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Experimental procedure for warm spinning of cast aluminum components

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Abstract:	High performance, cast aluminum automotive wheels are increasingly being incrementally formed via flow forming/metal spinning at elevated temperatures to improve material properties. With a wide array of processing parameters which can affect both the shape attained and resulting material properties, this type of processing is notoriously difficult to commission. A simplified, light-duty version of the process has been designed and implemented for full-size automotive wheels. The apparatus is intended to assist in understanding the deformation mechanisms and the material response to this type of processing. An experimental protocol has been developed to prepare for, and subsequently perform forming trials and is described for as-cast A356 wheel blanks. The thermal profile attained, along with instrumentation details are provided. Similitude with full-scale forming operations which impart significantly more deformation at faster rates is discussed.
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Question	**Response**
If this article needs to be "in-press" by a certain date to satisfy grant requirements, please indicate the date below and explain in your cover letter.	

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To: Journal of Visualized Experiments
Re: Experimental procedure for warm spinning of cast aluminum components

May 27, 2016

Dear Mr. Werth,

We would like to submit the attached manuscript, titled "Experimental procedure for warm spinning of cast aluminum components", to be considered for publication with the Journal of Visualized Experiments. The paper details both the equipment and protocol for performing instrumented manufacturing trials at elevated temperatures. We believe that the submitted work is novel, of benefit to industry and development of incremental forming technology, has archival significance and is therefore worthy of publication.

This paper has not been published elsewhere or accepted for publication. Its publication is approved by both authors and if accepted, it will not be published elsewhere in the same form, in English or in any other language, without the written consent of JoVE.

Warmest regards,

Matthew Roy

cc: Daan Maijer

TITLE:
Experimental procedure for warm spinning of cast aluminum components

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KEYWORDS:
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SHORT ABSTRACT:
An experimental protocol for instrumented warm rotary forming of cast aluminum alloys employing a bespoke industrially scaled apparatus is presented. Experimental considerations including thermal and mechanical effects are discussed, as well as similitude with full-scale processing of automotive wheels.

LONG ABSTRACT:
High performance, cast aluminum automotive wheels are increasingly being incrementally formed via flow forming/metal spinning at elevated temperatures to improve material properties. With a wide array of processing parameters which can affect both the shape attained and resulting material properties, this type of processing is notoriously difficult to commission. A simplified, light-duty version of the process has been designed and implemented for full-size automotive wheels. The apparatus is intended to assist in understanding the deformation mechanisms and the material response to this type of processing. An experimental protocol has been developed to prepare for, and subsequently perform forming trials and is described for as-cast A356 wheel blanks. The thermal profile attained, along with instrumentation details are provided. Similitude with full-scale forming operations which impart significantly more deformation at faster rates is discussed.

INTRODUCTION:
One of the more challenging metal forming operations currently being practiced in the aerospace and transportation sectors is metal spinning, including derivatives such as shear

forming and flow forming[1,2]. In this process, an axisymmetric workpiece is placed on a mandrel representing the final desired shape, and spun into contact with one or more impinging rollers. The workpiece being compressed between the roller and mandrel then plastically deforms, with a diverse response including combined bending, thinning and axial elongation. In a material which has limited ductility or is otherwise difficult to form, this is sometimes carried out at elevated temperature to decrease flow stress and increase ductility.

From a processing standpoint, there are a wide range of parameters which can dictate the shape and properties of the manufactured component. Numerous studies have focused on statistical techniques for optimizing various parameters[3–5]. Variables include tooling geometry, such as the shape of the tool and mandrel; forming speeds including both mandrel rotation rate and tooling feed rates; as well as material properties. When elevated temperatures are required, practitioners need to assess the minimum temperature required while still retaining a sound product.

Cast aluminum alloys are employed in a wide variety of automotive and aerospace applications, with alloy A356 used in automotive wheels. However, this alloy is not suitable for forming at room temperature[6,7] owing to its limited ductility and must be formed at elevated temperatures. This introduces a host of processing complexity, principally in controlling temperature. As this material's properties change significantly with temperature[8], it is particularly important to perform instrumented trials in which thermal conditions can be kept to within a reasonable processing window and be monitored. Detailed data on the thermomechanical behavior of as-cast A356 ranging from ambient temperature to 500 °C over a wide range of strain rates can be reviewed elsewhere.[9]

In order to support development and optimization of flow forming operations for wheel manufacturing, custom forming equipment has been developed at the Department of Materials Engineering at the University of British Columbia (Figure 1). This apparatus has been built primarily from a manual, belt-driven capstan lathe with a total output of 22 kW, and a propane torch heating system with a peak output of 82 kW (Figure 2). A mandrel with embedded thermocouples along with a rigid roller assembly (Figure 3) has been installed, which is capable of forming workpieces up to 330 mm in diameter. The mandrel has a manually activated clamping system which is able to account for large changes in workpiece diameter occurring during processing (Figure 4). A battery operated Data Acquisition (DAQ) system containing a miniature wireless computer capable of monitoring the temperature of the mandrel during forming and the blank for characterizing heating has been installed on the quill of the lathe. While other flow forming processes have been synthesized using adapted lathes[4,10], the present apparatus is the first to embody *in situ* heating and thermal data acquisition.

A processing protocol for industrially-scaled forming operations has been developed to provide indicative processing conditions. Described subsequently, this protocol consists of tooling and workpiece preparation, forming practice, concluding with end of forming trial operations.

[Figures 1-4 here]

PROTOCOL:

1. Workpiece preparation for forming trials

1.1 Acquire as-cast workpieces machined to the mandrel size such that the inner diameter runout is 0.2 mm, while the outer diameter retains as much cast surface as possible.

Note: If blanks are drawn from full-size wheel castings, machining operations are required to remove all hub and spoke portions, while providing features which can be employed to clamp the workpiece to the mandrel. This includes removal of the in-board flange.

1.2. Pre-heat a coffin furnace able to receive the entire workpiece to 135 °C, clean the workpiece with degreaser and place in furnace for an hour to prepare for thermal barrier coating application.

1.3. Rapidly remove the workpiece from the furnace, and place on a coating jig. Using an automotive-type paint sprayer, apply a thin layer of thermal barrier die coating to the inner diameter.

Note: This coating will provide lubrication and reduce heat transfer to the mandrel during forming operations.

2. Tooling preparation

2.1. Wipe down the mandrel surface with a damp cloth. Ensure that the mandrel has a total rotational runout of < 0.5 mm using a dial gauge indicator along the forming length. Assess this with a live tooling center engaged on the tailstock plate. Using a torque wrench, ensure that all fasteners aside from those on the clamp assemblies are tightened to specified torque values for Grade 12.9 bolts (in Nm: M8 – 40, M12 – 135, M16 – 340).

