AMTC, Seattle, September 2001 (Society of Automotive Engineers, Paper Number 2001-01-2610

2001-01-2610

Laser Forming of Aerospace Alloys

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ABSTRACT

Non-contact forming by application of a thermal source has been known for some time. Recently, it has been shown that much greater controllability can be introduced by replacing the thermal source with a laser. This yields a process with strong potential for application in aerospace, including the rapid manufacture of prototypes and the adjustment of misaligned components.

This paper briefly reviews the mechanisms involved in laser forming and then summarises experimental work carried out on aluminium alloys and titanium alloys that led to the development of a prototype system for the forming of 2-D sheet materials. Emphasis is placed on the process advantages, including the high accuracy (arising from the progressive nature of the process) that can be achieved in forming or adjustment of misalignment. Future work in a new collaborative programme to develop 3-D laser forming is summarised.

INTRODUCTION

Laser forming has become a viable process for the shaping of metallic components, as a means of rapid prototyping and of adjusting and aligning. The laser forming process is of significant value to industries that previously relied on expensive stamping dies and presses for prototype evaluations. Relevant industry sectors include aerospace, automotive, and microelectronics. In contrast with conventional forming techniques this method requires no mechanical contact and hence offers many of the advantages of process flexibility associated with other laser manufacturing techniques such as laser cutting and marking[1]. Laser forming can produce metallic, predetermined shapes with minimal distortion. The process is similar to the well established torch flame bending used on large sheet material in the ship building industry but a great deal more control of the final product can be achieved[2]. The laser forming process is realised by introducing thermal stresses into the surface of a work piece. These internal stresses induce plastic strains, bending or shortening the material, or result in a local elastic plastic buckling of the work piece depending on the mechanism active[3]. The principle of the process is that the laser beam 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, in other cases it may be a straight line across the whole part and, for spatially formed parts and extrusions the paths would be very sophisticated radial and tangential lines.

The range of metals that can be laser formed is considerable. As there is only localised heating involved below the melting temperature the bulk properties are not altered and good metallurgical properties are retained in the irradiated area[4]. Materials of particular interest are specialist high strength alloys[5]. These include titanium and aluminium alloys. These materials are widely used in the aerospace industry where the implementation of laser bending as a replacement for existing manufacturing processes is under investigation[6] as well as other industry areas[7].

LASER FORMING MECHANISMS

There are three main mechanisms for the laser forming of sheet, tubes and extrusions (fig. 1). The active mechanism is dependent upon the processing parameters used:

TEMPERATURE GRADIENT MECHANISM (TGM) – This mechanism is the most widely reported, and can be used to bend sheet material out of plane towards the laser. The conditions for the temperature gradient mechanism are energy parameters that lead to a steep temperature gradient across the sheet thickness (fig. 1). This results in a differential thermal expansion through the thickness. The beam diameter is typically of the same order as the sheet thickness, or slightly less. The path feed rate has to be chosen to be large enough that a steep temperature gradient can be maintained. The feed rate/temperature gradient has to be increased if materials are used which have a high thermal conductivity. The laser path on the sheet surface is typically a straight line across the whole sheet. This straight line coincides with the bending edge.

Initially the sheet bends in the direction away from the laser. This is called counter bending. With continued heating the bending moment of the sheet opposes the counter bending and the mechanical properties of the material are reduced. Once the thermal stress reaches the temperature dependent yield stress any further thermal expansion is converted into plastic compression. During cooling the material contracts again in the upper layers, and because it has been compressed, there is a local shortening of the upper layers of the sheet and the sheet bends towards the laser beam. The yield stress and Young's modulus return to a much higher level during this cooling phase and little plastic re-straining occurs. Bends of approximately one degree per pass are achieved with this mechanism. [8]

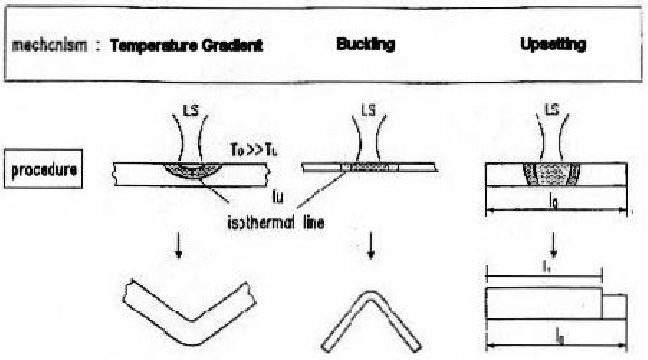

Fig. 1: Illustration of the three main laser forming mechanisms[3]

