanium, nickel-based alloys and stainless steel are generally regarded as being difficult to machine. Product developers and their suppliers are therefore faced with the challenge of realizing complex parts economically using these materials. In contrast to other forming technologies metal spinning as incremental forming technology offers advantages such as high geometrical flexibility, short set-up times and low tooling costs as well as the option of performing several process steps in one single clamping [4]. Metal spinning processes thus represent a technologically and economically efficient alternative to other manufacturing techniques [5] and offer the possibility for near net shape manufacturing of thin sectioned lightweight parts [4]. They are also particularly suitable for machining high-strength materials since the tools affect only a small localized area and therefore require significantly lower forming forces than those needed for deep drawing, for example [6]. However, even metal spinning technology is pushed to its limits when processing difficult to machine materials.

In industrial practice, mainly two different approaches for heat treatment have been adopted to expand the forming limits, even though both show considerable drawbacks in terms of production. One of these approaches is recrystallization annealing usually performed in separate furnaces alternating with several cold forming steps. As consequence long throughput times incur that usually involve high efforts for set-up, transport and storage because the geometrical flexibility per forming step is limited. Using gas burners instead to reduce the material strength during processing (see figure 1), the energy introduced into the work piece can only hardly be controlled [7]. This can cause detrimental impact on the microstructure of the finished component. An innovative approach to avoid the aforementioned drawbacks is the use of a high power laser for the selective heating of the zone directly ahead of the forming roller. Like that deformation degrees can be enhanced significantly while the applied thermal energy to the work piece can be controlled reproducibly and reduced to a minimum because the heating is locally and temporally limited (see figure 2).

![Figure 1. Gas burner assisted metal spinning of stainless steel](source: Radkersburger Metallwarenfabrik GmbH, Austria)

![Figure 2. Laser-assisted metal spinning of stainless steel](source: Radkersburger Metallwarenfabrik GmbH, Austria)

1.2. Laser-assisted metal spinning

In general plastic deformation of metallic materials is based on dislocation movement. By further deformation the density of the dislocations increases, this leads to higher strength (strain hardening) on the one hand and to a decrease of the fracture strain (ductility) on the other hand. Elevating the temperature of the metal increases the mobility of the dislocations or activates other mechanisms for dislocation movement. Therefore the material’s strength drops (thermal softening) and in most cases the ductility of the material increases with increasing temperature [1]. Quantitative measurements of the temperature dependence of the material's strength and ductility are given in section 3.1 for all three metals presented in this work.

The use of a laser as heat source in metal spinning operations is aiming at the generation of an adequate temperature field for the material being processed in order to reduce both the yield stress and any strain hardening occurring during the forming process. Therefore a laser beam is used to heat the
area of the work piece just ahead of the forming roller contact zone as illustrated in figure 3. Thus the main benefits of laser-assisted metal spinning operations are:

- Improved formability of challenging materials such as titanium and nickel-based alloys
- Improved component quality due to temporally and locally limited heating
- Improved reproducibility compared to manual heating by means of gas burners
- Reduced forming forces

![Figure 3. Process principle of laser-assisted multi-pass spinning](image)

Former developments of laser integrations into spinning lathes, e.g. published in [8] or a provisional experimental set-up published by [9] facilitated to proof the general feasibility and the advantages of laser-assisted shear forming and multi-pass spinning operations but suffered several limitations. Especially with regard to multi-pass spinning limited flexibility and high programming efforts have been deficits. Thus a recently developed laser-integration into a spinning lathe published in [10] has been used for this work facilitating to realize laser-assisted multi-pass spinning operations without limitations. Scope of this publication is:

- To demonstrate the functionality of the newly developed laser integration by means of increased formability achieved on stainless steel, commercially pure titanium and a nickel-based alloy via laser-assisted metal spinning operations,
- To demonstrate the amount of force reduction achieved through laser heating during metal spinning operations and
- To discuss part quality achieved via laser-assisted forming in comparison with cold forming.