2.2. Start the pre-heating system by first powering the gas supply solenoid, and then igniting the torches with a flint spark lighter. Run the pre-heating system for 10 min to expel any condensate collected in the torches/hoses. Extinguish by deactivating the gas supply solenoid.

2.3. Remove any loose/oxidized coating layer on the mandrel with dry 600/P1200 grit silicon carbide paper while turning the mandrel at 20 rotations per minute (RPM).

2.4. Power the on-board data acquisition module, and run the pre-heating system until the thermocouples embedded in the mandrel surface read 200 °C with the live center engaged.

2.5. Using an automotive-type paint sprayer, lightly coat the mandrel surface with a water-based forging lubricant and allow the rotary tooling to cool to ambient temperature with the live tooling center engaged.

2.6. Loosen the jam nut assembly on the roller stand (Figure 3) with a wrench. Set the approach or attack angle on the roller assembly using a toolmaker's protractor, and tighten both internal and external nuts (M35 – 750 Nm).

2.7. Assemble the 3 clamp assemblies (Figure 4) by first engaging the M12 shoulder bolt to connect element 2 to the clamp bracket. Inspect for any thermal distortion which will prevent element 2 in Figure 4 from smoothly running against the clamp bracket. Ensure that they move freely, lightly sanding the contact surfaces with dry 320/P400 grit silicon carbide paper. Apply a thin layer of high temperature molybdenum-based lubricant with a cloth as needed.

3. Forming operations

3.1. Move the roller tool stand completely away from the mandrel towards the spindle, move the tailstock and center to be clear of the mandrel. Manually slide the workpiece onto the mandrel ensuring even engagement.

Note: As the blanks are nominally axisymmetric, there is no preferred orientation.

3.2. Assemble the clamps onto the mandrel by engaging the tapered die pins and hand tightening M16 bolts running through the mandrel into the clamp blocks. Ensure that there is even pressure being applied by rotating and manually tightening, followed by a pneumatic impact wrench set to 50 Nm.

3.3. Start the heating system and immediately start the mandrel rotating at 20 RPM. Keep applying heat until clamps loosen. For the process considered, this is approximately 3 min.

Note: This time will be slightly different for each workpiece due to subtle differences in workpiece/mandrel fitment.

3.4. Extinguish the heating system and stop the rotation of the mandrel such that the first clamp is accessible with an impact wrench. Within 30 s, tighten all clamps with the impact wrench and record the surface temperature of the workpiece in 3 locations along the length of the forming region with a reed-type thermocouple probe.

3.5. Repeat step 3.4 until the workpiece is at an appropriate forming temperature; at a minimum, 350 °C for A356.

3.6. Move the roller axially and radially (approx. 2-5 mm from workpiece surface) into position for forming, and perform one last clamp tightening (*i.e.* step 3.4).

3.7. With the heating system on, increase the rotation rate of the lathe to the intended forming speed, engage the roller to a pre-set depth into the workpiece, and activate the screw-cutting feed to move the roller axially along the length of the workpiece.

Note: For the present geometry, reasonable results were attained at 281 RPM with an axial movement of 0.21 mm/revolution.

3.8. Repeat Step 3.7 as required to increase levels of deformation. After each forming pass, ensure that the temperature does not drop below the optimal forming temperature by stopping the mandrel and using the same reed-type thermocouple probe as employed in step 3.4. If the optimal forming temperature has dropped, repeat steps 3.4 and 3.5 to reheat.

Note: Reheating can be employed, however at the expense of potentially reaching the extent of the clamp system's ability to restrain the workpiece.

4. Post forming operations

4.1. Once the desired level of deformation has been obtained, stop the heating system, and undo all clamps, and disengage the tailstock to obtain clearance for workpiece removal.

4.2. Gently tap the workpiece with a piece of brass to separate from the mandrel. If this proves to be ineffective, re-engage the heating system and rotate the mandrel at 20 RPM gently tapping until the blank separates.

4.3. Using an appropriate manipulation tool such as tongs or heavily insulated gloves, either quench the workpiece in water at 60 °C to prevent further ageing, or leave to air cool to minimize residual stress/distortion.

REPRESENTATIVE RESULTS:
As-cast aluminum A356 workpieces were formed according to the method described in this paper. The workpieces were obtained from as-cast wheels from a North American wheel manufacturer employing the low-pressure die casting process. One workpiece instrumented with thermocouples was not formed, but underwent the pre-heating cycle (Protocol Section 3, steps 3.3-3.5) to capture the distribution of temperature across the surface of the blank during this aspect of the process. This response is shown in Figure 5. A further 3 samples were deformed to various levels, including one which received two forming passes for a high level of deformation. The first two samples and the first pass performed on the latter sample served to straighten the workpiece with little demonstrable change in wall thickness. The latter sample peak wall thickness reduction was approximately 10%, the majority of which was achieved in the second pass. Cross-sections and microstructure of the as-cast blank and those obtained in multi-pass sample are shown in Figure 6. Here, the as-cast microstructure is shown to significantly be refined by the process with dendritic features barely discernable. The interdentritic eutectic is broken up by the deformation imposed, creating a much more homogenous microstructure than in the as-cast state. This improves the overall ductility as well as fatigue and fracture properties of the component. The authors have previously described more details of workpiece geometry, specific cross-sectional changes in wall thickness, defects observed, and dimensional variation in microstructure on the full set of samples[8,13].

[Figures 5-6 here]

Figure Legends
Figure 1: Experimental apparatus overview. Principle components which have been added to a

modified capstan lathe for forming at elevated temperatures. Photograph of equipment (top) and main working directions and components labelled on a computer-aided design depiction (bottom).

Figure 2: Heating system detail. A propane heating system with four discrete burners (top and bottom right) actuated from a central manifold containing a gas control solenoid (top and bottom left). Gas pressure and a discrete flow rate to each of the burners is possible, along with placement along the blank to conform to different geometries.

Figure 3: Roller stand assembly detail. The original tool holder on for the lathe has been adapted to hold a roller at arbitrary angles relative to the turning axis of the mandrel via a jam nut assembly.

Figure 4: Instrumented mandrel and clamp system overview. The rotary tooling has been designed to bolt directly to the lathe spindle, which is in turn supported by a live center on the tailstock (top and bottom left). Clamp assembly/operation is also depicted (top and bottom right).

