Manufacturing the London 2012 Olympic Torch

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Abstract

A key part of the build-up to the London 2012 Olympic Games was the Torch relay for which each one of the 8,000 runners required a Torch. The design of the Torch comprised inner and outer skins of perforated aluminium formed into a triangular cross-section, which flared out towards the top to house the gas burner. Dutton Simulation was asked to assist with development of a process to manufacture the skins to the required accuracy and quality of finish; some of the key technical challenges are described in the paper.

The first task was to develop a blank shape for the two forms and then confirm these with incremental forming simulation (using eta/DYNAFORM with the LS-DYNA® solver). The validated shapes – both the profile and the thousands of holes – were then cut by laser. In conjunction with developing the blank, the optimum forming process also had to be determined, to form the perforated sheet to the accuracy required for laser welding the joining seam. Several process concepts were explored before arriving at a four stage method.

With aluminium as the raw material springback was already expected to be a factor; this was compounded by the holes further reducing the material stiffness and the relatively low strain in the form due to the large radii. Nonetheless, the geometry had to be formed to a very tight tolerance, both for the weld process and also to create a result free of cosmetic defects. LS-DYNA was used to determine the springback at each step of the forming process and the springback compensation solution was used to provide the correction. DYNAFORM's tools for cosmetic defect detection (stoning, reflect lines) were employed to check the result to the highest level of detail.

Introduction

Most people in the United Kingdom would agree that the 2012 London Olympics was a national triumph, not simply in sporting terms but also for the way that the activities to support the Games involved so many people around the country. One of the major factors in engaging the British public was the Olympic Torch relay. Over the course of 70 days, starting from Land's End in Cornwall on May 19th to its arrival at the Olympic Stadium in July, some 8,000 runners carried the flame on its 8,000 mile route throughout the UK. Each runner ran with their own torch meaning that a total of more than 8,000 torches had to be produced. The contract for manufacturing these was awarded to The Premier Group in Coventry, UK.

Design

The design of the 2012 Olympic Torch (Figure 1) by UK design studio Barber Osgerby was widely praised; the torch won many awards, including Design of the Year 2012 from The Design Museum [1]. Such high quality design naturally demanded the highest quality manufacturing process to ensure that every example produced met the same exacting standards.

The torch featured a triangular cross-section with slight curvature to the sides and more rounded vertices. The lower part was straight sided creating a handle for the runner to hold; half-way up the cross-section transitioned into an outward tapering upper part housing the burner and gas canister, with a valve covered by the Games logo towards the top. The main body was created by two perforated aluminium skins, one within the other, with cast caps on each end.

Figure 1 The Olympic Torch for the London 2012 Games

Every detail of the design had significance – and the manufacturing process had to re-produce these details to maximum precision. The triangular cross-section reflected the three elements of the Olympic motto *Citius, Altius, Fortius* (faster, higher, stronger); three was also significant as this was to be the third time that London had hosted the Games. The perforations in the two skins of the main body comprised exactly 8,000 holes, representing the 8,000 relay runners. The holes were arranged to align between inner and outer skins in a consistent pattern echoing the five ring Olympic emblem. The holes changed in size over the length, increasing in diameter as the cross-section grew towards the top, requiring the alignment to be modified continuously from handle to burner.

Manufacturing Process – Blank Development

The requirement for high quality as well as the number of torches to be produced demanded a reliable and repeatable manufacturing approach. The Premier Group was appointed to fabricate the main body of the torch (as well as carry out the final assembly). It was determined that press forming using CNC cut tools should be adopted to make the inner and outer perforated skins. The proposed process for each skin required an initial flat blank to be cut from sheet stock. Laser cutting was used to cut the outer profile as well as all the required holes. The blank was then formed into the tapered triangular shape using a sequence of forming operations – the number and type of operations was not initially known. When formed, each skin would be closed with a laser weld requiring a very tight tolerance where the two folded edges met.