BUCKLING AND UPSETTING MECHANISMS – Both of these mechanisms are activated by the use of laser parameters that do not yield a temperature gradient in the depth of the material (fig 1). For the case of the buckling mechanism a beam diameter much larger than the sheet thickness and a slow traverse speed is used. This results in a large amount of thermoelastic strain that in turn results in a local thermoelastic-plastic buckling of the material. The buckle is traversed along the length of the sample and once the buckle reaches the exiting edge of the sheet the elastic strain dissipates and the remaining plastic strain causes a deflection. This mechanism can be used for out of plane bending of sheet material, it may be accompanied by some in plane shrinkage as well. The part can be made to bend in either the positive or negative directions. The direction depends on a number factors including the pre-bending orientation of the sheet, pre-existing residual stresses and the direction in which any other elastic stresses are applied, (for example a forced air stream acting on the bottom of the sheet.) The buckling mechanism results typically in bending angles between 1 and 15 degrees. This is significantly larger than observed for the temperature gradient mechanism. This is not a result of a higher degree of performance but a result of the fact that using the buckling mechanism more energy can be coupled into the workpiece in one step.

For the upsetting mechanism the geometry of a workpiece would prevent buckling due to the increased moment of inertia compared to sheet material. This mechanism is used to shorten or upset a workpiece in plane, it may be used in different ways for a wide range of forming results such as the bending of extrusions and tubes. By the careful selection of the sequence of the sides of the geometry heated, a section can be made to step out of plane. The mechanism can also be used for the shortening of small frames. This is useful for aligning operations in micro parts production.

The mechanisms of laser forming can accompany each other to some extent because there is a transition region of processing parameters and geometries where a switch from one mechanism to another takes place. Additionally there is usually a coupling between in plane and out of plane deformation in forming operations. [8]

EXPERIMENTAL

The experimental work summarised in this paper consists of empirical work carried out on AA 2024 T3 aluminium alloy and Ti6Al4V titanium alloy. Parametric investigations were carried out by J. Magee [8] into the single and multi-pass, large and small beam diameter 2D laser forming of these materials, which led to the development of a 2D laser forming demonstrator system for a part cylinder shape. Development of scan strategies for the 3D laser forming of dish shapes was also carried out. This work was part of a joint research programme between the University of Liverpool and BAE Systems.

As part of a collaboration between a number of UK universities including the University of Liverpool and BAE Systems and Rolls-Royce an ongoing investigation into the further development of 3D laser forming of aerospace alloys is also summarised.

PARAMETRIC STUDY – This work investigated the factors influencing the angular dimensions of laser formed 80x80mm 0.8-1mm gauge plates of Ti6Al4V and AA 2024 T3, commonly used aerospace alloys. The plates were clamped at one end, graphite coated and irradiated with a PRC 10.6μm CO_2 laser. Altering the power density and the interaction time of the laser beam incident on the samples varied the energy input to the plate surface.

The experimental results revealed that the bend angle development is critically dependent on the energy supplied to the plate surface. Two distinct studies were carried out (using a large and small beam diameter) on two materials (a titanium and aluminium alloy), with different thermal and mechanical properties. In the case of the titanium alloy it was found that the temperature gradient mechanism was active for both studies, both for the large and small laser beam diameter to sheet thickness ratios. This was attributed to the low thermal conductivity of the titanium alloy. An optimum traverse velocity in terms of maximising the bend angle achieved per scan was identified for this material when the beam diameter was in the order of 12 times the sheet thickness (fig 2).

