Recent Investigations on Shot Peen Forming of GLARE Sheets and Rotary Peen Forming

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Abstract

To meet the demands of the industry like weight optimization and cost reduction new materials have been formed with the traditional Shot Peen Forming (SPF) and new peen forming processes have been developed. In this paper, SPF of sandwich sheets is investigated and the recent developments in Rotary Peen Forming (RPF) are presented. The need of lightweight structures in aeronautic engineering leads to the demand to form extensive structural parts made of new material combinations like GLARE. Usually, GLARE parts are formed using the self-forming technique. This process offers a good formability of sandwich material combinations of aluminum and glass fiber epoxy. Nevertheless, the process is very cost intensive due to the high amount of manual labor. This led to the idea to form flat stock GLARE sheets with conventional Shot Peen Forming. The results of the Shot Peen Forming of single and doubly curved GLARE sheets are presented in this paper. Furthermore, the Rotary Peen Forming process has been developed as a new peen forming process in which the shot is moved on a circular trajectory held by a flexible connection. RPF has the main advantage compared to traditional Shot Peen Forming processes that it does not need recirculation of shot particles. Hence, RPF offers a compact machine design enabling a flexible and adaptable handling. The RPF process causes localized plastic deformation just as in traditional SPF but involves tangential components which can create shear deformation in the plastic layer. Compared to traditional SPF, RPF shows different process characteristics in terms of coverage and the shape of indentations created on the surface of the workpiece. To improve the forming potential and the flexibility of the process, more degrees of freedom for the tool movement are necessary. In this paper, a new test setup using a robot is presented.

Keywords

Incremental sheet forming, Shot peen forming, New processes, Sandwich material

Introduction

Glass Laminate Aluminum Reinforced Epoxy or Glass-fiber reinforced aluminum (GLARE) is a laminate material with a combination of aluminum sheets and layers of glass fiber that are bonded using epoxy. Roebroeks [1] explains that the setup of GLARE, i.e. the number, type and orientation of the layers can be tailored to meet the specific requirements of the aeronautic industry. Besides having a lower specific weight than aluminum, GLARE also has superior properties compared to conventional aluminum with respect to tensile strength, fatigue resistance, damage tolerance, corrosion and fire resistance as well as residual and blunt notch strength. A drawback of GLARE is the expensive and time-consuming manufacturing process of complex parts. The standard manufacturing process for GLARE parts is the so-called self-forming technique (SFT), where aluminum sheets and glass fiber reinforced prepreg layers are adhesively joined to their final shape. The SFT is a very costly and labor-intensive manufacturing process, but until now it is the only practical way to form GLARE. A more economical approach to form GLARE parts would be to form flat stock material. This could mean a substantial cost reduction due to an automated production of flat stock GLARE without the need of manual operation. Different attempts to form Fiber Metal Laminates like GLARE are reported in the literature. Most of the investigated processes to form GLARE have process-related or economical disadvantages. This paper gives an overview of the investigations using SPF to form GLARE flat stock material. Usually, SPF requires large and

extensive equipment to accelerate, collect and sieve the shot particles. This leads to high investment costs as well as additional maintenance and energy costs. As detailed in [2], RPF is an evolution of the Flap Peening Process [3], which uses elastic flaps with embedded shot to peen part surfaces. As in Flap Peening, the basic idea of RPF is to move an impactor on a circular trajectory instead of using loose steel balls as in traditional SPF. Therefore, RPF promises to be a simple and cost-effective alternative to SPF because it does not require expensive additional equipment.
In this paper, an overview of the results of the RPF research project is given. Different tool concepts are tested concerning their forming capabilities and resulting sample surface qualities. The results of the experiments are briefly displayed and discussed.

Experimental Methods: Shot Peen Forming of GLARE
The sandwich material GLARE was developed at the University of Delft in the late 1980s. Vermeeren [4] gave an overview of its development. GLARE is manufactured in different grades which can be distinguished by the used aluminum cover- and intermediate layers, the sheet thickness, the number of layers and the different fiber orientations. The three GLARE types this paper focusses on are GLARE-1 3/2 .4, GLARE-2 3/2 .4 and GLARE-3 5/4 .4 since these grades represent a selection of typical GLARE grades with different aluminum cover sheets, numbers of layers and preimpregnated fibres (prepreg) orientations. The fractional numbers give the ratio of aluminum layers to fibre layers while the ending indicates the aluminum layer thickness (e.g. .4). An overview of all GLARE grades used in this work is given in Table 1.