The first challenge for the manufacturing process was to determine the required shape for the outer profile, i.e., to develop the flat pattern for the two skins. This required calculation of not only the outline for the blank but also the location and shape of each of the holes. Determining the precise blank shape to achieve a consistent weld seam with a gap controlled to a fraction of a millimeter was more challenging than originally realised, particularly through the transition from straight to taper. Standard CAD unfolding methods proved to be unable to predict the correct profile. In addition, the slight distortion of the pre-cut holes in the blank, especially at the rounded vertices where the amount of curvature was greatest, needed to be calculated to ensure that the formed holes were perfectly circular and correctly aligned between inner and outer skins.

Premier turned to Dutton Simulation for help with developing the flat patterns. Dutton identified that FTI's FormingSuite software, specifically the FASTBLANK module for blank development, would be able to calculate a trial development. FASTBLANK takes the 3D part geometry and, using an inverse finite element method, determines the 2D flattened form. Using an FEA approach rather than simply a geometry-based calculation means that the strain in the material due to forming is taken into account resulting in a very accurate blank shape prediction.

Applying FASTBLANK to the challenge of calculating the flat pattern for the two skins required some attention to detail; the input geometry had to be carefully managed to handle the large number of trimmed holes in the surface model, and the material properties had to be accurately captured to ensure that the relatively low strains in the part were correctly predicted. FASTBLANK not only calculated the blank outer edge profile, taking into account material stretch and compression, but also predicted the shape and position for the thousands of holes to ensure that the final result was as required after forming; the blank was then exported from the software directly to the laser cutter. The predicted shapes for both inner and outer skins proved to be perfect when the torch was fabricated, giving the required alignment of holes and a consistent narrow gap for laser welding. The blank for the outer skin, complete with the tabs added for manufacture, is shown in Figure 2 – a half model was used for the calculation. Figures 3 & 4 show the laser cutting process creating the holes and cutting out the final blank shape. NB the tabs on the ends were added for assembly; and the final perforations along the weld line are cut after the welding process.

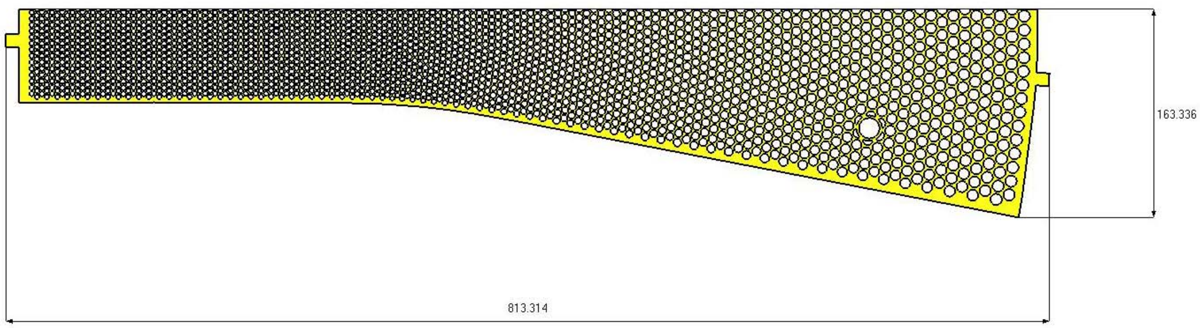

Figure 2 Outer skin final blank development from FASTBLANK (half-model)

