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Laser Forming of Titanium and Its Alloys – An Overview

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***Abstract*—**Laser beam forming is a novel technique developed for the joining of metallic components. In this study, an overview of the laser beam forming process, areas of application, the basic mechanisms of the laser beam forming process, some recent research studies and the need to focus more research effort on improving the laser-material interaction of laser beam forming of titanium and its alloys are presented.

***Keywords*—**Aerospace, Deformation, Laser forming, Mechanisms, Titanium, Titanium alloy.

I. Introduction

LASER Beam Forming (LBF) is a non-contact forming process and is based on the flame bending process which was traditionally used for ship construction. Laser Beam Forming can be regarded as a flexible manufacturing process with great potential for sheet metal forming. It is considered as a novel manufacturing method for forming and shaping of metallic components. It is a thermo-mechanically forming process that enables component parts (sheet metals, rods and pipes) to be formed without external forces and does not require the use of dies as found in most traditional forming methods [1-2]. The LBF process is achieved by irradiating the surface of the material with a defocused laser beam, thereby inducing rapid localized heating followed by cooling as the laser energy is either moved to the adjacent area or switched off. The process can be considered as a green technology as no fumes are evolved during the process. The schematic of the process is presented in Fig. 1. As a consequence of the thermal induced forming process, no spring back occurs in the material after the laser forming process [2].

The Laser Beam Forming (LBF) process has the potential to revolutionize rapid prototyping in the automotive and aerospace industries. Generally, these industries require expensive tooling (stamping dies and presses) in order to form parts from sheet metal to develop prototypes for testing and evaluation.

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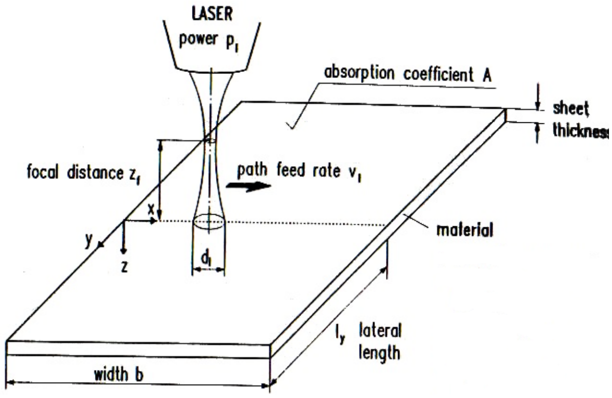

Fig. 1 Schematic of the Laser Beam Forming Process [3]

High power lasers have already been commonly used in production lines for welding, cutting, and surface treatments [4]. Using a laser to bend sheet metal is a novel and innovative process which has created a lot of interest and was first proposed in 1981 [5-6].

Three major process variables that are significant during the LBF process are the material parameters [7] which include; the coefficient of thermal expansion, the thermal conductivity, the material density, latent heat, the mechanical elastic and plastic parameters (Young’s modulus, Poisson’s ratio, flow-stress vs. strain curves) and the rate of laser absorption. The parameters of the laser and this include; the laser power, the beam diameter, the feed rate and the beam wavelength which depend on the type of laser in use. And lastly the geometric parameters of the sample being formed which include the sheet thickness and width.

The major advantage of the LBF process over flame bending is controllability. With LF, it is possible to accurately control the power and geometry of the heat source [4,8]. LBF process also offers many of the advantages of process flexibility and automation associated with other manufacturing techniques, such as laser cutting, drilling, welding and marking. The major benefit of LF, from a metal forming perspective, is that springback is completely eliminated [9-10].