Table 1: Overview of used GLARE grades [5]

GLARE grade	Sub grade	Metal sheet thickness	Alloy & Temper	# of prepreg layers	Prepreg orientation[a]	Main characteristics
GLARE-1	-	0.4 mm	AA7475-T761	2	0°/0°	fatigue, strength, yield stress
GLARE-2	2A	0.4 mm	AA2024-T3	2	0°/0°	fatigue, strength
GLARE-3	-	0.4 mm	AA2024-T3	4	0°/90°/0°/90°	fatigue, impact
[a]: Rolling direction of the aluminum sheets is defined as 0°, transverse rolling direction is defined as 90°						

Since SPF is a process in which the global curvature is created by the impact of shots, it is essential to study the behavior of GLARE when indented by hard steel balls to understand the deformation mechanics and forming limits of GLARE. To investigate the influence of the layer configuration on the indentation characteristics and the deformation occurring in the intermediate layer, quasi-static ball indentation tests were carried out. Ball indentation tests are well understood from a theoretical point of view and there are analytical solutions available that form the basis for the Brinell hardness test. In this work, quasi-static indentation tests are used to analyze the indentation behavior of GLARE in terms of the macroscopic characteristics of force vs. indentation depth, the deformation modes sink-in and pile-up, the anisotropy and the deformation of the individual layers. To investigate the dynamic effects that occur in SPF, single shot impacts are analyzed, where a single shot particle with a defined kinetic energy is shot onto the surface of the sample. In this way the available forming energy can be determined approximately by comparing the impact and rebound velocity or energy. These tests are followed by practical SPF tests to identify the forming capabilities of GLARE and the forming of a doubly curved 3D-structure. The practical shot peen tests are accompanied by the Lock-In Thermography [6] to detect delamination and other defects. Thus, it is possible to define a process window, in which the samples can be formed either convex or concave with high efficiency and without detectable damages.

Experimental Results: Shot Peen Forming of GLARE

The quasi-static indentation tests show that the indentation profile in prepared cuts perpendicular to the fiber orientation is not parallel to the fiber orientation. The direction of the glass fibers evokes this anisotropic behavior. Perpendicular to the fiber direction, a pile-up is observed while the longitudinal section shows a sink-in. The reason for this behavior seems to be that the fibers are pushed aside when the ball penetrates the specimen so that a higher density of fibers is obtained laterally, perpendicular to the fiber direction which causes a pile-up of the aluminum cover sheet. GLARE 1 and 2 show a strong anisotropic behavior due to the unidirectional fiber orientation. As expected, GLARE 3 with its bidirectional fiber orientation shows less anisotropy. The dynamic indentation test gives a hint for the optimal shot peening parameters. The test shows that GLARE with less layers like GLARE 1 and 2 can be formed more efficiently with smaller shot diameters. In contrast, the 5/4 layer GLARE 3 offers a better impact to forming energy ratio for larger shot diameter. Subsequently, real shot peening tests are conducted to establish a process window for the Shot Peen Forming of GLARE material. These tests are accompanied by material damage examination by Lock-In Thermography, which has been proven to be a feasible detection method. Only test samples that are peened with low pressure and solidity show no signs of damage. Also solidity ratios under 75% lead to only low curvatures. Peening pressures of less than 0.1 N/mm² result in insignificantly small curvatures. For peening pressures of more than 0.2 N/mm² delamination can be observed independent of the shot diameter. The defects can partially be detected visually if they lead to bulging of the cover sheet (cf. Figure 1)

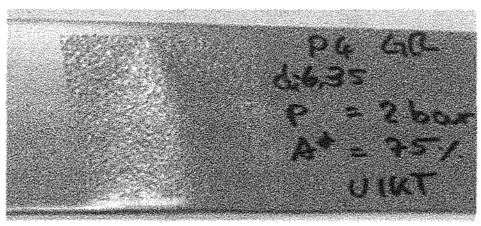

Figure 1: Delamination of a test sample, ball diameter d_B of 6.35 mm, 0.2 N/mm² peening pressure p, 75% solidity ratio A*