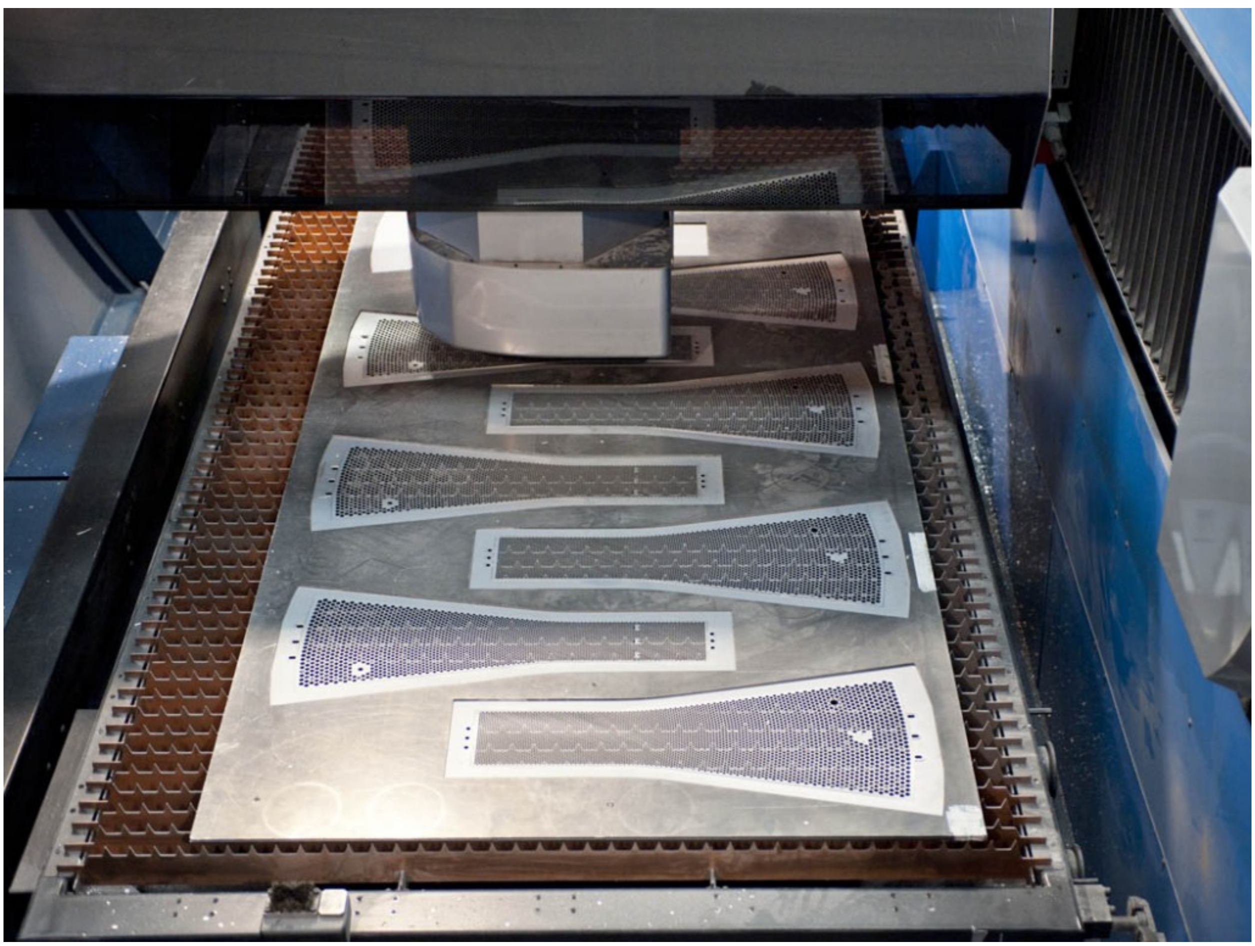

Figure 3 Laser cutting operations to create the outer skin blank

Figure 4 Laser cutting operations to create the outer skin blank

Manufacturing Process – Forming Operations

Blank development was the first challenge to be met in order to develop a successful manufacturing method for the torch; the forming process itself also had to be verified, to establish the number and type of forming operations and the tooling geometry for each one. Both The Premier Group and Dutton Simulation have considerable experience in forming and simulating manufacture of automotive panels in aluminium and one of the main challenges is correcting the tool geometry for the inevitable springback. With the process proposed for the torch, the correction had to be extremely precise or else the taper angle would vary from edge to edge when viewed from different directions – clearly not an acceptable outcome.

A number of forming processes ranging from two to four operations were initially proposed for investigation. Dutton Simulation proposed use of ETA's DYNAFORM, based on the LS-DYNA solver, to simulate alternative sequences of operations in order to determine the best method in terms of accuracy and quality of the end product. The combination of implicit and explicit solution methods seamlessly integrated in LS-DYNA, accessed via DYNAFORM's AutoSetup menu, allowed the required degree of accuracy and analysis efficiency to be attained.