2. Experimental

The experimental set-up in a spinning lathe is shown in figure 4. For the investigations a high power diode laser with maximum output power of 5 kW has been used in combination with a 8 x 3 mm² focussing optic with homogenized laser intensity distribution. The experimental set-up included two two-colour-pyrometers for temperature measurement respectively control of laser power and a dynamometer mounted behind the forming roller in order to record forming forces in three directions.
For all investigations presented in this work, the initial sheet metal thickness was 2 mm. The rotational speed was between 250 and 300 min\(^{-1}\) and the feed rate varied between 50 and 300 mm min\(^{-1}\) depending on the material and forming operation. For the investigations on multi-pass spinning the same forming paths have been used for the forming operation and the feed rate has been adjusted in order to generate a suitable temperature field in the forming zone. Forming operations have been performed with controlled temperature on the work piece surface in front of the forming roller by means of a pyrometer closed-loop control of the laser output power.

3. Results

3.1. Material characterization prior to forming

Tensile tests were performed to characterize the material properties at room temperature (RT) and at elevated temperatures. The tensile tests were performed with flat specimens taken from the same 2 mm thick sheet metal blanks that were used for the forming tests. As a measure for the materials strength and toughness at the different forming temperatures the ultimate tensile strength (UTS) and fracture strain \(\Delta\) were evaluated according to DIN EN 6892-2. The results are summarized in table 1.

| Temperature range \[^\circ C\] | Ultimate tensile strength \[MPa\] | Fracture strain \[\%\] |
|-----------------------------|---------------------------------|---------------------|
|                             | Room temperature                | Elevated temperature|
| Ti grade 2                  | 430                             | 130…60              |
| Inconel 718                 | 890                             | 636…180             |
| X5CrNi18-10                 | 700                             | 360…150             |

As all three materials are common in metal production, detailed investigations on the evolution of the local microstructure and the corresponding material properties during forming operations can be found in literature, e.g. in [11] for Inconel 718.

3.2. Analysis of formability by laser-assisted shear forming

A first indicator for the formability of a blank material with the chosen process parameter set is the appearance of cracks in the final product. The processing of Inconel 718 and stainless steel have been possible in cold condition without crack formation. But compared to hot forming a clearly noticeable spring-back of the material occurred. Furthermore, the images in figure 5 show that in the case of Ti grade 2 forming at room temperature led to failure by circumferential cracking along the whole perimeter at a very early stage of the shear forming process.

Figure 4. Experimental set-up for laser-assisted multi-pass metal spinning

Figure 5. Left: Image of Ti grade 2 formed at room temperature with the shear forming setup. A large crack around the whole perimeter appeared at the early stage of deformation. Right: Application of laser heating enabled a successful forming operation.
By using a laser to heat the Ti blanks locally to temperatures between 450 °C and 600 °C in the forming zone the shear forming process could be successfully finished. Figure 6 shows images of Ti cones that were formed at 450 °C and 600 °C, respectively. Laser heating to 450 °C resulted in a successful completion of the forming process (figure 6 a), however the final product showed cracks on the inside of the cones (figure 6 b). Figure 6 c) shows a representative depth profile measured with a NanoFocus µsurf light-optical profilometer in the region of those cracks. The profile shows that the cracks were between 100 and 150 µm deep. Using the laser to heat the Ti blanks to 600 °C (figure 6 d) resulted in Ti cones without these cracks on the inside, as demonstrated by the images (figure 6 e) and the corresponding profile (figure 6 f).

Beneath surface integrity of the formed components process forces have been analysed to evaluate the forming process. For shear forming the radial forces are the highest.

**Figure 6.** a) Image of a Ti cone formed with laser heating to 450 °C; b) image of the cracks detected on the inside of the final part after forming at 450 °C; c) representative depth profile measured in the region of the cracks of the part shown in b); d) Image of a Ti cone formed with laser heating to 600 °C; e) image of the inside of the cone shown in d); f) representative depth profile measured on the inside of the part formed at 600 °C.

**Figure 7.** Mean radial forming forces for conventional and laser-assisted shear forming of titanium grade 2, Inconel 718 and stainless steel X5CrNi18-10
Thus in order to evaluate the laser-assisted process compared to cold forming, the mean radial forces during processing have been used as characteristic factor in this work. Figure 7 shows the mean radial forming forces for the investigated materials in dependence of forming temperature and feed rates.