Figure 5: Typical temperature profile of mandrel and blank. A representative transient thermal response of the blank and mandrel obtained with the heating system. Vertical dashed lines indicate where clamps were tightened during the preheating steps, and the black arrow depicts forming. The last vertical line shows where the heating system was turned off whilst the system cooled.

Figure 6: As-cast and formed result. The as-received, as-cast blank surface and geometry having a minimum inner diameter of 330 mm (top) was deformed in two passes to provide the result shown (middle). The as-cast dendritic microstructure (bottom left) is visibly modified by the forming operation and a subsequent T6 heat treatment (bottom right) as observed with optical microscopy[8,13].

DISCUSSION:

The representative results shown above highlight that the protocol and equipment employed is capable of forming cast aluminum at elevated temperatures, and has provided a platform to determine a processing window for flow forming of wheels. The technique demonstrated can be used to explore aspects of forming envelopes, including how both formed and unformed material responds to heat treatment[8]. However, there is room for improvement with the current processing protocol with this apparatus.

Regarding further instrumentation, which would accelerate process model development, the inclusion of machine-tool dynamometer and tribometers[11,12] to measure forming loads and friction factors on the roller would provide important information about the process conditions. This is a widely employed instrumentation technique for orthogonal machining studies, and could be readily implemented on the current machine. This additional instrumentation would provide useful data to accurately validate of modelling efforts[13,14] and support the increasing industrial interest in this process. In order to effectively capture the evolution of temperature of the blank during processing, a non-contact measurement technique is desirable. However, common infrared-based techniques are hampered by aluminum's low emissivity and how the surface changes during processing. This is the principal reason why an instrumented, commissioning blank was employed to capture the typical thermal response achieved with the protocol described, and served to populate a baseline heat transfer analysis to relate mandrel surface temperature to the workpiece.

As it is largely a manual forming process for a material which is sensitive to time at temperature, some inconsistencies between run to run are to be expected. Aluminum alloys have microstructures that are highly sensitive to temperatures above 100°C due to ageing mechanisms. Therefore, the most critical steps within the protocol are 1.2 and 3.3-3.7, where the blank is at elevated temperatures. Tightening and re-seating the clamps must be conducted as quickly as possible to maintain repeatability between forming operations.

The *in situ* workpiece heating employed during the pre-heating step is quite inefficient and could be improved via radiative heating. The overall processing speeds in terms of mandrel and tool movements that can be attained are somewhat limited by the capabilities of the lathe employed. Higher forming speeds require a more rigid frame with a higher load capacity, particularly if the forming of a stronger material were to be attempted. Workpiece clamping and release could be improved with the addition of hydraulic or pneumatic actuation. As heat transfer from the blank to the mandrel is largely a function of the pressure imposed by the workpiece onto the mandrel, this addition could also improve a model-based approach to ascertain the workpiece temperature during forming with the existing system.

The apparatus and procedure described has shown that forming loads for this material under these conditions approaches those for standard turning operations, and remains a very cost effective process by which to perform manufacturing trials. Research into different manufacturing routes and formability can be performed away from commercial forming equipment, which is exceedingly expensive to operate. With the apparatus and protocol described, processing parameters can be investigated prior to constructing larger scale, higher throughput equipment, and to the authors' knowledge, is a unique approach.

As the protocol developed has only been applied to one specific variant of cast aluminum alloy, there is a multitude of other aluminum foundry alloys which could be investigated for a variety of applications beyond automotive wheels. As these alloys have approximately similar processing windows from a temperature perspective, the protocol developed can be readily adapted.

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DISCLOSURES:
The authors have nothing to disclose.

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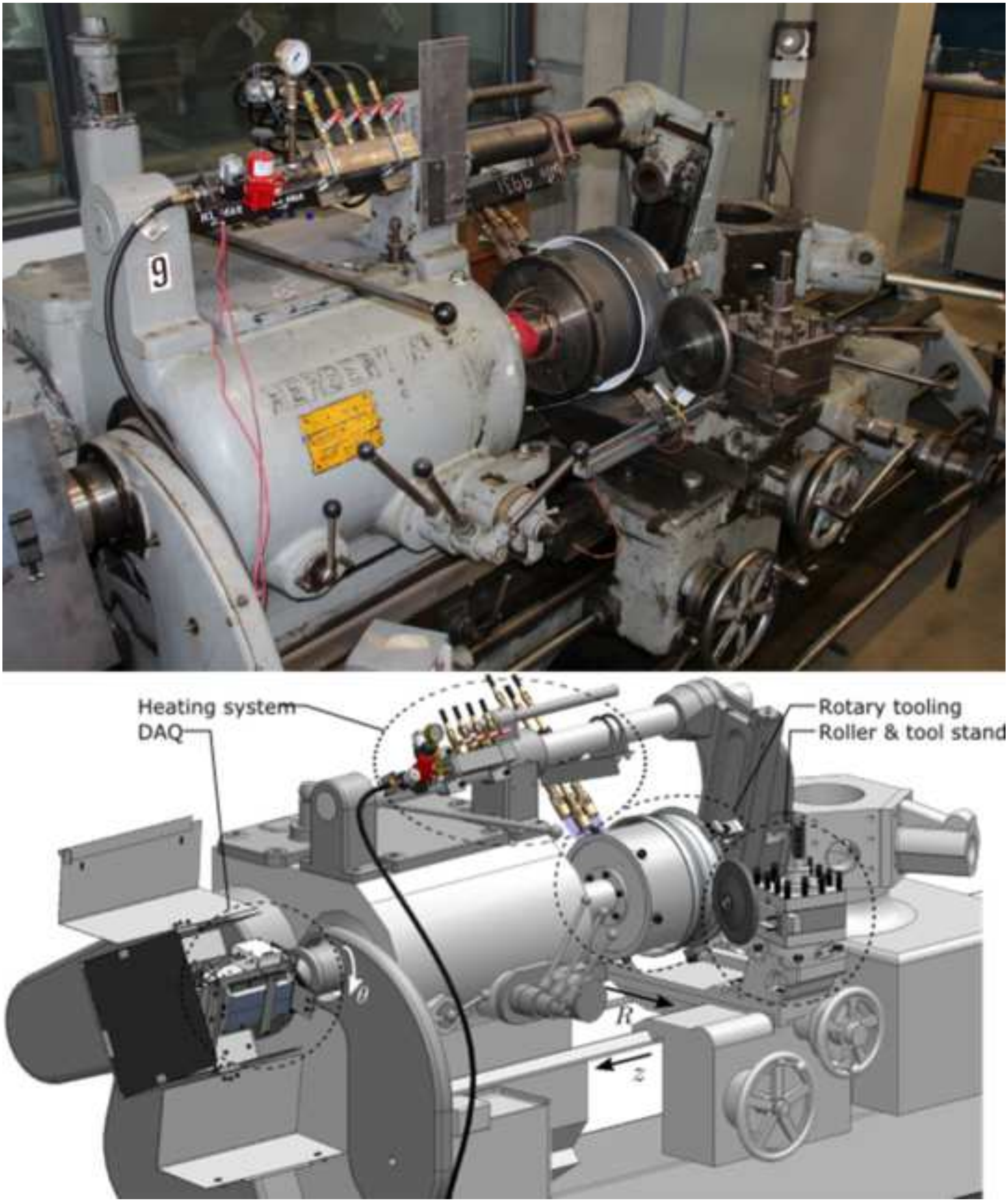
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Figure