Initially a three stage process was proposed, applying a modified form of press brake bending with bespoke tooling; each operation required only an upper and lower die (no blankholder was used). The initial process was as follows: the first operation was to introduce the first small bottom to top transition from straight to taper while at the same time curving up the outer edges (which would eventually meet for laser welding); then the next two operations were to use a "V" bend tool, re-positioning the blank between forming operations, to create the two vertices each with 60 degree internal angle, with the second of these operations intended to bring the outer edges together.

Manufacturing Process – Simulations

DYNAFORM was applied to model the full sequence of forming operations to confirm that they would create a high quality result – this meant that the method should not only analyse the forming of the material to flat but also predict the resulting springback (i.e., the geometry change due to recovery of elastic strain at the end of the forming operation). This led to use of a fully integrated shell element (type 16) to model the blank, with seven through-thickness integration points, to reliably predict the stress distribution due to both bending and membrane stretching through the material thickness.

Because of the need to model the blank with the thousands of perforations included, a very small element size was required to provide a suitably smooth mesh around each hole. The model therefore had a large number of rather small type 16 elements – leading to a very small timestep and potentially an unacceptably long run time, unless mass scaling was used (i.e., application of a limiting time step on the *CONTROL_TIMESTEP card).

Mass scaling is a useful technique to help simulate complex processes with detailed models in a practical turnaround time. Depending on material properties (density and Young's Modulus), small elements require a small time step in order to satisfy the Courant stability condition – this is fundamental to achieving a reliable explicit solution. When applying mass scaling, each element in the blank is checked against a target time step and, if necessary, its density is increased to maintain stability. It is a great help in single and double action process simulation where the material is well supported but can potentially introduce additional inertial forces if the elements with higher density undergo large accelerations.

The bending-like processes proposed for manufacturing the torch meant that large regions of the blank were unsupported for much of the time and hence mass scaling would have been problematic, especially with the small element sizes being used; unrealistic motion of the unsupported blank material would be likely. However, using the implicit method avoids the need for mass scaling as the Courant condition does not apply. Correct modelling of contact between tool and work piece to ensure solution convergence can be challenging with an implicit approach but LS-DYNA's combination of robust time step control and specially adapted contact algorithms made the solution relatively straightforward. One particularly important control parameter that can have a significant effect on both the convergence behaviour and the simulation results is IGAP, which is set on the contact Optional Card C. Dutton Simulation's previous experience simulating forming processes such as profile roll forming using the implicit solution method in LS-DYNA was critical in establishing a successful methodology [2].

Manufacturing Process – Refining the Process

Simulation of the initial process soon revealed some problems with the second and third "V" bend operations. Firstly a straight line "V" bend isn't actually correct – the tool needs to twist in the taper region otherwise the hole alignment begins to wrap around the form rather than remaining aligned along the vertex. But more significantly, the large amount of unsupported material was found to be unstable and showed a tendency to buckle (Figures 5 & 6). Even after the final operation the distortion of the second form meant that the edges were not coming together with sufficient accuracy.