As described above the cold shear forming of the used titanium grade 2 was not possible without failure within the investigated parameter range. Using a laser to heat the forming zone locally to temperatures between 450 °C and 600 °C the mean radial forces decreased nearly linearly in this range for the applied feed rates $v_f$ of 50, 100 and 200 mm min$^{-1}$. Comparing the values between 450 °C and 600 °C the mean radial force has been reduced by up to 27%. In order to achieve the defined temperature in the forming zone moderate laser power ($< 1.75$ kW) was required. With feed rates $v_f$ of 100 and 200 mm min$^{-1}$ small surface cracks occurred on the inside of the components which resulted most likely from non-sufficient heat transfer through the entire material thickness due to the low thermal conductivity of titanium. Thus feed rates below 100 mm min$^{-1}$ should be applied for the laser-assisted shear forming of Ti grade 2. Alternatively a bigger laser spot can be applied in order to increase the heated area.

For laser-assisted processing of the nickel-based alloy Inconel 718 the forming temperatures 900 and 1000 °C have been investigated. With a feed rate of 100 mm min$^{-1}$ and forming temperature of 1000 °C the mean radial force was reduced by 20% compared to the forming operation at room temperature. Applying the feed rates $v_f$ of 200 and 300 mm min$^{-1}$ a mean laser power of 4 to 4.5 kW was required for the forming operation but the maximum available laser power of 5 kW has not been sufficient to ensure a forming temperature of 900 respectively 1000 °C during the whole forming process. The slightly increasing trend of mean radial forces between the values for 900 and 1000 °C reflects this fact.

For the laser-assisted shear forming of stainless steel X5CrNi18-10 the mean radial force decreased most intensively with increasing forming temperature. At 800 °C the radial force reduced up to 40% compared to cold forming. For the feed rate $v_f$ of 100 mm min$^{-1}$ the radial force increased slightly between 600 and 800 °C which was most likely caused by thermal expansion of the tools due to the comparatively slow feed rate.

3.3. Laser-assisted multi-pass spinning

Figure 8 shows the laser-assisted multi-pass spinning operation of Inconel 718. At the beginning of the process the sheet metal blank has been pre-heated (a) in order to reduce thermal gradients in the work piece resulting in heat removal out of the forming zone. During the forming operation (b) the required forming temperature is generated in the forming zone directly in front of the forming roller. At the end of the process a flow forming step has been performed for achieving a homogenous wall thickness.

![Figure 8. Laser-assisted multi-pass spinning of Inconel 718: a) Pre-heating, b) intermediate forming step, c) flow forming operation](image)

During the forming operation the temperature has been kept constant by means of a pyrometer closed-loop-control. In the case of Inconel 718 it has not been possible to form the component at forming temperatures below 900 °C without failure (see figure 9, left). By using a controlled forming temperature of 900 and 1000 °C the cylindrical component with spinning ratio 2.0 could successfully be manufactured in one single clamping by laser-assisted multi-pass spinning (figure 9, right).
The manufacture of the defined spinning part made of Ti grade 2 was basically possible at room temperature but resulted in crack formation at the rim of the work piece and poor dimensional accuracy due to spring back. By laser-assisted hot forming between 400 and 600 °C the component could successfully be manufactured without any cracks and enhanced dimensional accuracy. For 600 °C forming temperature the deviation in roundness has been reduced by 77% compared with forming at room temperature. At the same time the surface roughness Ra was reduced from 0.8 µm to 0.4 µm.

Stainless steel X5CrNi18-10 could also be processed at room temperature but with very poor dimensional accuracy due to spring back. Compared to the cold formed component the forming forces could be reduced by 30%. Comparing the results of forming at room temperature and 700 °C the dimensional accuracy could be improved in terms of deviation in roundness by 43% and the surface roughness Ra was reduced from 0.5 µm to 0.2 µm.