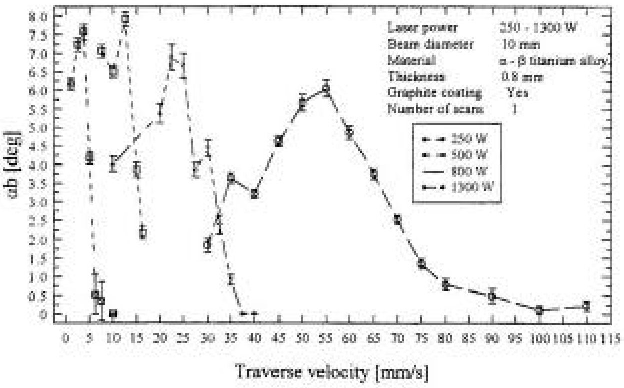

Fig. 2: Bend angle with increasing traverse velocity for Ti6Al4V using a large beam diameter [8]

Below the optimum velocity the bend angle dropped due to the loss of a high temperature gradient and hence a smaller amount of differential straining through the thickness direction. These results support the idea that the temperature gradient, and the efficiency of the process, increase as the processing speed increases. This efficiency increase is offset by a reduction in the bend angle after the optimum point. This is because the increasing velocity results in less coupled energy, less thermal expansion, and a smaller reduction of the flow stress in the heated zone. Since all of these factors contribute to overcoming the elastic share of the bending, the bend angle begins to drop off again.

For the aluminium alloy it was found that for one laser scan using a large beam diameter the bend angle is decreasing with increasing traverse velocity (fig 3), this is in contrast with the titanium alloy where a peak occurs. Since the thermal conductivity of the aluminium alloy is high, the temperature gradient in the depth direction of samples was small for the lower traverse speeds. Under these conditions the buckling mechanism (BM) was thought to be active. In the higher velocity range, for the small beam diameter to sheet thickness ratio the TGM was active, the bend angle continued to drop sharply. This is attributed as before to the reduction in coupled energy and the elastic effects becoming more pronounced.

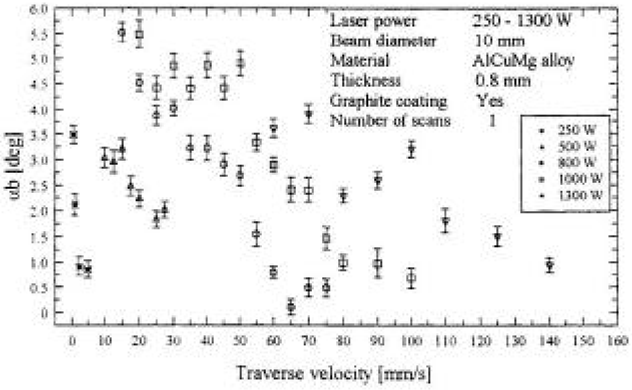

Fig. 3: Bend angle with increasing traverse velocity for AA 2024 T3 [8]

The experimental results were compared with calculations from the existing two-layer model for the TGM[3]. There were considerable differences in the results obtained compared with the empirical data, these differences were attributed to no account being taken of the strength of the material, the elastic counter bending and the determination of the temperature field.

The decrease in bend angle with number of scans was also investigated (fig 4).

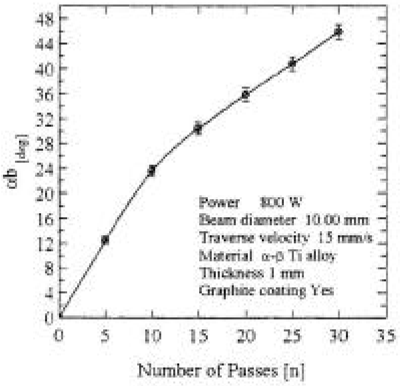

Fig. 4: Bend angle with increasing number of scans over the same track [8]

The cause of this reduction has been reported as being due to the strain hardening of the material[10] and a change in absorption as the number of scans increase. This study concluded that for the materials studied the effect of sheet thickness increase in the irradiated area per scan, is of greater significance than strain hardening.

This study also looked at edge effects or the changing bend angle along the length of the bending edge in laser forming. The laser forming process is asymmetric about the laser beam, as a result the bend angle cannot be constant along the entire bending edge until the laser beam has completely scanned the sample. Ideally, after the process, the bend angle would be constant along the bending edge, however normally the bend angle varies with plate location (fig 5).