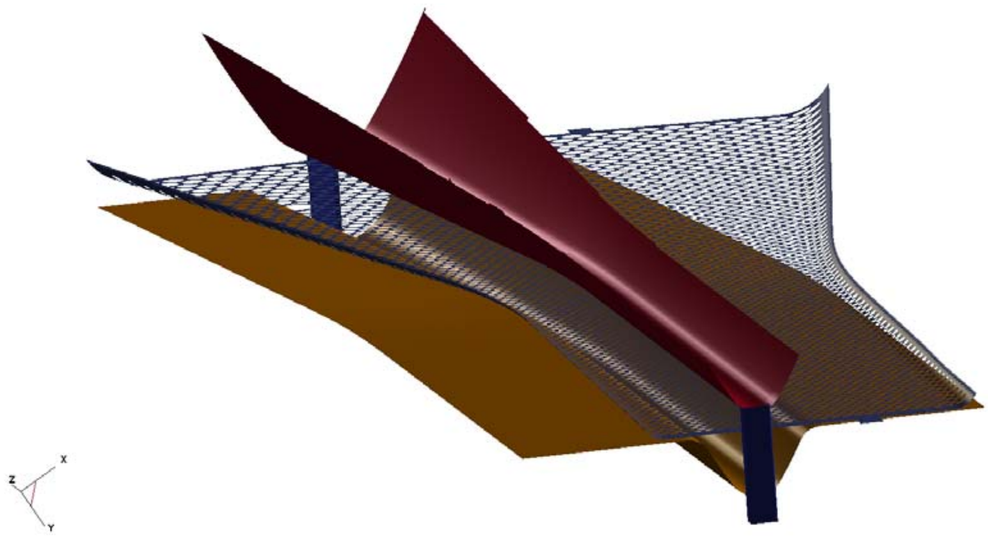

Figure 5 Initial tooling setup for "V" bend process

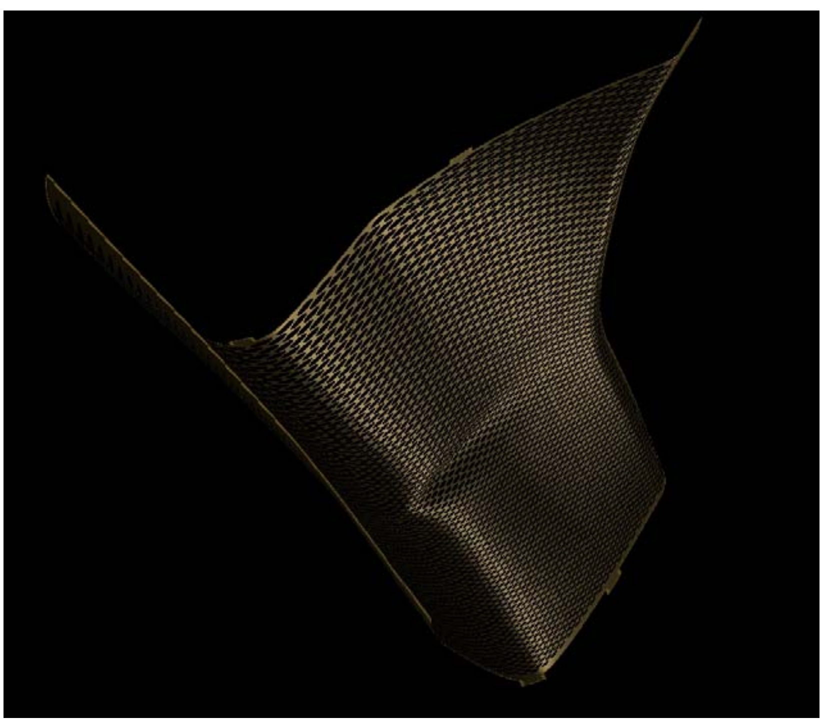

Figure 6 Unstable material with the initial "V" bend process

After review of these initial results a four operation process was proposed. The first stage remained as before but then a new “U” form stage was introduced to partly fold up the two sides simultaneously. Then two final “V” bend operations closed the two 90 degree bends to 60 degrees using the same set of tooling each time, with the part re-positioned between press strokes. This tool was a similar setup to the initial “V” bend process – but now that the material was pre-formed into the “U” shape it was much more under control so less prone to instability; also the alignment of the vertices was now pre-set in the “U” form so no twisting occurred.

A final outcome of the LS-DYNA simulation was to confirm that the predicted blank shape would successfully form to bring the edges together to the required tolerance, giving further confidence in the initial blank pattern calculation.

Springback Prediction

As with most parts formed in aluminium, springback after opening the tooling was always expected to be an issue to be dealt with for the torch manufacturing process – this was going to be especially so because the perforations in the skins further reduce the panel stiffness, and the gentle radii also meant that there was low levels of plastic strain to hold the form. Simulation was identified as a good way to understand the degree of springback and also to help generate a corrected tool geometry so that the end product would be the required shape.

The first round of forming simulation was carried out using tooling models built directly from the final CAD geometry, knowing full well that this would not end up being the final tooling shape – this would simply set the baseline for the springback analysis. The first forming operation (to initiate the transition from straight to tapered shape and form the two edges up) created very low levels of plastic strain and considerable springback (over 20mm) was predicted, as shown in Figure 7. The wider end of the form has rebounded almost 24mm compared with the handle end (fixed in this view).

