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TOWARDS PEEN FORMING PROCESS OPTIMISATION

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ABSTRACT

The modelling of peen forming is currently addressed by modelling local impacts. This is adequate for small surfaces with no other mechanical inputs. However, most components that are manufactured by the peen forming method have large surface areas and, in many cases, some level of prestress is imposed on the part during the peening operation. Simple through-thickness modelling of peening effects is thus necessary so that attention can be focused on developing maps of planned peening intensity over the component, in combination with elastic preloads, to achieve desired shape change outcomes. The paper reports new modelling approaches being developed for this in Cambridge University's Manufacturing Engineering Department.

KEYWORDS

Peening, Forming, Prestress, Simulation, Finite Element Analysis.

INTRODUCTION

The shot peen forming process has been recognised as a suitable manufacturing process for various aircraft components since the 1960s. The ability to produce double curvature sheet parts, such as wing skins, without the use of a large press or hand beating has been exploited for commercial aircraft for many years. However, much of the knowledge developed in regard to the process parameters for the operation has been through trial and error. In trying to simulate the shot peening process there has been a lot of work done in the modelling of individual contacts and this has been extended to several contacts over a small area. However this work treats each impact separately and although it is theoretically possible to extend the model to the whole area of a wing the shear number of impacts involved makes the number of calculation steps unmanageable. This means that a way has to be found to treat the whole peened area in a general manner. There has been some work attempting to accomplish this, such as the squeeze layer model [1], which has produced reasonable approximation of the physical reality but this sort of model has not been thoroughly investigated.

A second requirement is that the model must account for the interaction with any prestress applied. This is required for the ability to model the actual manufacturing process of, for example, a wing. The individual contact models can integrate any pre-existing conditions with the peening operation but the distributed models can not do this easily. The reason for this is that they model the residual stress due to the peening operation. This is perfectly acceptable if there are no pre-existing conditions and, if this is the case, the correct displacements should be developed. However any prestress interacts with the peening operation to give an altered residual stress distribution. Hence to model the residual stress distribution requires calculating the effect of the prestress. This paper suggests a method for doing this, which is currently undergoing calibration and testing.

MODELLING PEENING STRESSES USING TEMPERATURE

Levers and Prior [2] introduced the concept of using a temperature subroutine to model the peening stresses. This initial concept has been taken and developed as described. If the complete peened area is considered in a single step, as opposed to the build up of individual peen impacts, then the applied stress distribution must be uniform over any area with the same process parameters. However, if one looks through the thickness of the peened component then the stress profile varies. In effect there are multiple layers of uniform stress as shown in Figure 1.