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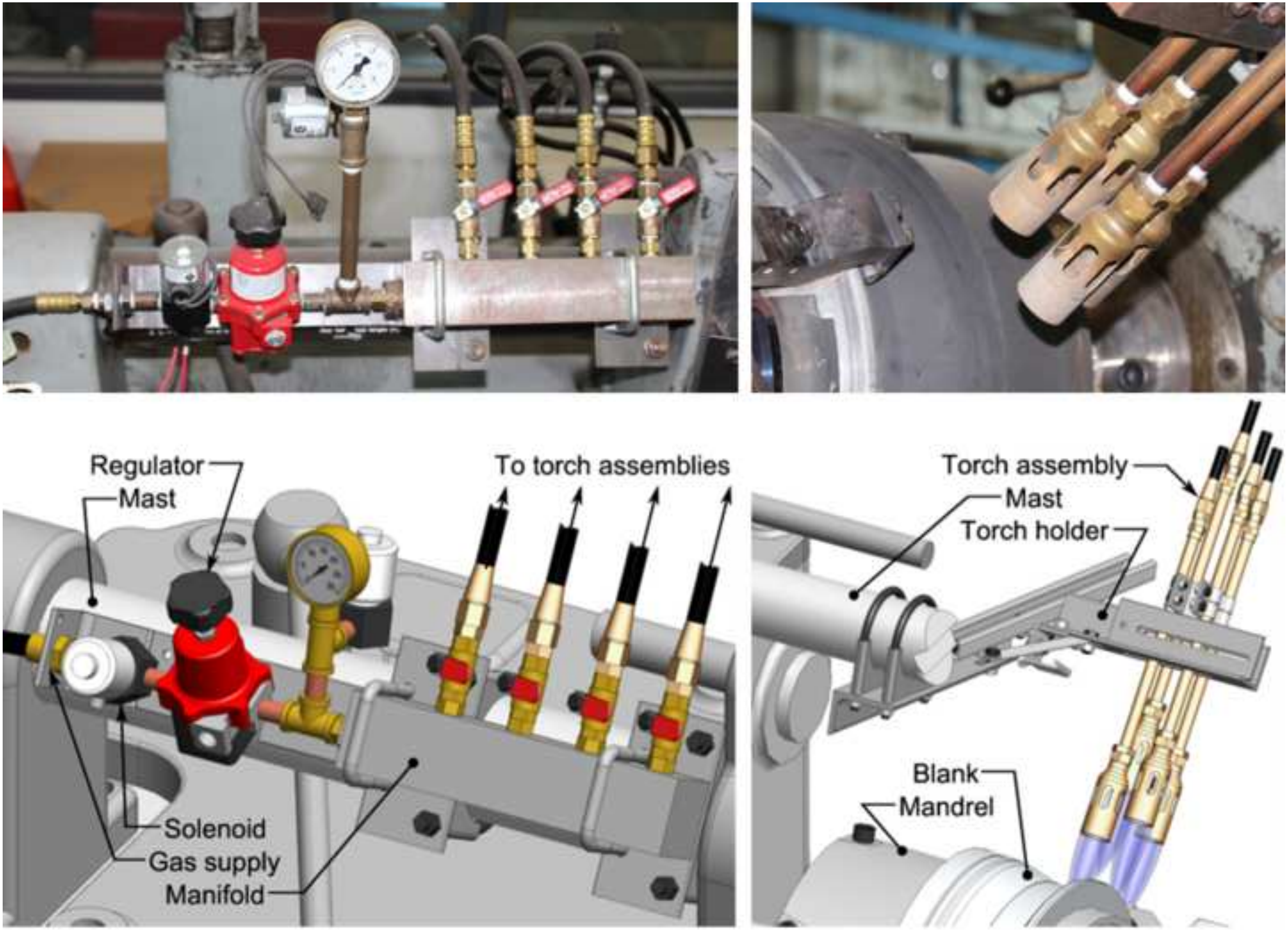