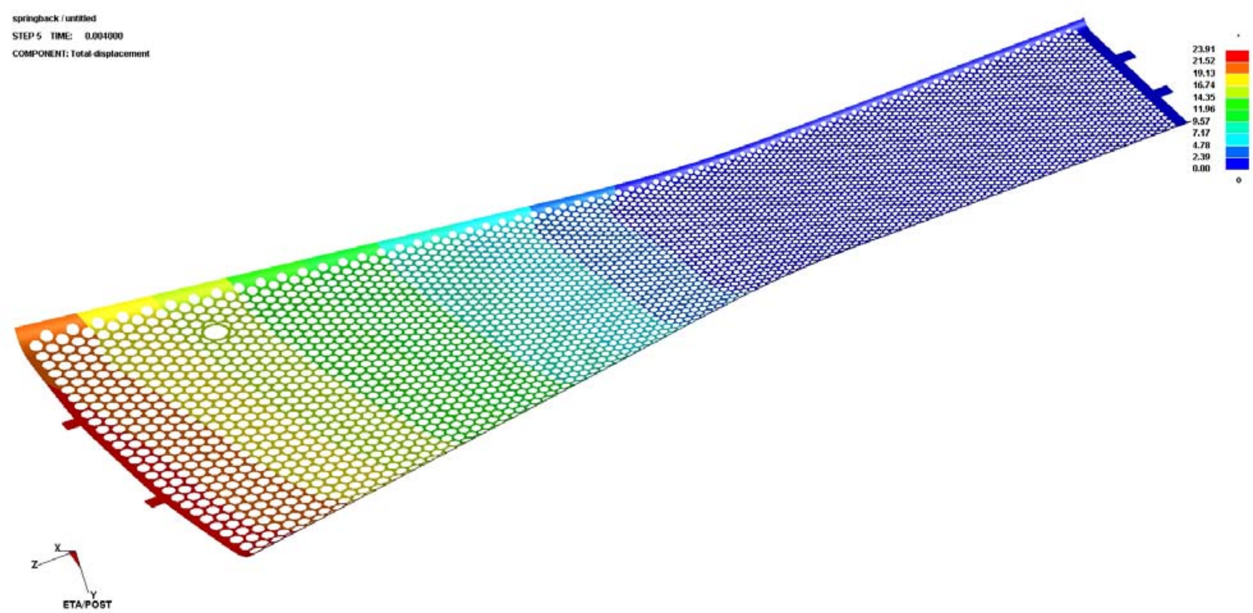

Figure 7 Predicted springback from first form operation

The second operation to bend the pre-form into a "U" shape, wiping up the two sides, also predicted considerable springback (Figures 8 & 9) – the maximum displacement here is ~14mm with the side walls both opening and lifting up with respect to the handle. If this error were not corrected then the torch would end up with different taper angles when viewed from different sides – again, clearly not acceptable. However, the process could by this stage be seen to be successful – so the next challenge was to adjust the tooling to correct for the springback.