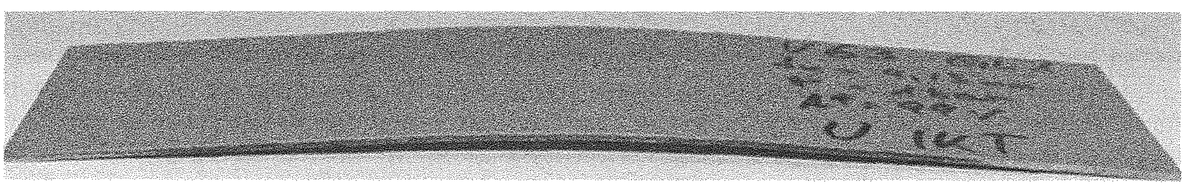

Figure 2: GLARE 1 sample with maximal curvature ($1/r_C$=3.72/m and r_C=2690 mm), peening parameters: d_B=4.13 mm, p=0.1 N/mm², A*=99%

The best results could be achieved with smaller shot diameters, higher solidity ratios and lower peening pressure. A successfully formed part with no detectable material damage is shown in Figure 2.

With these results a process window could be established for each GLARE grade and shot diameter. Based on these findings, shot peening tests of GLARE were conducted with the main goal to form doubly curved structures without any detectable damage. Assuming minimal curvature radii of 2500 mm (curvature ≥ 4.1/m) for a typical structural part used in the Airbus A380, it can be concluded that Shot Peen Forming is applicable to produce such a structure from GLARE material. Curvature radii down to 1000 mm can be obtained without any detectable damages using SPF.

Experimental Methods: Rotary Peen Forming

Three different tool concepts (see Figure 3) were developed and tested with a setup consisting of a cross table and a turret, which holds the forming tool. The cross table can be moved in x- and y-direction holding the test sample. The clearance between workpiece and impactor can be manually adjusted using a rotating spindle. In addition, a pneumatically operated cylinder can lower the tool holder by about 40 mm. Thus, the tool can be lowered or lifted to the preset distance from the workpiece. In this way, the intrusion depth, i.e. the distance of the workpiece surface to the circumference of the rotating impactor, can be adjusted before the actual test. Thereafter, the tool is lifted again. Once the test is running, the tool may be remotely lowered and lifted.

a) Pivot mounted bar tool b) Wire based tool c) Spring steel strip based tool

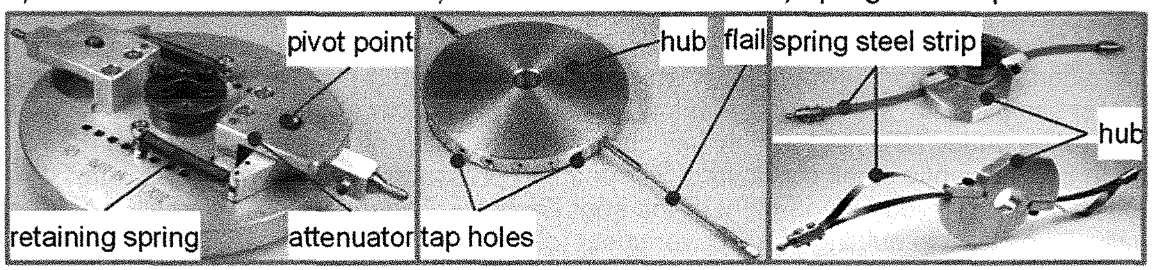

Figure 3: Three different RPF tool concepts

The sample is safely fixed on the cross table. A plastic mat is installed between cross table, workpiece and the clamp to absorb vibrations. In this way, the workpiece is fixed properly but still has a certain degree of freedom to assume convex or concave deformed shapes. The wire based tool is the only one that can be equipped with more than two impactors because of its tap holes being arranged on the lateral surface of the hub. As a workpiece material aluminum alloy EN AW-5083 (AlMg4.5Mn0.7) has been chosen.

Experimental Results: Rotary Peen Forming

The surface quality obtained by the wire and spring steel connector tool concept is acceptable and only slightly below shot peening level. The possibility of forming concave curvatures with the pivot mounted bar tool (cf. Figure 5) is detrimental to the surface quality. This tool concept causes severe material accumulations orthogonal to the impact groove which leads to an extremely rough surface. Additionally, cracks orthogonal to the tool movement direction can occur (cf. Figure 4). Concave curves can only be achieved using the pivot mounted bar tool (cf. Figure 5).