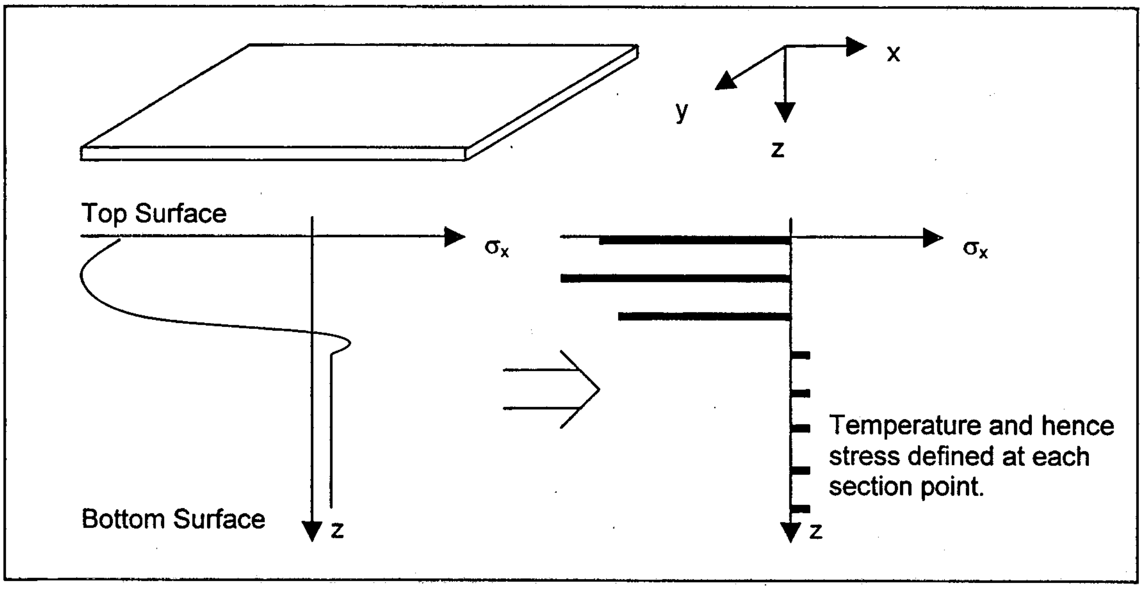

Fig.1 Residual stresses post peening in x and y direction, actual and sectioned.

Defining differing stresses over multiple layers through the component thickness is difficult to do directly. If one looks closely at the requirements for the stresses applied then it can be seen that the stresses in the plane of the component, due to peening, are equal in the x and y directions.

Using the temperature subroutines in a finite element program can fulfil this condition. In this case the ABAQUS finite element code is used. The code allows the definition of multiple sections through the thickness of shell elements with a different temperature for each layer. If the thermal expansion coefficient, α, is calculated as shown in Equation 1, where ν is the Poison's ratio and E is the Young's modulus, then the temperature is calibrated to be equivalent to MPa. In effect any stress profile required can be directly added by defining it as a temperature profile.

$$\alpha = \frac{1-\nu^2}{E(1+\nu)} \times 10^{-6} \qquad (1)$$

The use of shell elements adds further constraints to the model that have to be considered. Firstly shell elements can only be used for a thin sheet of a single element in thickness. This constraint is perfectly acceptable, as this is the only type of component that is suitable to be peen formed. The second constraint is that stresses can not be applied in the z direction through the component. The peening operation does cause internal stresses in the z direction so their lack has to be accounted for. However, as the model is trying to predict the final shape, the residual stresses only have to be accurate in the x and y directions as it is the relative expansion in these directions that causes the curvature. This means that the lack of fine control of the z direction stresses is not a concern for modelling the shapes produced by peen forming. What it does mean is that the method is not expandable to all peening operations, such as fatigue resistance on more complicated components.

DEVELOPMENT OF THE PEENING MODEL

Once it is shown that using shell elements and the temperature subroutines is a valid approach, the temperature profile applied to the model to simulate peening is required. When models such as the squeeze layer method were used the model applied the residual stress required to give the displacement. It is possible to do precisely the same thing with the temperature model [2] but this will not model the effects of a prestress. Prestress is used to produce a differential effect in, for example, the x and y directions so different curvatures can be produced in each direction. This is accomplished by causing the stress required to reach plasticity to be different in the two directions. Hence the peening will cause a differing amount of plastic flow in each direction. Therefore the residual stresses in the two directions will be different and the resulting curvatures will differ. It is preferable for the model to calculate this effect so the stress profile input has to be that which will interact with the prestress. Hence the stress applied should be the peening stresses that cause the plastic deformation. This stress can be applied for a single step and then removed. This should leave the correct residual stresses on the component for both the simple and prestressed cases.

Hence the model needs to use the stresses that would be the equivalent of those found at the instant of maximum indentation of the peens. For the purpose of this paper all peening operations are considered to be at complete saturation, defined as the point where further peening shows no further increase in the Almen height. At this point the peen impacts can be considered to have overlapped to such an extent that, on the macro scale, the stress profile through the thickness of the sheet is equivalent to that found under the centre of an individual peen contact. This means that the profile can be developed by considering the normal indentation of sphere into a half-space. Lower coverage requires a suitable scaling factor but this is not a concern for this paper. As stated at the beginning the indentation of a single peen has been considered in much greater detail, most notably by Sinclair, Follansbee and Johnson

[3]. They considered the exact stress distributions produced during the indentation and the residual stresses caused. From their work it can be seen that calculating the exact stress distribution at the point of peen contact is not a user-friendly solution. If a suitable approximation can be found, it would be extremely useful.

It is the calculation of the plasticity that causes difficulty in determining the stress profile applied. It is suggested that the elastic model should be used to determine the applied profile. If the material plasticity data is input to the finite element program, the program will truncate the elastic stresses and return an approximation of the stress with plasticity included. Calculating the elastic stresses is a much simpler analysis to run. It is this method that is being used and calibrated at this time. The initial results are promising as will be seen.