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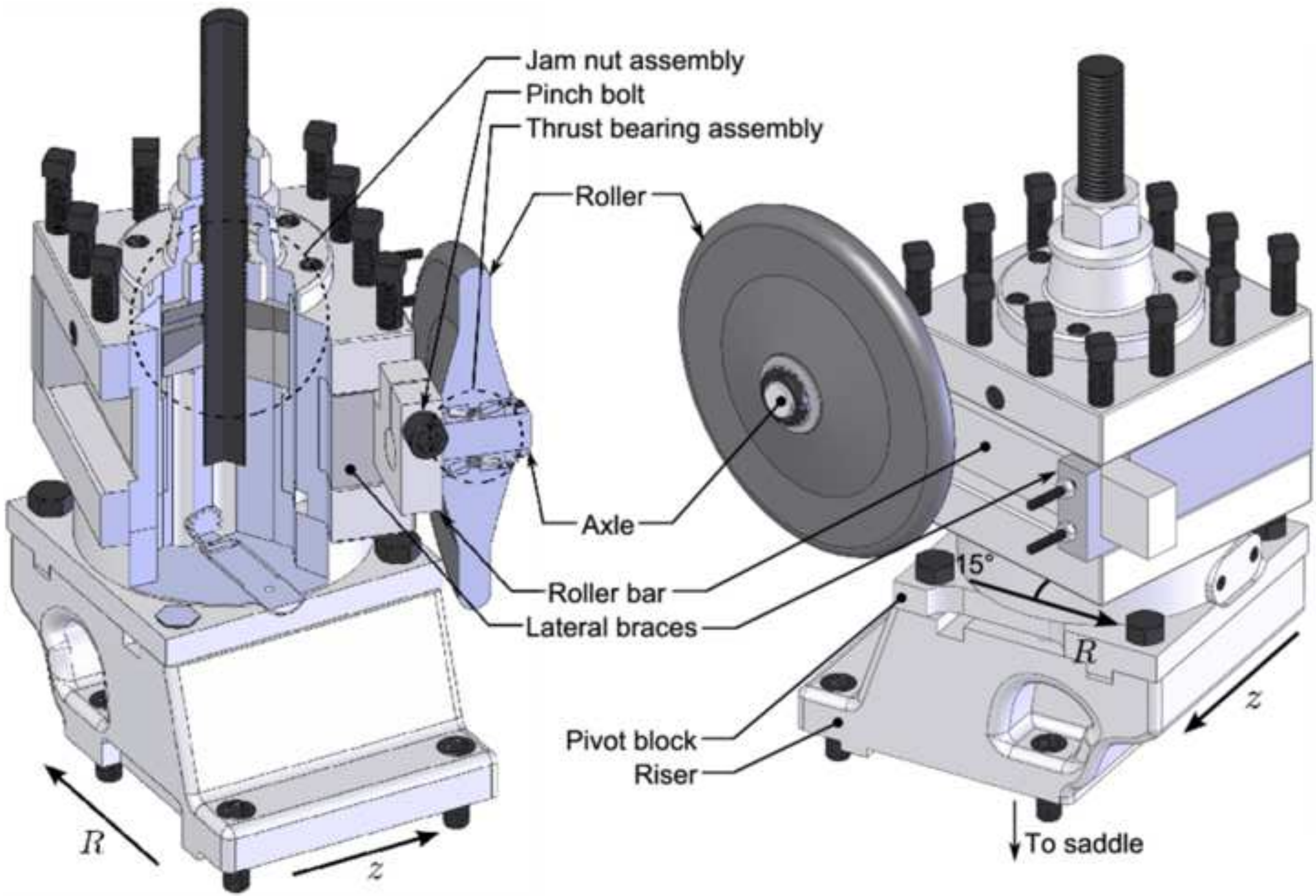

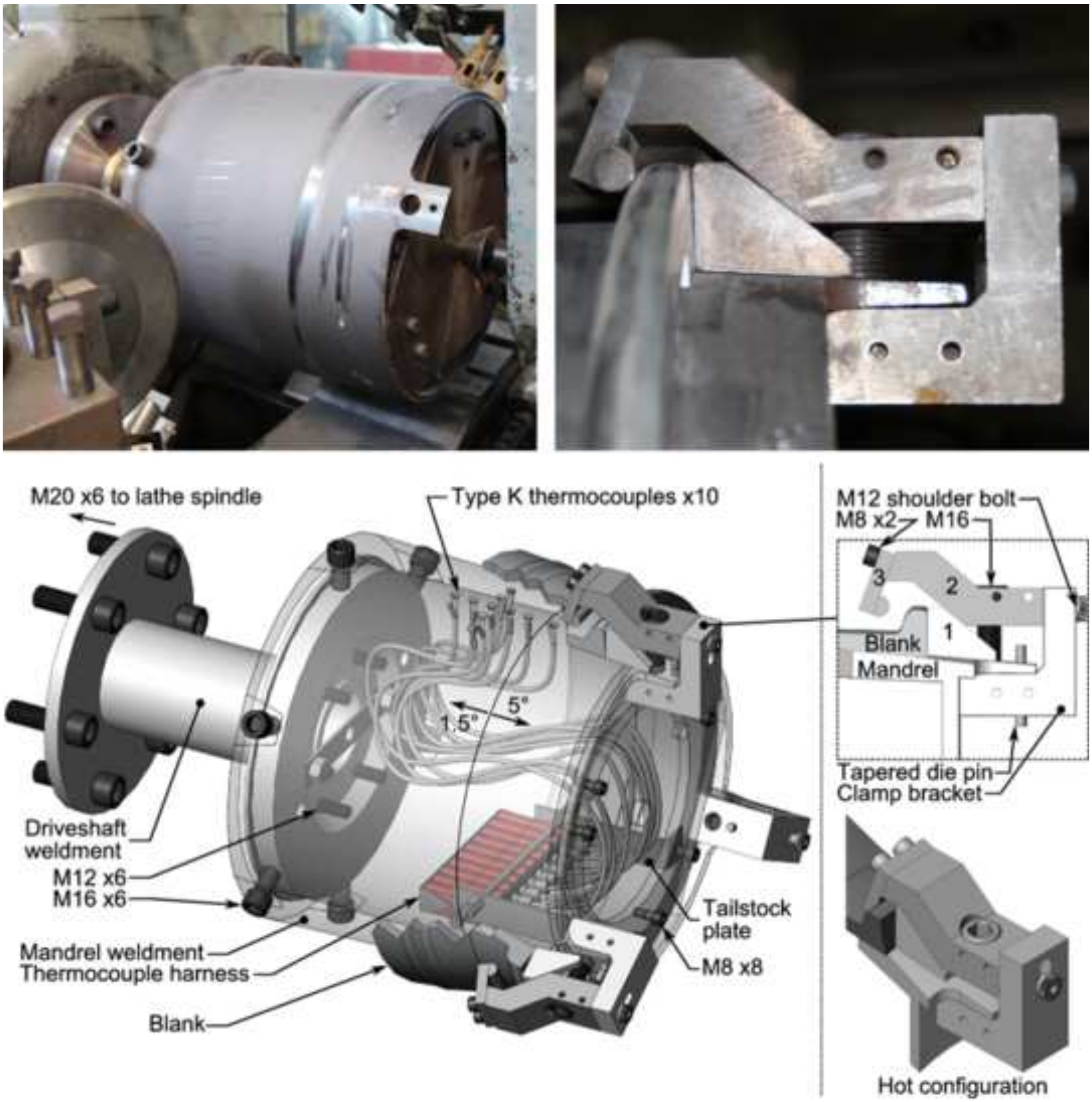
M20 x6 to lathe spindle
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M12 shoulder bolt
M8 x2
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Tapered die pin
Clamp bracket
5"
1.5"
Driveshaft weldment
M12 x6
M16 x6
Mandrel weldment
Thermocouple harness
Blank
Tailstock plate
M8 x8
Hot configuration