Materials such as steels and other light alloys such as Aluminium, Magnesium and Titanium have a high coefficient of thermal expansion. These materials significantly deform when heated with the laser beam. The temperature gradient developed during the process compels the material to expand non-uniformly, which in turn leads to non-uniform thermal stresses. Plastic deformation results when the thermal stresses exceed the yield point of the material [11-14]. The laser beam forming process has been investigated in applications that involved many materials such as mild steel [Akinlabi -15-17], stainless steels [18], aluminium and its alloys [19], fibre metal laminates [20]. Materials commonly formed are steel and aluminium. Akinlabi *et al* [15] conducted a research study on the effect of laser beam forming on the evolving microstructure and mechanical properties of AISI 1008 Steel and found that the resulting mechanical properties of the formed components were characterized and the potential of the process for manufacturing industries was studied. The results showed that 120 mm curvature of 4 mm mild steel plate were successfully formed at 0.9 m/min scan velocity, 1.7 kW power and a beam diameter of 12 mm. Furthermore, the results revealed that the grain structure of the irradiated surface was refined, which consequently strengthened the material after the forming process. The yield strength and the Vickers hardness of the formed component were higher compared to the parent material. The increase is attributed to strain hardening and grain refinement. The microstructural evaluation effectively validated the mechanical properties of the formed components which showed that the LBF is a potential forming process. Also, the effects of the laser forming process on the mechanical and metallurgical properties of low carbon steel and aluminium alloy samples were studied by Knupfer and Moore [3]. The formed components were characterized through microstructure, microhardness and tensile testing. They concluded that the laser formed low carbon steel AISI1010 generally produced a decrease in the strains while the formed 2020-T3 aluminium alloy produced a decrease in the ultimate tensile strength compared to the parent materials. The various regions within the heat affected zone were identified from the hardness distributions and correlated to the peak temperature reached at the corresponding depths in the laser formed components. Generally, it can be concluded that the enhancement in the properties of the materials resulting from the laser beam forming process compared to the traditional forming process and the overwhelming advantages has positioned LBF as a potential manufacturing process; however few research studies have been conducted on the LBF of Titanium and its alloys.

The content of this paper is organized as follows: the mechanisms of the Laser Beam Forming process is presented in Section II. Typical applications and prospects of the LBF process of various materials and especially titanium and its alloys is discussed in Section III, current research work and future research focus in the field of LBF of titanium and its alloys are presented in Section IV and V respectively. Finally, the concluding remarks are presented in Section VI.

II. The Mechanisms of the Laser Beam Forming Process

The laser beam forming process is achieved by introducing thermal stresses into the surface of a workpiece with a high power laser beam. These internal stresses induce plastic strains that result in local elastic/plastic buckling [17]. The process is principally used at the macro level to form metallic sheet material. The principle behind the process of forming sheet material uses a laser beam that is guided across the sheet surface. The path of the laser is dependent on the desired forming result. In the simplest case, it may be a point and in another case it may be a straight line, rotating and wavering beam across the whole part. The degree of deformation is often dependent on the forming mechanisms being employed. During the laser beam forming process, photons travel to form a beam of light. The beam, which may not be visible, comes out from the laser cavity and is directed towards the material process station. Based on the laser wavelength, the beam travels either via optical fibers or directly through optics to the workpiece. There are five (5) different types of mechanisms identified in LBF process and are hereby discussed.

A. The Temperature Gradient Mechanism (TGM)

This mechanism is widely reported in the literature [21-25] and can be used to form sheet material out of plane towards the source of the laser beam. The temperature gradient mechanism develops from processing conditions, one of which is rapid heating of the workpiece surface in order to generate high temperature gradients in the workpiece. The thermal expansion of the heated surface brings about the initial bending of the sheet away from the heat source or towards the cold side of the workpiece during the heating process. The bend angle at this stage is very small (about 0.05^o); this is often regarded as counter bending. It is approximately the size of the beam diameter or even less, this small beam size has to generate enough forces to produce the counter bending. The counter bending phenomena is also regarded as been detrimental for the development of a plastic bending angle towards the laser beam. This is because the phenomenon is similar to relaxation of the surface stresses at the heated surface. As such, the thermal expansion leads to reduced surface stresses and therefore the fraction of the thermal strain which is converted into plastic strain is less without counter bending.

B. The Buckling Mechanisms (BM)

The buckling mechanism occurs in relatively thin sheets where the ratio of the beam diameter of the heated area to the sheet thickness is relatively high that is, it could be in the order of 10 or above. This is when the laser beam diameter is large compared to the sheet thickness and the processing speed is low resulting in a small temperature gradient across the sheet thickness. The buckling mechanism operations can be summarized as follows: heating of large area of the sheet metal to develop compressive stresses, onset buckling takes place, there is a growth of the buckle, the buckle shifts throughout the whole sheet material and lastly the elastic stresses are relaxed; thereby resulting in the sheet forming.