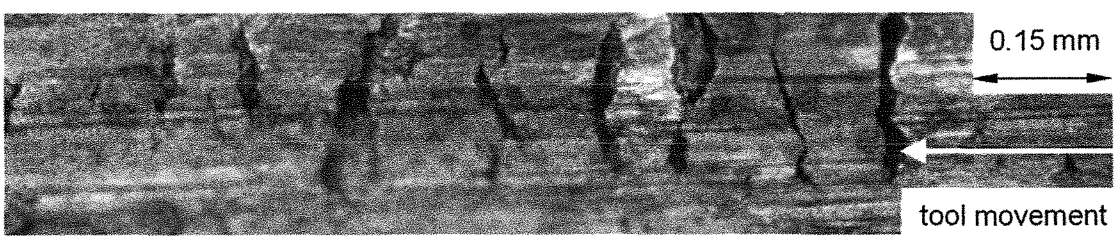

Figure 4: Surface cracks of a sample formed with the pivot mounted bar tool concept

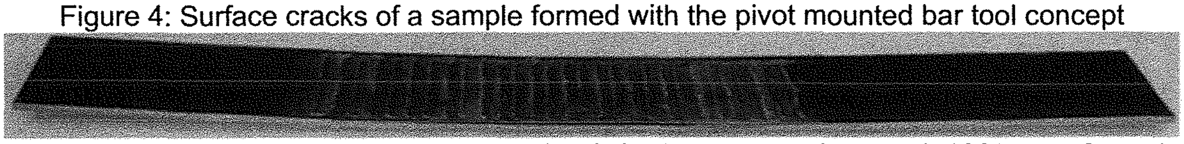

Figure 5: Sample with a concave curvature (0.6/m), pivot mounted bar tool, 1000 rpm, 2 mm intrusion depth, 1.356 N/mm spring stiffness

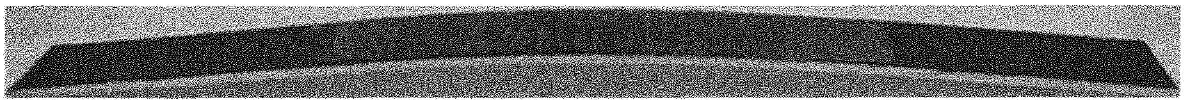

Figure 6: Sample with a convex curvature (1.22/m), wire based tool, 1200 rpm, 1 mm intrusion depth

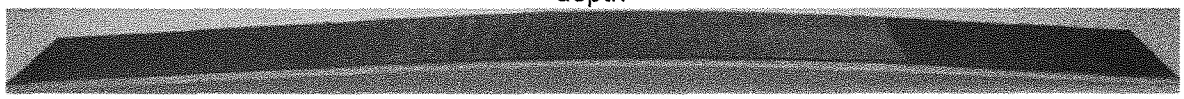

Figure 7: Sample with a convex curvature (1.27/m), spring steel connector tool, 1000 rpm, 1 mm intrusion depth, 0.8 mm strip thickness

Figure 6 and Figure 7 show that good forming results in terms of the achievable convex curvature can be realized by using the wire and spring based tool concepts. So far, the wire- and spring steel connector concepts lead to convex curvatures of about 40 % lower compared to the shot peened reference samples. In order to handle the above presented RPF tool concepts with a maximum number of degrees of freedom, a robot has been installed to move the tools. To meet safety requirements, the setup has been cased preventing the operator and surroundings to be harmed in case of unconnected tool pieces flying around.

Figure 8a shows the new setup for Rotary Peen Forming at the Institute of Metal Forming, RWTH Aachen University, Germany. To perform further experiments, several essential constructions have been manufactured, e.g. a flange to mount the rotation motor to the robot (cf. Figure 8b) as well as a bracket fixing the samples properly. A built-in clutch attenuates the flaps and simultaneously bridges a shaft offset.