Figure

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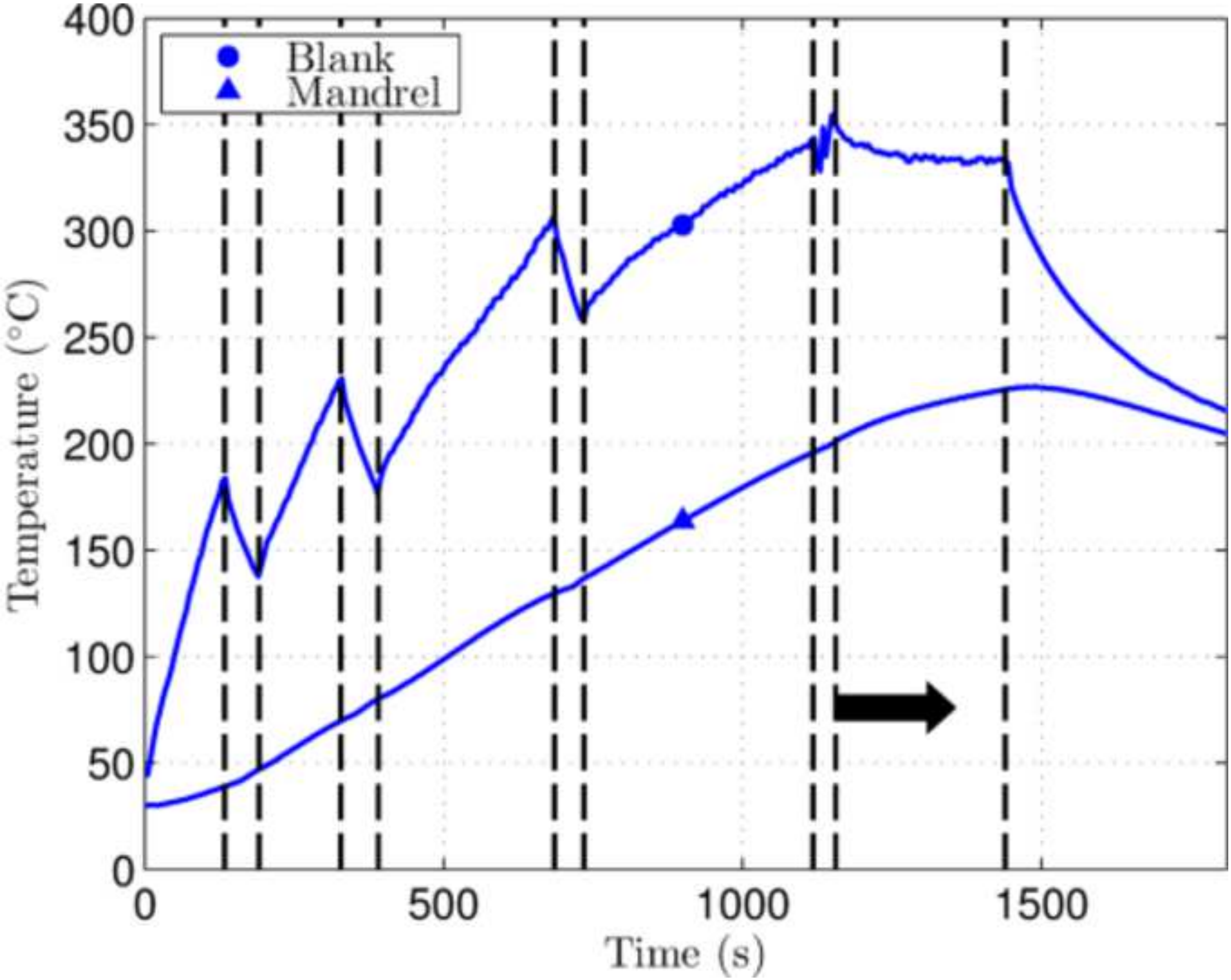

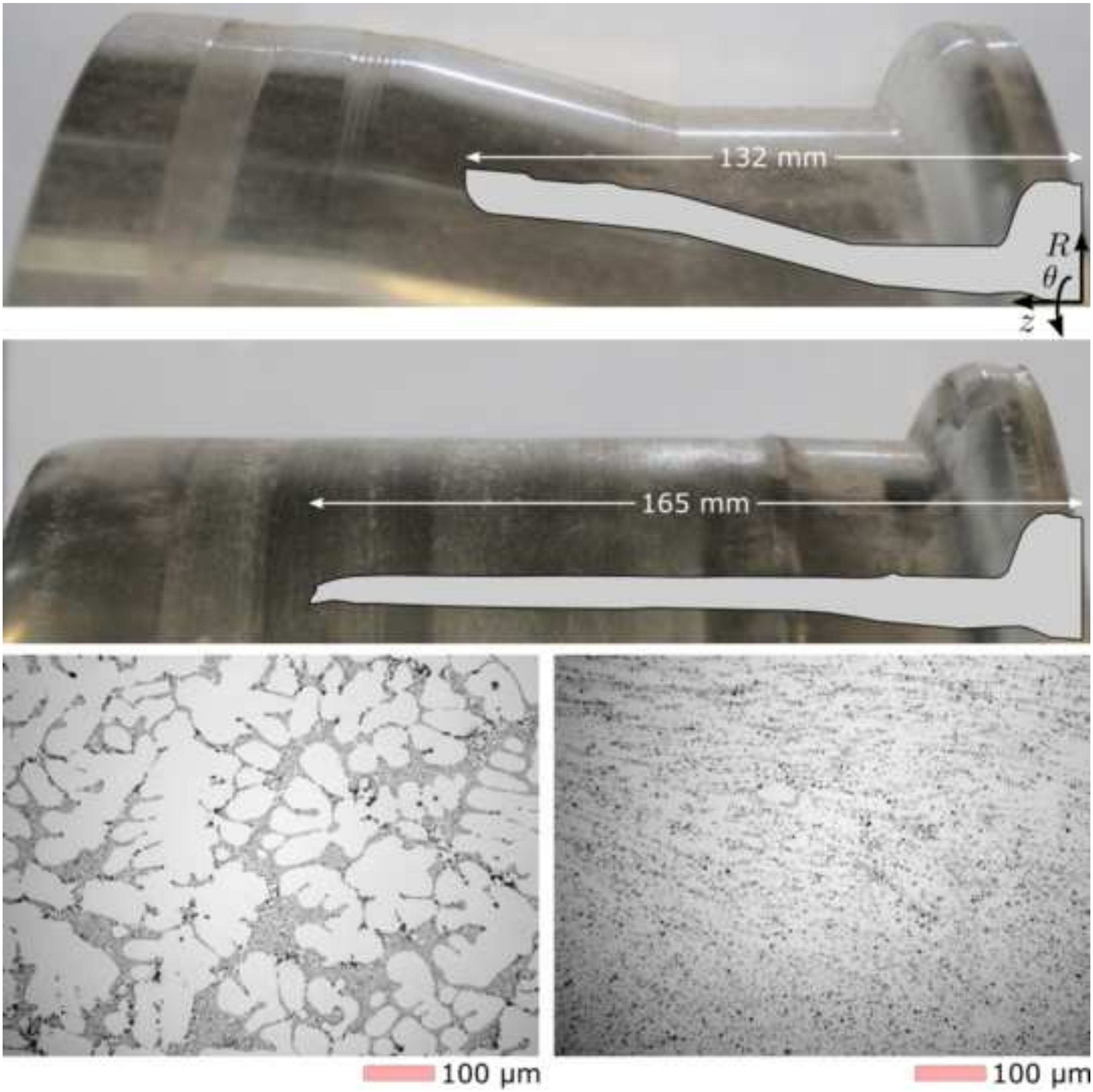
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Name	**Company**
High temperature grease	Dow Corning
High temperature lubricant	Superior Graphite
High temperature die coat	Vesuvius/Foseco
Live center	Riten Industries
Live center adapter	Riten Industries
Impact wrench	Chicago Pneumatic
Torque wrench	Westward Tools
Air-powered paint sprayer	Cambell Hausfeld
Air-powered paint sprayer	Cambell Hausfeld
Data acquisition unit	Measurement Computing
Reed thermocouple	Omega Engineering
Propane tank	Generic
Solenoid valve	Aztec Heating
Gas regulator	Aztec Heating
Burner tips	Exact
Roller bearings	SKF
Remaining equipment designed and fabricated in-house	