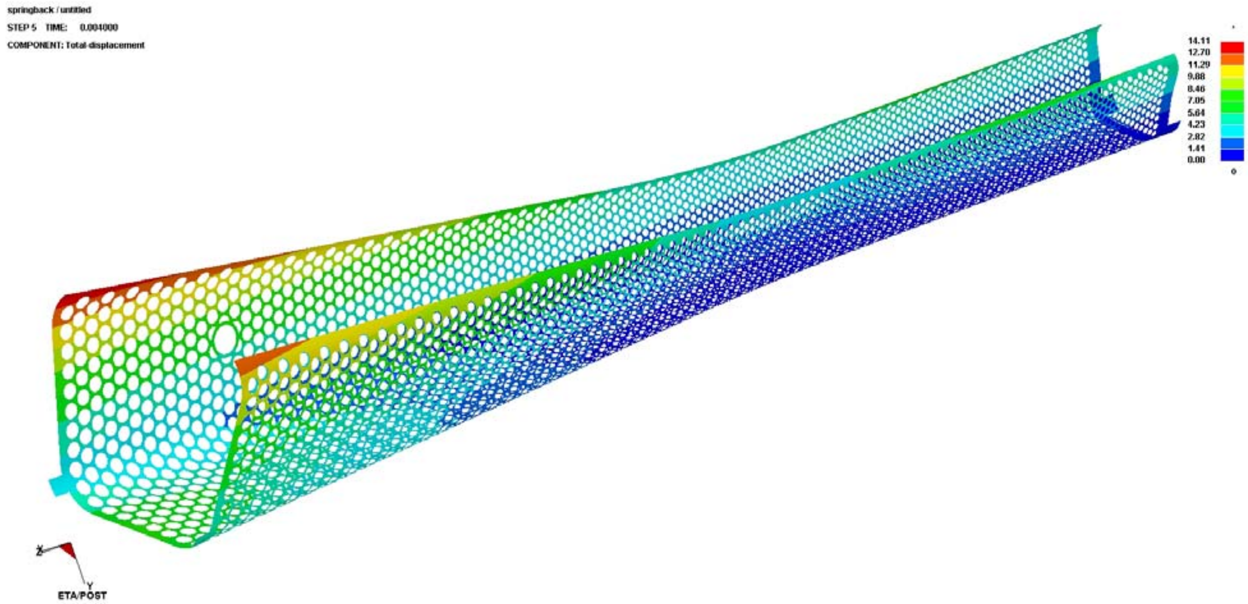

Figure 8 Predicted springback from second form operation

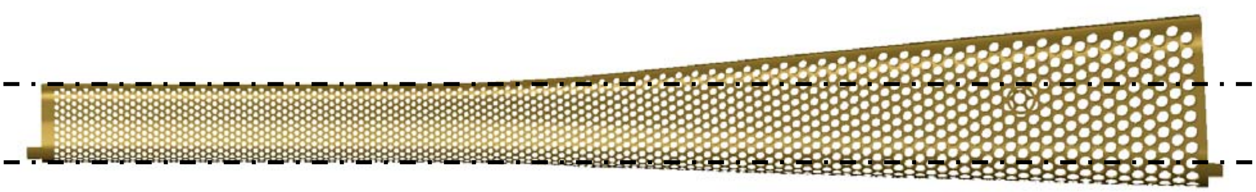

Figure 9 Predicted springback from second form operation – misalignment indicated

Springback Compensation

Once the preferred manufacturing method had been established, DYNAFORM's Springback Compensation Process was applied for each operation in turn, using the desired shape compared to the predicted shape to adjust the shape of the tooling. LS-DYNA includes an additional solution routine that generates a modified finite element mesh for the tooling based on the error between predicted and target shapes; the *INTERFACE_COMPENSATION keyword is used for this process. DYNAFORM's SCP interface provides an easy way to define the input models and parameters required for the solution. One tool (e.g., the Upper) is chosen as Master; the compensation is applied to this and other tool(s) are created by offsetting.

The modified shape can be scaled according to the user input – usually ~80% correction is tried in the first iteration as 100% usually results in a new formed shape that goes too far in the opposite direction. The updated tooling is then imported back into the original model replacing the first set of tools, and the process re-simulated to check the results against the design data once again. More than one round of compensation is often required, especially where springback displacement is relatively large.

Compensation was applied for each set of tooling required for the torch forming so that the form transferred from one operation to the next was as close as possible to the desired shape – this made controlling the final geometry easier but meant that every tool in the sequence would need to be morphed to a compensated shape.

The compensation (i.e., tool shape morphing process) is applied directly to the initial finite element mesh, as opposed to the base surfaces used for the initial iteration. Success therefore depends on the refinement and quality of the original mesh, so different mesh generation settings are often used when compensation is going to be needed.

Once the final FE mesh has been determined (i.e., a morphed tool mesh that creates a sprungback shape to the required tolerance), the final step in the process is to map the original surfaces to this modified FE mesh. The quality of the resulting surface depends on the amount of change between original and final shapes; the surfaces generated may require re-building before CNC machining of the final tool because the surface control parameters become significantly altered in the mapping process, making it difficult to capture the geometry with the original surface order while maintaining tangency.

Springback not only causes overall gross errors in the geometry but also leads to smaller but nonetheless problematic distortions in the formed surface. These distortions, often just a few 10's of micron deep, are enough to cause cosmetic defects that are quite obvious to the naked eye, especially with highly polished finishes – the gold finish on the torch was particularly unforgiving of even the slightest surface deviation.