Laser-assisted multi-pass spinning facilitated for all three materials to eliminate conventionally needed intermediate annealing operations in separate furnaces. Like that the manufacture in one single clamping becomes possible reducing the throughput times drastically. Additionally, parts with complex shapes can be formed without the negative impact caused by conventionally used gas burners for simultaneous heating of the work piece during manufacturing.

3.4. Mechanical properties after laser-assisted spinning

Vickers hardness measurements have been chosen as an indicator for the local material properties after the shear forming operations shown in section 3.2. Table 2 shows a comparison of hardness measurements performed after RT and laser assisted shear forming of stainless steel X5CrNi18-10, Ti grade 2 and Inconel 718 with 200 mm min⁻¹ feed rate. HV1 hardness measurements across the walls of the cones showed a uniform hardness across the walls within the measurement accuracy limit of ±1.5 HV1. All three materials showed a comparable reduction of the wall thickness that is typical for the shear forming process, as discussed in section 2 and reference [7].

For all three materials the position of the minimum wall thickness in the final part correlated with the position of the maximum hardness, as given in the 4th column in table 2. This indicates a correlation between the local degree of deformation and the local hardness, i.e. strain hardening. The relative hardness increase and the corresponding wall thickness reduction are indicated in the last two columns in table 2.
Influence of forming parameters on the local hardness after laser assisted shear forming

| Forming temperature | Initial blank hardness | Hardness at position of min. wall thickness | Hardness increase at min. wall thickness | Wall thickness reduction |
|---------------------|------------------------|--------------------------------------------|----------------------------------------|-------------------------|
| °C                  | HV1                    | HV1                                        | [%]                                    | [%]                     |
| X5CrNi18-10 25      | 160                    | 370                                        | 131                                    | 38                      |
|                    | 600                    | 300                                        | 88                                     | 44                      |
|                    | 800                    | 300                                        | 88                                     | 44                      |
| Ti Grade 2 25       | 144                    | -                                          | -                                      | -                       |
|                    | 450                    | 150                                        | 5                                      | 38                      |
|                    | 600                    | 180                                        | 25                                     | 45                      |
| Inconel 718 25      | 209                    | 440                                        | 111                                    | 38                      |
|                    | 900                    | 440                                        | 111                                    | 39                      |
|                    | 1000                   | 400                                        | 91                                     | 46                      |

For stainless steel X5CrNi18-10 the wall thickness reduction and the strain hardening were the same for 600 °C and 800 °C forming temperature despite the ongoing reduction of the forming forces indicated in figure 7. For Ti formed at 450 °C and 600 °C the measured higher hardness at 600 °C seems to be in contradiction with the reduced forming forces shown in figure 7. The low hardness measured on the cones formed at 450 °C can be explained by the micro-cracks detected on the Ti cones formed at 450 °C and shown in figure 6. The presence of the micro cracks reduces the local strength of the material and thus leads to the lower Vickers hardness. For Inconel 718 the higher forming temperature of 1000 °C resulted in a reduction of the maximum hardness and the forming forces but less reduction of the wall thickness indicating a reduced strain hardening at the higher forming temperature.

4. Summary and outlook

In this paper the effects of laser heating simultaneously to shear forming and multi-pass metal spinning on forming forces, formability and the preliminary investigations of the resulting material properties have been demonstrated for Ti grade 2, Inconel 718 and stainless steel X5CrNi18-10. For all three materials the formability could be enhanced significantly while improving the component quality at the same time. Laser-assisted multi-pass spinning facilitated to eliminate conventionally needed intermediate annealing operations in separate furnaces thus to manufacture complex geometries in one single clamping. Especially the successful manufacture of components with a high spinning ratio made of Inconel 718 is remarkable, because cold forming resulted in failure of the work piece at an early stage of the forming process. Like that the potential of the technology has been proven to reduce the throughput times drastically. Because the heat is applied only briefly to the area in which it is needed the thermal load of the work piece can be reduced to a minimum and controlled accurately by the use of a laser.

In order to benefit from the advantages of laser-assisted shear forming and multi-pass spinning operations in an industrial environment the main objectives for further developments are to develop a suitable machine tool and CAM-module. This will facilitate to make the new process available and manageable for industrial companies in order to process high-strength materials flexibly with increased reproducibility.

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