Catalog Number		Comments
		Reagent/Material
Molycote M-77		
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DYCOTE 32		
		Equipment
	17124	Bell-head, spring loaded
	431	Adapter for lathe
CP7749-2		1/2" drive, 0-545 ft-lb
6PAG0		1/2" drive, 0-250 ft-lb
DH4200		For die coat
DH5500		For graphite-based lubricant, high volume low pressure (HVLP) ty
USB-2416		
	88108	
		20/40 lb, POL fitted
SV-S121		
67CH-743		0-30 psi
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CORRESPONDING AUTHOR:

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Department: School of Mechanical, Aerospace and Civil Engineering
Institution: University of Manchester
Article Title: Experimental procedure for warm spinning of cast aluminum components
Signature: [signature] Date: 27/05/2016

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Mala Mani
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Re: JoVE55061 "Experimental procedure for warm spinning of cast aluminum components"

June 25, 2016

Dear Dr. Mani,

Thank you for your editorial review of the manuscript referenced above. I have made changes to the text to reflect your feedback, and these are contained the latest draft. 'Track changes' was employed to highlight the modifications made; please find attached a description of how each of your comments were addressed.

Warmest regards,

Matthew Roy BESc MESc PhD

cc: Daan Maijer

Response to editorial review

Comment 1: JoVE is unable to publish manuscripts containing commercial sounding language, including trademark or registered trademark symbols (TM/R) and the mention of company brand names before an instrument or reagent. Please remove all commercial sounding language from your manuscript text and figures. Examples of commercial sounding language in your manuscript are: Foseco DYCOTE, SureCOAT, Dow Corning Molycote, Omega Engineering model 88108, etc. All commercial products should be sufficiently referenced in the table of materials/reagents. Please replace all commercial sounding language in your manuscript with generic names that are not company-specific.

Response: References to Foseco DYCOTE, SureCOAT, Dow Corning Molycote, Omega Engineering model 88108 have been eliminated.

Comment 2: Please indicate if the article should be published as Standard Access or Open Access. The scanned copy of the Article and Video License agreement indicates Open and Editorial Manager indicates Standard.

Response: The Editorial Manager has been changed to reflect the article and video license agreement.

Comment 3: Please define all abbreviations before use. For e.g., DAQ, PC, SiC, etc.

Response: This has been done. SiC has been replaced with silicon carbide.

Comment 4: Please ensure that all text in the protocol section is written in the imperative tense as if you are telling someone how to do the technique (i.e. Do this, Measure that etc.). Avoid usage of phrases such as could be, should be, and would be throughout the Protocol. Any text that cannot be written in the imperative tense may be added as a Note, however, notes should be used sparingly and actions should be described in the imperative tense wherever possible.

Response: Passages which were not imperative (Note in 1.1) have been amended.

Comment 5: Step 2.1: How is the surface of the mandrel cleaned? How are the fasteners tightened? There should be enough detail in each step to supplement the actions seen in the video so that viewers can easily replicate the protocol.

Response: This has been amended. The mandrel is cleaned with a damp cloth/rag, and fasteners are tightened with a torque wrench. The model has been included in a revised table of equipment.

Comment 6: 2.2: Please mention how to pre-heat and extinguish.

Response: These details have been included.

Comment 7: 2.3: Please mention the speed.

Response: This detail has been included.

Comment 8: 2.7: How is the 3 clamp assemblies assembled? Please mention how to inspect thermal distortion. How is the lubricant applied?

Response: The step has been amended to direct the reader to Fig. 4 where the clamp assembly is shown in detail, lubricant application is detailed.

Comment 9: 3.3: What temperature?

Response: There is no target temperature for any of the components aside from the stipulation of the workpiece temperature (Step 3.4/3.5). The heat output from the torches is fixed, and transfer is complicated. The step is dictated by physical response of the overall system, driven by thermal expansion.

Comment 10: 3.5: Repeat step 3.4 alone or 3.3 and 3.4? Please clarify.

Response: Clarified that step 3.4 can be repeated.

Comment 11: 3.8: Please specify which step(s) are repeated. Is the optimal forming temperature 350 deg C? What is the reheating temperature?

Response: As per Step 3.5, the optimum forming temperature for the specific material is 350 deg C. Steps 3.4 to 3.5 have been identified as those to be repeated to re-heat the work piece.

Comment 12: 4.3: Please mention the tool used in your studies.

Response: Tongs or heavily insulated gloves have been identified.

Comment 13: After you have made all of the recommended changes to your protocol (listed above), please re-evaluate the length of your protocol section. There is a 10-page limit for the protocol text, and a 3- page limit for filmable content. If your protocol is longer than 3 pages, please highlight (in yellow) 2.75 pages or less of text (which includes headings and spaces) to identify which steps should be visualized to tell the most cohesive story of your protocol steps. Please see JoVEs instructions for authors for more clarification. Remember that the non-highlighted protocol steps will remain in the manuscript and therefore will still be available to the reader.

Response: The protocol remains less than 3 pages.

Comment 14: Please disregard this comment ...