C. The Point Mechanism

The point mechanism is the dividing line between the two previously discussed mechanisms, that is, the TGM and BM. The point source mechanism creates a heated zone in the shape of a spot rather than a line. Using short pulses of the laser to introduce a thermal gradient, yet the mechanism remains a point source since the beam is stationary when heating the component. Longer pulses enables heating through thicker materials, and may be mistaken for another type of mechanism for instance buckling, however the beam and workpiece are also stationary when in contact. Micro components may be formed with the Point source Mechanism.

D. The Upsetting Mechanism

The upsetting mechanism develops when uniform heating of a localized zone is achieved through the thickness of the sheet metal. The process parameters may be similar to the buckling mechanism, except that the diameter of the heat source is the same as the plate thickness or larger than it. As a result of the near homogenous heating of the sheet in the localized zone, and prevention of thermal expansion by the surrounding material, the sheet is subjected to near uniform compressive strain through the thickness of the material. At cooling, the region contracts, and deformation occurs in the sheet. This mechanism finds applications in spatial sheet metal forming and profile forming [26].

E. Coupling Mechanism

According to Shi et al. [19], Coupling Mechanism (CM) is the combination of the Temperature Gradient mechanism (TGM) and Upsetting Mechanism (UM). The process parameter for the CM lies between that of TGM and UM. From a TGM analysis, the plastic compressive deformation does not occur at the bottom surface and for UM, plastic compressive deformation at the top surface of the materials is nearly same as the plastic compressive deformation at the bottom surface of the material. On the other hand with Coupling Mechanism, plastic deformation occurs at both the top and the bottom surface of the material but greater at the top surface.

III. Typical Applications and Prospects

The Laser Beam Forming (LBF) process has become viable for the shaping of metallic components. It is of significant value to industries which previously relied on expensive stamping dies and presses for prototyping evaluations. As a result of the flexibility of the process, laser beam forming can be used for numerous industrial applications ranging from both 2D and 3D forming of complete serviceable parts, to distortion removal and rapid prototyping and adjusting and aligning. Some of the relevant industry sectors include aerospace, automotive, shipbuilding, and microelectronic [27]. Titanium alloys are specialist high-strength materials which are widely used in the aerospace industry. Titanium and its alloys have highly desirable properties which make them suitable for aerospace applications LBF can offer an affordable and flexible rapid prototyping method for the automotive and aerospace industries [27]. The prospect of the LBF processing in general could also find application in areas such as flight vehicles, automobiles, boats, pipelines, building, roads, and bridges.

IV. Current Research Work

Recent research attempts conducted on laser beam forming of titanium and its alloys are reviewed in this section. First of such attempts is the research work conducted by Walczyk and Vittal [7] titled '*bending of titanium sheet using sheet forming*', the bend geometry and the resulting material microstructure were studied; they concluded that laser forming is best suited for rapid prototyping of titanium sheet parts especially for the aerospace industries. An analytical model for the optimization of laser bending of titanium alloy Ti6Al-2Sn-4Zr-2Mo was conducted by Marya and Edwards [4], the beam power and the beam diameter were varied and their models demonstrated that the laser forming process can be described by the heat flow during the process. A number of other research studies conducted on laser forming of titanium and its alloys also exist [28-30]. However, there are still more to be done in terms of research in this field of study to improve the understanding of laser-material interaction of titanium and its alloys in order to achieve the commercialization of the process.

V. Future Research Focus

The Laser Beam Forming process is a relatively new metal forming technology. There is an inadequate of numerical and experimental investigation and knowledge of the LBF process for Titanium and its alloys in general especially with respect to forming the widely used aerospace Titanium alloys such as Ti-6Al-4V. The underlying parameters for laser-material interaction of Titanium and its alloys need to be researched and properly defined to encourage its commercialization.

VI. Conclusion

Laser beam forming alternatively is a flexible manufacturing process that forms metal sheets by means of thermal stresses induced by external heat instead of external force common in mechanical forming process. Empirical evidences from the reviewed literature suggests laser beam forming as a viable process for the production of sheet metal prototypes, springback free and non-contact process. Furthermore, the process has demonstrated potential uses in many different engineering applications. An overview of the Laser Beam Forming process has been presented in this study as it is been applied in the industry, with special attention to the LBF of titanium and its alloys.

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