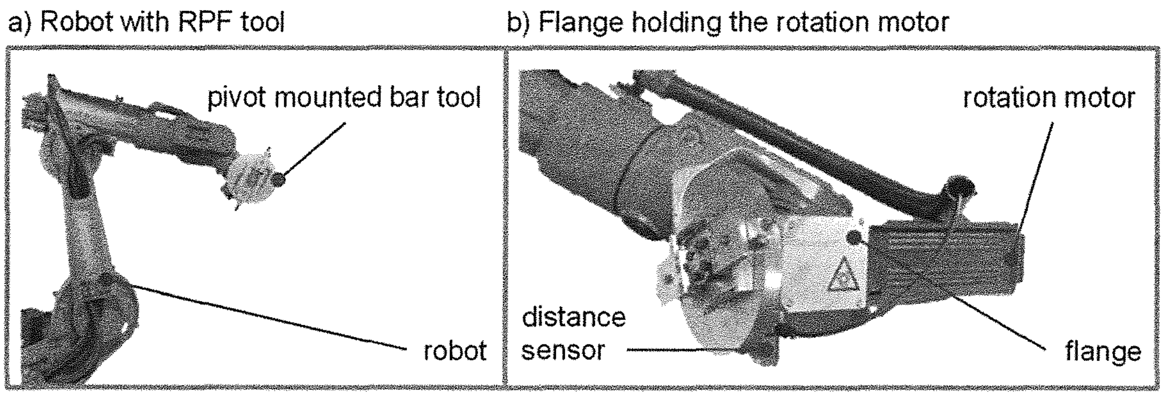

Figure 8: a) New RPF setup, b) flange to mount the rotation motor

Using the robot control system, the RPF tools can be moved easily on prescribed paths. Thus, new path strategies can be examined more flexibly to form samples compared to the old setup. Furthermore, a software tool will be implemented soon adjusting the distance from the tooltips perpendicular to the samples with the assistance of a sensor.

Discussion and Conclusions

The conducted tests depict that the sandwich material GLARE shows a strong anisotropic behavior due to the fiber orientation. Especially, GLARE with unidirectional orientated fibers shows high anisotropy. Generally, the indentation behavior of GLARE differs significantly from the behavior of monolithic metal sheets. The forming behavior of the various GLARE grades diverges especially due to the aluminum cover sheets. GLARE with less layers, like GLARE 1 and 2, can be formed more efficiently with smaller shot diameters. In contrast, the 5/4 layer GLARE 3 offers a better impact to forming energy ratio for larger shot diameter.

Generally, GLARE can be formed predominantly to convex geometries using SPF. Only GLARE 2 can be peen formed such that slight concave curvatures are obtained under certain process

conditions. Nevertheless, only a small process window is available to shot peen shapes without damaging the material. The best forming results could be achieved using smaller shot diameter, less peening pressure and a higher solidity ratio.
It could be shown that flat stock GLARE material can be formed using SPF even with doubly curved geometries. For GLARE 3, radii down to 1000 mm can be realized without detectable damage, which is sufficient to form fuselage components, e.g. for the A380 airplane.
The experimental results of the RPF show that shaping with shots following a circular trajectory is feasible. Generally, it has to be stated that the curvature obtained by RPF is less than using SPF. The constructed tool concepts show fundamental differences in terms of curvature. The wire and spring steel based tool concepts lead to convex curvatures depending on the adjusted angular velocity and intrusion depth. Concave curvatures can be achieved by using the pivot mounted bar tool. The difference between the applied curvature bases on the diverging kinetic energy. Obviously, the wire and spring steel based tool concepts apply similar energies. The kinematics and the wear resistance of these tool concepts only allow less inducible energies. The residual stress caused by the pivot mounted bar tool is dissimilar compared to the other tool concepts. Furthermore, this tool concepts leads to severe material accumulations orthogonal to the impact path ending up in a rough surface quality.
First tests using the robot to move the RPF tools on prescribed paths provide promising results. Prospectively, it will be examined how different paths go together with the presented tool concepts and their impact on curvature and surface quality. Besides, it has to be investigated what kind of parameters have to be adjusted in order to achieve reproducible shapes.

Acknowledgments
The authors from the Institute of Metal Forming of RWTH Aachen gratefully would like to acknowledge the funding obtained from the Deutsche Forschungsgemeinschaft (DFG) within the projects HI 790/19-2 and HI 790/25-1.

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