The DYNAFORM Post-processor includes a number of tools to assess these small cosmetic defects. Stoning simulates the actual process of scratching a panel with a stone to reveal hollows; Face Reflection creates a pattern of line reflections simulating the appearance of a panel under an array for strip lights – the movement of these lines across the panel reveal distortions in the surface. Figure 10 shows a Face Reflection result for the outer skin during tool development; here you can see the slight hollow at the transition from straight to taper. Using this result we were able to fine tune the amount of overbend or over-crown in each of the tooling stages to eliminate almost all of this distortion.

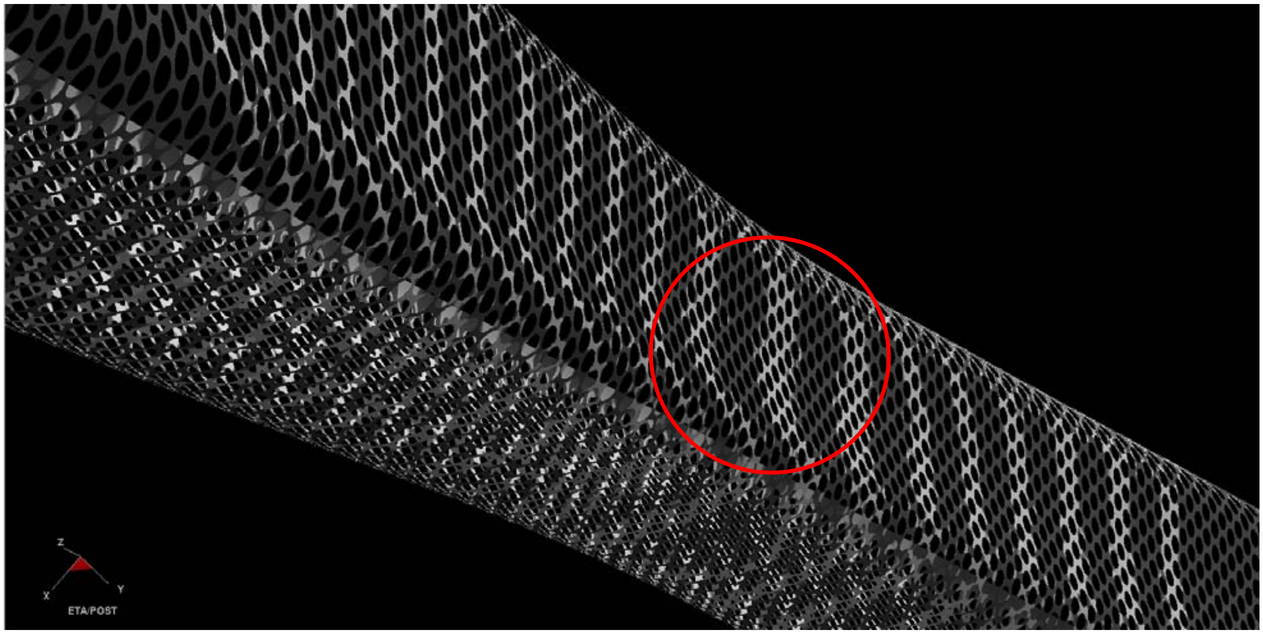

Figure 10 Cosmetic defects predicted due to springback, visualised with DYNAFORM

Conclusions

The combination of one-step and incremental finite element analysis methods proved vital to developing a successful manufacturing process for the 2012 Olympic Torch. Working to a tight schedule, Dutton Simulation were able to apply LS-DYNA to provide tooling geometry that not only corrected for the springback but also confirmed that the high quality cosmetic finish required would be achieved, allowing Premier to proceed with production of the 8,000+ Torches in good time for the Torch Relay that led up to the 2012 Games.

References

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2. "Simulating the Complete Forming Sequence for a Roll Formed Automotive Bumper Beam", Trevor Dutton, Paul Richardson - Dutton Simulation Ltd, Matt Tomlin, Tom Harrison - Wagon Automotive plc, 6th European LS-DYNA Users' Conference, Gothenburg, Sweden, May 2007.