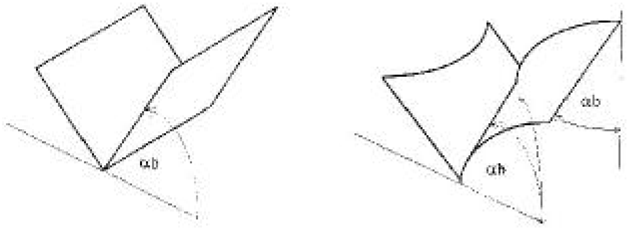

Fig. 5: Ideal bend angle and exaggerated view of edge effects[8]

This is attributed to the changing mechanical restraint, which is available to hinder the free thermal expansion with distance from the edge of the sample and the temperature dependent material properties. The effect is also attributed to the contraction of the material in the direction the laser beam scans. This behaviour is termed as edge effects. It was found that these effects could be minimised by varying the energy supplied to the plate surface, with in plate location, by varying the speed. The speed was varied in order to balance the thermal strain required to cause the same amount of yielding, as the mechanical restraint hindering the thermal expansion changed with distance from the edges of the plate and the temperature dependent material properties.

A metallurgical study into the implications of the laser forming process using the titanium and aluminium alloys was also carried out. It was concluded that in order to apply laser forming to aerospace components it is necessary to restrict the process parameter envelope to a range which does not adversely affect the metallurgical or mechanical properties of the alloys. For the titanium alloy it was found that oxygen uptake during processing in air contributes to the formation of an alpha case and an increase in micro-hardness on the upper surface. To avoid this it was concluded that processing should be carried out in an inert atmosphere such as argon. In the case of the aluminium alloy the as received microstructure could be maintained when an average energy density (AED) of less than 25 J/mm^2 was used for forming. At higher AED re-crystallisation occurred and at extremes (greater than 133 J/mm^2) a cast dendritic structure resulted from melting underneath the pure aluminium clad layer on the surface of this alloy. A fluctuation in the micro-hardness level about the as received value was found in samples processed at AED less than 25 J/mm^2. This oscillatory nature can be explained by the re-crystallisation and precipitation theory for this alloy.[5,8,9,11]

2D LASER FORMING DEMONSTRATOR SYSTEM – A laser forming demonstrator system was developed to demonstrate the process on a large primitive 2D shape. Data from the parametric and metallurgical study on the smaller tokens discussed earlier was used to develop the processing parameters for the system. The demonstrator part after some initial trials with larger parts was chosen as a flat rectangular AA2024 T3 sheet of dimensions 450x225 x0.8mm that was to be formed into a part-cylinder of radius 900mm (fig 6). The part was large in terms of laser forming operations to date, and the shallow radius of curvature is almost at the spring-back limit of conventional forming operations. The system was set up using a CO_2 CW laser, CNC tables, a pneumatic clamping system and a 3-D CAM laser stripe measurement system.

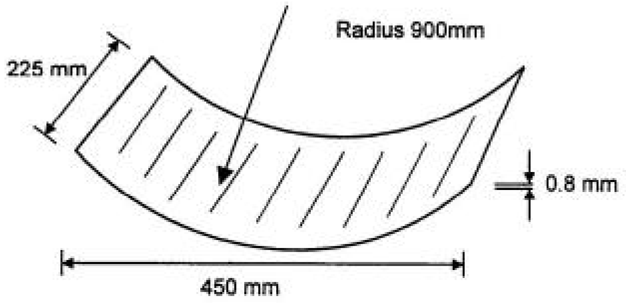

Fig. 6: Demonstrator Part[8]

The primary objectives of the demonstration were to obtain:

1. Geometrical accuracy, surface smoothness, and reproducibility.
2. Metallurgical integrity.
3. Specifications of the processing information required to automate the part.

With this system the scan conditions were set and then the program instructions were executed. The surface was then profiled using the 3D CAM laser stripe and this information was used to give the heights at various points over the sheet surface. This data was used to give a measure of:

1. The radius of curvature
2. Any deviations in the radius of curvature along the length of the bending edge, i.e. any longitudinal distortion or curvatures in the wrong direction.

The demonstrator system then relied on user intervention in order to determine what the next processing steps were. These steps included:

- Next scan pattern
- Next Starting point and direction for scan pattern
- Next clamping location
- Next energy input

This adaptive approach was taken because the part produced by a constant scan pattern, direction and clamping arrangement was twisted and distorted. The part produced by altering these parameters and the energy input at different stages of the process had increased accuracy, surface smoothness and reproducibility.[6,8]

3D LASER FORMING OF DISH SHAPES – A case study was also made by J. Magee et al [8,12] into the 3D laser forming of a dish shape from flat circular 2mm gauge mild steel CR4 sheet. The objective of the investigation was to establish rules about the positioning and sequencing of the laser irradiation lines for the symmetrical laser forming of such a dish shape. The scan patterns investigated employed radial or circular scan lines, or a combination of both to form the part. The samples were verified using a co-ordinate measuring machine.