As it is the indentation of a rigid sphere into an elastic half-space that is being considered it is a Hertzian analysis that is required. The process parameters for the machine define the peen radius and the velocity with which it impacts the sheet. These, along with the material specifications are enough to develop the stress distribution. The velocity can be used in the dynamic Hertzian analysis to calculate the approach of centres. An approximate static analysis can then be defined by stating the requirement that the loading gives the same approach of centres. This means that the x, y and z direction stresses can be fully defined.

At this point it would be preferable to apply these calculated stresses to the component but, as already stated, it is not possible to add z direction stresses using the temperature model. This causes a difficulty in that it is not correct just to use the x and y direction stresses as it is the shear stress that determines plasticity. If the z direction stresses are ignored the shear stresses and hence plastic zones are incorrect. It was therefore decided to use an equivalence model. The x and y direction stresses are calculated as though the loading is only in that plane so that they give the same shear stress as the Hertzian analysis. It was found that this stress distribution approximated to using the shear stress multiplied by a constant. It is the calibration of this work that is currently ongoing. However an example of the results produced is shown here.

An analysis was conducted assuming the use of S550 shot peening Almen C strips at 20, 30 and 40 psi. It was assumed that the strips were peened to complete saturation. The results obtained are shown in Table 1. The velocities were calculated using equations produced for a sister machine during velocity calibration trials.

Table 1, Results of theoretical model for peening of Almen strips

Air Pressure psi	Velocity m/s	Centre displacement mm	Approx. Almen Height 0.001"
20	24	1.28	9
30	30	1.56	10.5
40	35	1.67	11.5

Expected Almen heights for these parameters would be in the range of 0.008 to 0.018". It can therefore be seen that the model is producing reasonable results, although further calibration is required. It should also be noted that for ease of manipulation the number of layers used was 13. This is not fine enough to give an accurate description of the required profile. If 41 layers are used for the 20 psi test, then the centre displacement is increased to 1.37mm. For this reason further work needs to be done to determine the minimum required number of layers to give an accurate result.

A further check can be made on the analysis by examining the stress distributions produced. These are shown in Figure 2. It can be seen that the shape of the residual stress curves are as would be expected for a peening operation. Furthermore, it can be seen from Figure 3 that if the stresses in the x and y directions are normalised with the yield stress then the result gives a reasonable approximation of that expected by Sinclair et al. Note that in this case the value of the ratio a/R is 0.17 which will fall between the values calculated by Sinclair et al for a/R 0.06 and 0.32. Also, these results are actually normalised using the flow stress but they still can be compared to show the good agreement on such points as the depth of the plastic layer.