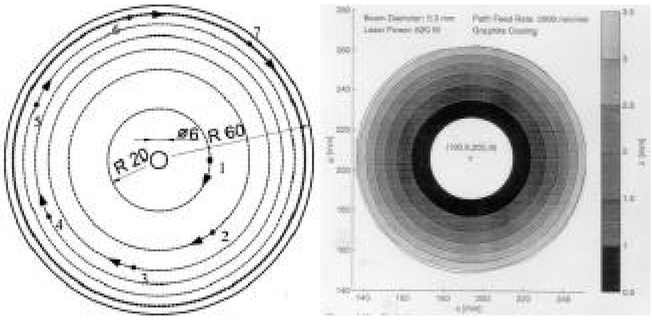

Fig. 7: Circle line system with square root radius increase (inside to out), and resulting contour plot of sample.[8]

It was found that in order to achieve a smooth and symmetrical dish shape:

1. Geometrical symmetry should be reached as soon as possible after the initial irradiations.
2. A symmetrical temperature distribution over the plate surface should be realised.
3. Any pre-orientation bend should be avoided
4. The laser beam parameters, particularly the irradiation angle of incidence and the irradiation spot diameter, should be held constant.

To these ends the circle line system with square root radius increase, irradiating from inside to out, was found to be one of the best strategies (fig 7). This strategy employed the upsetting mechanism along the concentric circular scan lines to achieve the forming result.

3D LASER FORMING - There has been a considerable amount of work carried out on two-dimensional laser forming, using multi-pass straight line scan strategies to produce a reasonably controlled bend angle in a number of materials, including aerospace alloys [1, 3-11] and some 3D work [8,12-15]. However in order to advance the process further for realistic forming applications and for straightening and aligning operations in a manufacturing industry it is necessary to consider larger scale 3D laser forming. It is possible to form complex 3D surfaces from flat sheet material in a controlled way using a non-contact laser forming approach, thus eliminating the need for expensive dies. The technique could also be used to align or correct pre-formed 3D surfaces.

There have been a number of studies in the 3D laser forming of symmetrical parts, [8,12,13] however this study aims to produce an understanding of the mechanisms and control parameters of the 3D process, in order to carry out in a controlled way any of the tasks in straightening and aligning and primary three-dimensional laser forming. As a starting point three primitive 3D shapes were chosen to be investigated, including the saddle shape, shapes that when combined could form the basis for any 3D surface. The saddle shape for instance was chosen due to its more complex 3D geometry, the double curvature (i.e. positive to negative curvature) providing a useful case study with which to build up the design rules for such 3D shapes.

This study is part of an EPSRC research programme, which involves collaboration with the aerospace companies BAE Systems & Rolls-Royce and a number of other UK Universities including the University of Liverpool. The scope of this research programme includes process simulation, sensor development, metallurgical implications and the development of a 3D laser forming demonstrator system which includes closed loop control and predictive qualities.

The development of the laser forming scan strategies for the generation of the 3D primitives will be a systematic empirical approach. It is thought that this approach will yield a better understanding of a complex process with many variables.

The geometries of the parts formed are verified using a laser range finder mounted on the Z-axis of a 3-axis CNC beam delivery system of a CO_2 CW laser. Custom software was written to use the system as a coordinate measuring machine (CMM), in that for a known grid, height data can be taken from the range finder to build up a contour plot of the part.

An investigation has been carried out into the 3D laser forming of the saddle shape using the less expensive material Mild Steel CR4 of dimensions 400 x 200 x 1.5mm.[15] The scan strategies tested consisted of straight and radial lines and concentric circular patterns. The active laser forming mechanism used varied from the temperature gradient to the upsetting mechanism depending on beam parameters and traverse speed used.