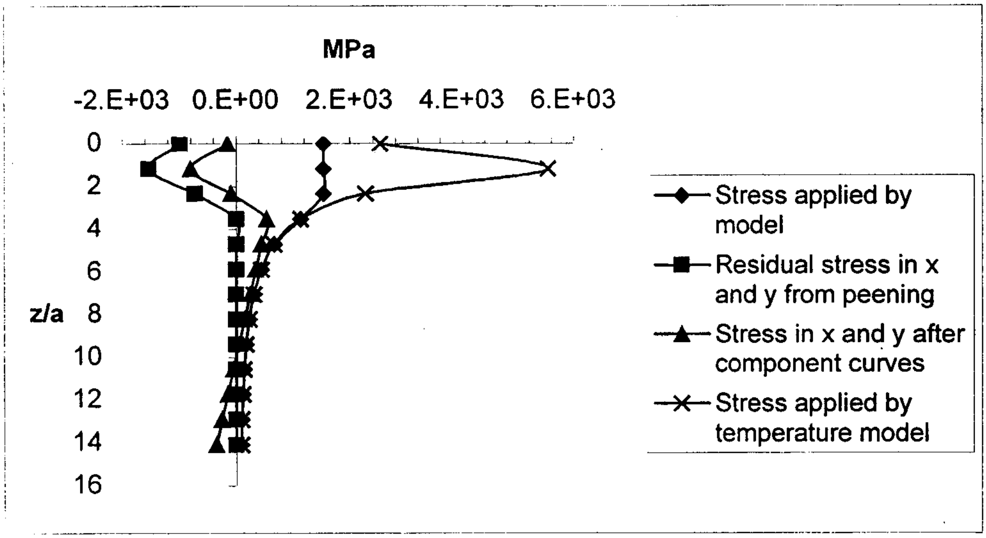

Fig. 2 Stresses produced by model for an Almen strip peened at 20 psi

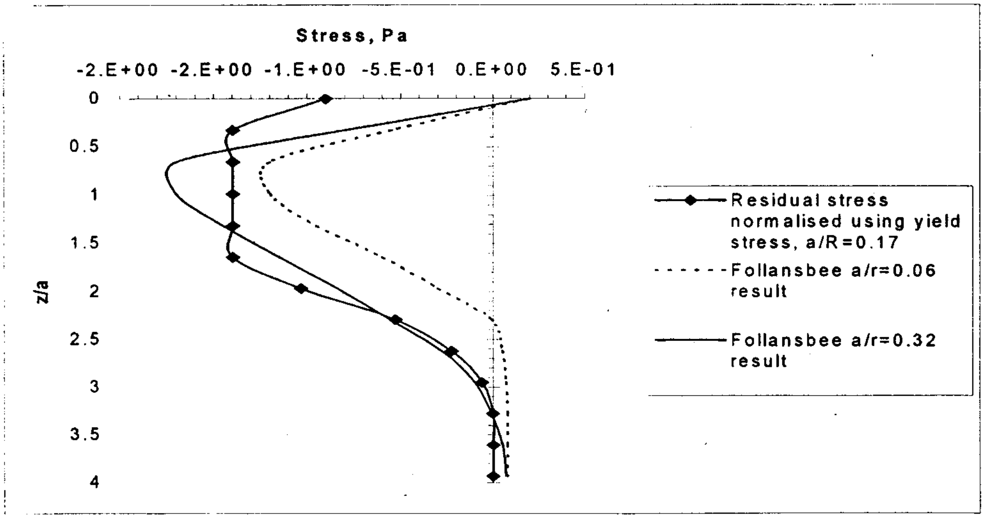

Fig. 3 Comparison of residual stress produced by model and expected result from Follansbee

ADDITION OF PRESTRESS

There is a need for further calibration and validation but initial testing of the peening model as shown in the previous section has produced realistic results. The results were also shown to vary with the input parameters in a way consistent with that expected for a peening operation. Therefore, although the exact accuracy has yet to be determined, the model has the potential to cope with all simple peening operations. One of the stated aims for the model, and the topic of this paper, is that the model should be extended to include the effects of prestress. This has already been accomplished in principle but validation has not been completed so the accuracy can not be stated. However, it is possible to show the method and show that differential residual stresses can be produced by the addition of prestress to the model. To highlight any differences between directions a square sheet was modelled, although still with Almen C strip thickness and material properties, and then analysed under three separate sets of conditions. Firstly the prestress was added and then removed with no peening taking place to confirm that the prestress loading alone was not causing the curvature. This was shown to be true and if Figure 4 is observed it can be seen that the stress values imposed were actually well below the elastic limit, which is approximately 1.1GPa. The second analysis run only applied the peening with no prestress. This gave a control analysis to compare the prestressed analysis against. The final analysis was with both the prestress and peening operations taking place.

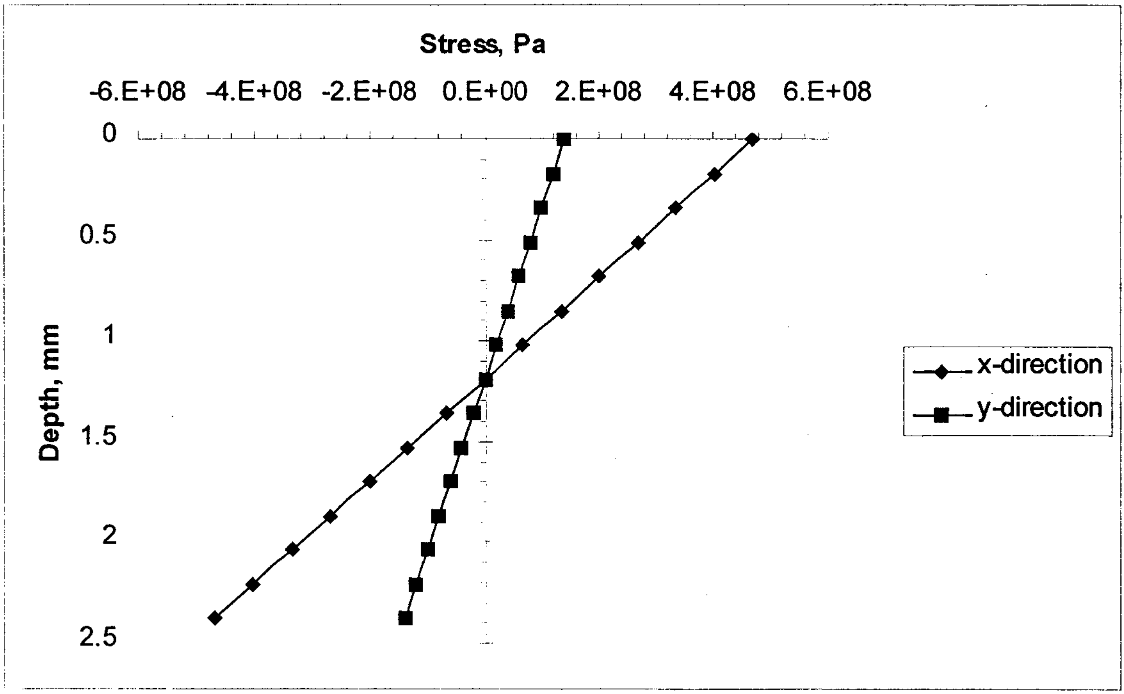

Fig. 4 Prestress applied to model by applying simple bending

Once the prestress has been added in the first analysis step by simply modelling the physical conditions actually used the peening analysis step can run. The temperature profile required for the peening can be simply added to prestressed component. Once the peening analysis step has been completed the constraints imposed on the component, to give the prestress, can be released and the final deformed shape is produced.

Figure 5 shows the stresses at the central node in the prestressed component during the analysis. It can be seen that the prestress has caused a differential to be observed between the stresses in the x and y directions. This can be compared with Figure 1 where the stresses in x and y were identical, as there was no prestress applied.

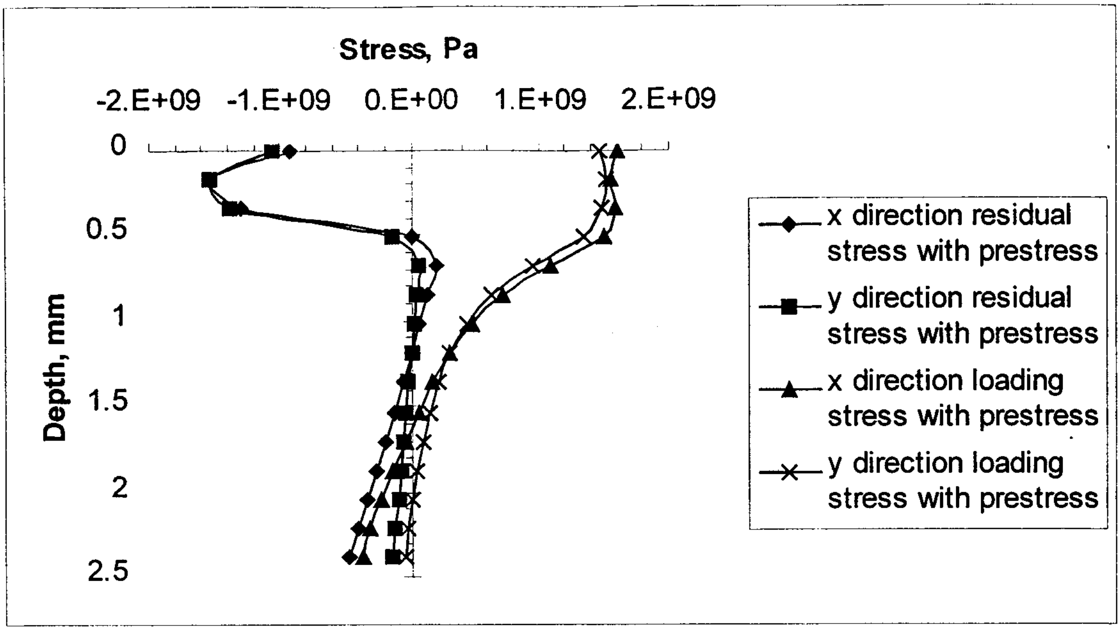

Fig. 5 Loading and residual stresses at the central node due to peening with prestress applied