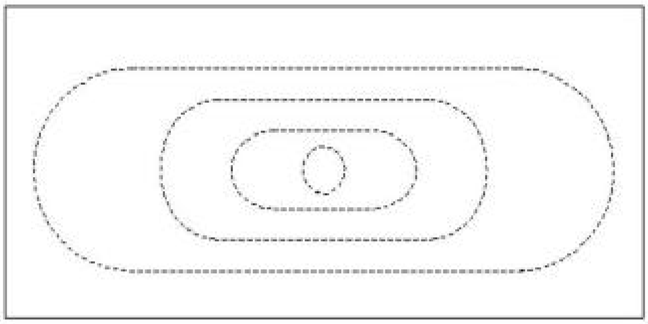

Fig. 8: Scan strategy to laser form the saddle shape, 800W 20mm/s[15]

The final successful strategy was a development of all the previous attempts. It was designed to shorten the plate across its length and width in order to give a smooth contoured saddle. The concentric circular pattern was found to work best when processing from the centre to the periphery (fig 8). The inner circle was processed clockwise then each subsequent outer loop in the opposing direction. The start points of the loops were spread evenly around the plate as dwell points occur due to a mechanical delay between the shutter opening and closing and table movement. It was found that this strategy allowed slowing of the processing speed in order to increase the magnitude of forming.

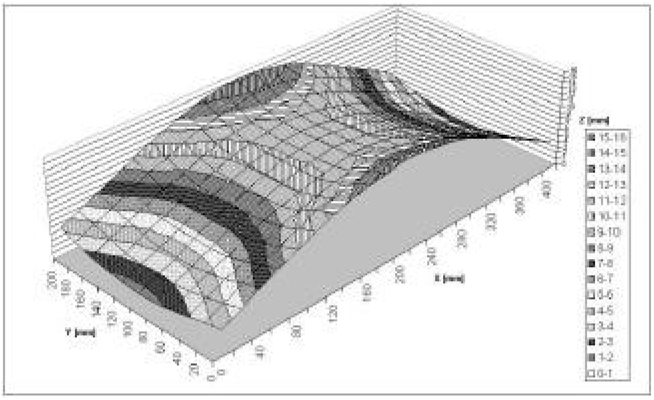

Fig. 9: 3D Contour plot of laser formed saddle shape [15]

This 'race track' strategy successfully produced a very symmetrical saddle shape. Figure 9 which is the contour plot of the formed part (from the co-ordinate measuring machine) confirms this. The concentric pattern appears to stabilise the saddle shape, even when processing at slower speeds for additional forming. The repeatability of this strategy was also very good. Samples processed at the same parameters are within a 2mm tolerance. It was also found that further forming could be achieved with this strategy for a given speed if the plate was supported centrally above the base plate and allowed to form freely without being hindered by its own weight. The next step in this study is to recalibrate this strategy for a material of more significance namely Ti6Al4V sheet.

It was concluded from this study that:

- The essential characteristics of forming a saddle shape from a flat rectangular piece of material are a shortening of both the diagonals and the length and width of the rectangle to give rise to the contours of a saddle.
- Any strategy to form a saddle shape must be symmetrical along the length and width of the plate and have a centre at the centre point of the rectangular plate.
- Symmetrical laser forming is hindered due to the asymmetric nature of the laser forming process itself, in that it is not possible to form the whole plate at once. A solution to this may be scanning optics.
- Any pre-stressing of a work piece is a large factor in the magnitude of forming and any distortion of the final part.
- Development of an online monitoring system with predictive distortion correction abilities is a requirement if any 3D laser forming operation is required to be used in a manufacturing environment.

Ongoing work will include continued empirical development of scan strategies for the laser forming of the 3D primitive shapes from 400x200mm Ti64 sheet of various gauges, based on thermo-mechanical analysis and experimental work, working towards a 3D demonstrator system. [15]

CONCLUSION

The conclusions from each of the individual investigations summarised in this paper have already been given. However to conclude the paper, laser forming has emerged as a process with strong potential for application in aerospace, including the rapid manufacture of prototypes and the adjustment of misaligned components. This has arisen due to the process advantages, including the high accuracy (arising from the progressive nature of the process) that can be achieved in forming or the adjustment of misalignment of a part. The ongoing work in this area will undoubtedly realise the potential of the process.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the support provided for this work and future work given by BAE Systems, Rolls-Royce and the EPSRC.

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