Direct comparison of the loading and residual stresses between prestressed and simple peening conditions is not particularly useful as the inclusion of the prestress obscures the difference in peening stresses. However, once the constraints have been removed, and the component has been allowed to deform, the comparison is possible. It is the residual stresses after deformation that are actually measured in most cases so this comparison, as shown in Figure 6, is probably the most useful.

It can be seen from Figure 6 that the residual stresses in both the x and y directions for the prestressed analysis are higher than that of the control analysis. This is to be expected from Figure 4 as the simple bending imparts tensile stresses in both directions on the top surface. The addition of these extra tensile stresses has caused a higher degree of plastic flow and hence greater residual stresses.

What also needs to be addressed is the difference in curvatures that are produced. The emphasis of this work is to model the production of peen formed sheet components, so the ultimate test is if the correct displacements can be produced. Again this needs validation but the model analysed above did give deflections well within reasonably expected parameters. This can be seen in Figure 7 where the edge displacements were plotted. The edges were used as they required no offset and the decision was arbitrary. Again, the x and y directions for the non-prestressed analysis were identical. The square modelled was 20mm by 20mm.

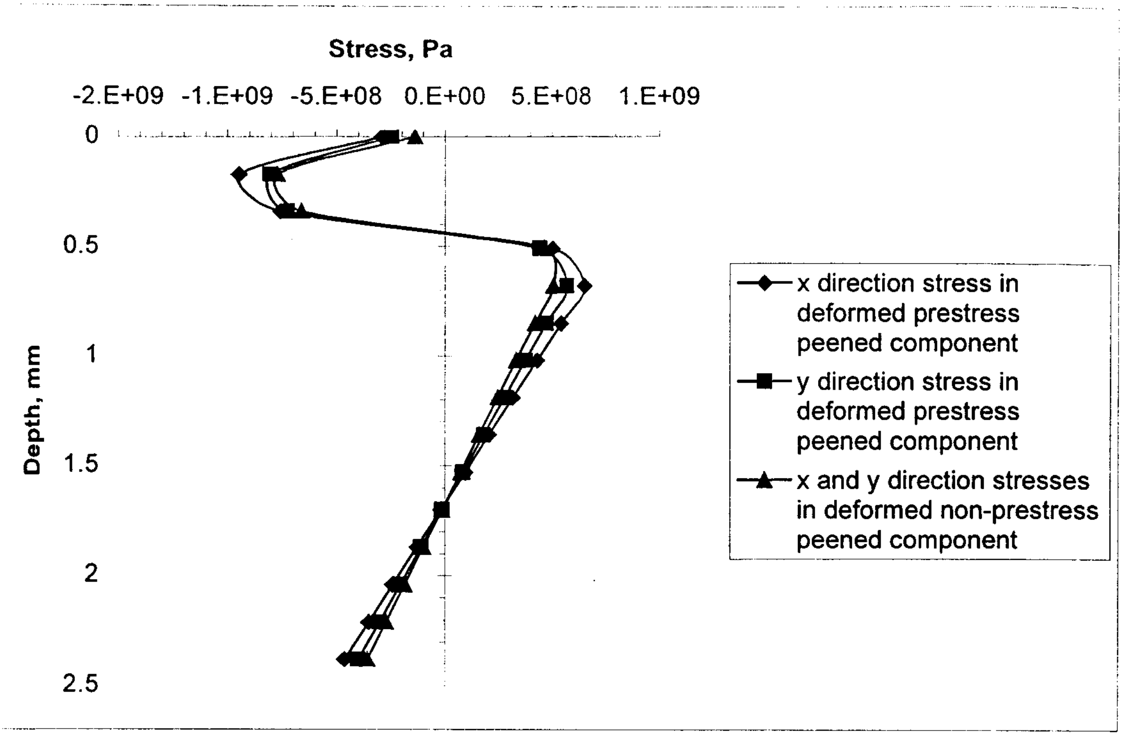

Fig. 6 Final stresses in peened components after external constraints released

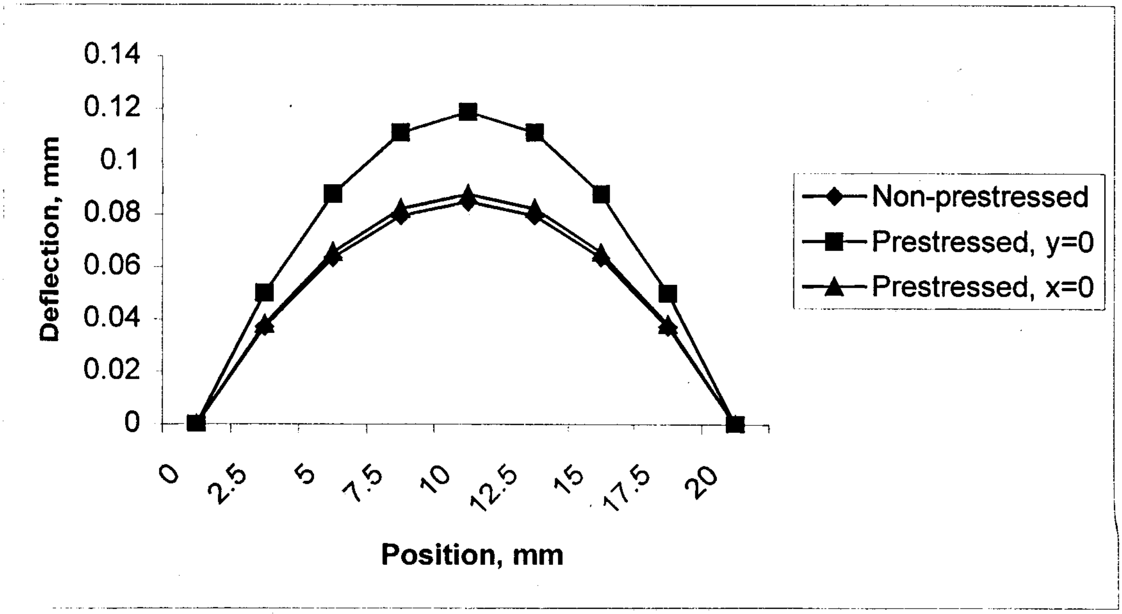

Fig. 7 Deflection along the x=0 and y=0 axes due to peening

FORMING PEENING MAPS

Once the model has been validated and the level of accuracy defined, the process requirements to form a particular shape can be produced as a peening map or pattern. The information would be held as a series of peening intensities and prestress values for each area segment, as defined by the element co-ordinates. Graphically this would look like two contour maps overlaid. This information could then be fed directly into a machine to produce the component.

The flexibility and actual operation of the system would then be defined by the ability to control the manufacturing process. Infinitely variable local prestress is hard to produce, especially as peening of previous areas affects the stresses in the adjacent ones. It is therefore more likely that the prestress values are kept at a known value and the peening intensities are altered to give the final desired shape.

Answering the question of the best way to set up the peening maps and using prestress is future work that can only be addressed when there is a comprehensive understanding of what stresses one is trying to produce. Being able to model the process on the computer allows much cheaper experimentation than the trial and error system currently employed. It also opens up the way to a predictive system that can produce the peening map and hence process parameters purely from a desired component shape and material properties.

CONCLUSIONS

The work set out in this paper has shown that the use of temperature to model peening stresses produces a very powerful analysis. The method has been shown to work and any stress field, symmetrical in the x and y directions, desired can be imposed on the component. The code that produces the temperature profile for particular peening parameters has not been completely validated but does produce the expected residual stress patterns and values in the correct range.

The model has also been shown to produce a differential stress field in the x and y directions as expected upon the addition of a prestress. This differing stress field has also been shown to produce an asymmetrical deflection of the component, which is again in the range expected.

Upon validation of the model the ability has been stated to define the process parameters required to manufacture a component as a peening map or pattern. This peening map can then be input directly into the manufacturing process, in an integrated system, as it contains all the information required to produce the part.

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