Response: All artwork is original or the authors currently hold the copyright to.

Comment 15: Please ensure that all parts/panels of the figures are mentioned in the figure legend. For e.g. description of Figure 5 left is missing.

Response: Changes to the figure legends for figures 1, 2, 4 and 5 have been made to reference each panel explicitly, where applicable.

Comment 16: Please expand your discussion to cover the following in detail and in paragraph form: 1) modifications and troubleshooting, 2) limitations of the technique, 3) significance with respect to existing methods, 4) future applications and 5) critical steps within the protocol.

Response: The discussion has been expanded and revised as recommended, with specific attention paid to highlighting critical steps within the protocol, significance and future applications.

Comment 17: References: Please abbreviate all journal titles.

Response: This has been done.

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Mala Mani
Science Editor
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Re: JoVE55061 "Experimental procedure for warm spinning of cast aluminum components"

August 14, 2016

Dear Dr. Mani,

Thank you for both your editorial review of the manuscript referenced above, as well as the reviewer's comments. I have made changes to the text to reflect both your feedback, as well as those from the reviewers and these are contained in the latest draft. 'Track changes' was employed to highlight the modifications made; please find attached a description of how each of the received comments were addressed.

We thank the reviewers for their efforts and believe that their comments serve to significantly strengthen the submission.

Warmest regards,

Matthew Roy BESc MESc PhD

cc: Daan Maijer

Response to editorial review

Comment 1: Formatting requests to specifically spell out author first names and italicising Latin phrases.

Response: The requested formatting changes have been implemented where possible, however, the first names of all authors are not known/accessible.

Comment 2: 2.1 How is the rotational run-out ensured?

Response: Modification to the manuscript and equipment list have been made to reflect the use of a dial gauge indicator.

Comment 3: 2.5 - Please clarify to ambient with the center engaged.

Response: Changed to ". . . to ambient *temperature* with the *live tooling* center engaged."

Comment 4: 2.6 - How is this loosened?

Response: Changed to "Loosen the jam nut assembly on the roller stand (Figure 3) *with a wrench*."

Comment 5: 2.7 Please describe how these should be assembled rather than referencing the figure if the assembly is to be filmed.

Response: This has been implemented.

Comment 6: 3.1 How is the workpiece loaded? Is there a particular orientation?

Response: This has been clarified.

Comment 7: 3.7 Are these actions done manually?

Response: Yes, it is a manual lathe. This detail has been included in the introduction.

Comment 8: 3.8 How is this ensured?

Response: Clarified.

Comment 9: 4.1 How does one know when forming is complete?

Response: Forming is complete when the experimentalist is satisfied with the level of deformation obtained. This has been clarified.

Response to Reviewer 1

Comment 1: The keyword of 'forging' is not consistent with the topic of this paper. The topic of this paper is experimental procedure for warm spinning of as-cast aluminum and the forging is not involved.

Response: We had included the keyword as there are elements to the process which encompass forging (lubricants, etc.) and for the purposes of reaching a potentially wider audience. We have removed the keyword.

Comment 2: The paper indicate that "this alloy is not suitable for forming at room temperature owing to its limited ductility and must be formed at elevated temperatures", please present the material properties of as-cast A356 aluminum at room temperature and the elevated temperature.

Response: We presume that the reviewer is requesting mechanical properties of the alloy. The authors have previously published a paper on the constitutive behaviour of this alloy, which we have now referenced. As the material is also rate-dependent, we feel that presenting mechanical properties will detract from the scope of the submission.

Comment 3: The forming parameters are important for obtain sound product. Please explain that in Fig 1 what inputs can be monitored by the battery operated Data Acquisition (DAQ).

Response: We have amended P2, 3rd paragraph to include "A battery operated Data Acquisition (DAQ) system containing a miniature wireless computer capable of monitoring the temperature of the mandrel during forming and the blank for characterizing heating has been installed on the quill of the lathe."

Comment 4: The temperature distributions of the workpeice influence the geometric dimension and microstructure obviously. But as described in step 3.4 to step 3.8, the spinning process has to be stopped to clamp as well as measure and adjust the temperature. The distributions of the workpeice temperature will be influenced. Therefore, it is better to use the on-line measurement and temperature automatic adjustment system.

Response: The authors agree, and this is evident in the discussion session. However, both budget and the interference of contact-based temperature measurements to the forming process preclude this addition at the present time. The most common contactless measurement is through measuring/correlating infrared emission, which is prone to error in the current application by aluminum's low emissivity. We have added a passage to that effect at the end of the 2nd paragraph in the discussion section: "In order to effectively capture the evolution of temperature of the blank during processing, a non-contact measurement technique is desirable; however common infrared-based techniques are hampered by aluminum's low emissivity and how the surface changes during processing. This is the principal reason why an instrumented, commissioning blank was employed to capture the typical thermal response achieved with the protocol described . . ."

Comment 5: The shape and geometric dimension of the blank and spun workpiece is the base to design a reasonable forming method and process parameters of spin-forming, the forming qualities (geometric dimension and microstructure) of the spun workpiece are the verification of the forming process. Please present the geometric dimension of the blank, as well as the forming quality of the spun workpiece.

Response: The authors have clarified the existing details provided in Fig. 6 with the last sentence in representative results being "Cross-sections and microstructure of the as-cast blank and those obtained in multi-pass sample are shown in Figure. 6, and the authors have previously described more details of workpiece geometry, specific cross-sectional changes in wall thickness, defects observed, and dimensional variation in microstructure on the full set of samples.[8,13]" citing the relevant papers.

Comment 6: The reduction ratio of wall thickness is one of the most important parameters used to indicate the deformation degree. Please show the reduction ratio of each pass during the warm spinning of as-cast A356 aluminum.

Response: Please see the authors' response to Comment 5.

Comment 7: The array of the burners in Fig. 5 is 1x4, it is different from the 2x2 in the other figures. The array of the burners would influence the temperature distribute of the workpiece, why the array of the burners for measure the workpiece temperature is different from that of the flow forming process?

Response: The reviewer's point is well taken. The photograph originally submitted with Fig. 5 of the heating system was from initial heating trials, while the representative results were from the arrangement shown elsewhere in the submission. We have removed the photo and modified the figure legend.

Response to Reviewer 2

Comment: Regarding the request for quantified levels of uncertainty over the thermal data collected and the recommendation of the inclusion of thermal camera equipment.

Response: This comment has largely been addressed by our response to Comment 4 from Reviewer 1; there is some confusion as to the function of the data acquired from the DAQ system. To bypass the issues of indirect measurement of the blank/workpiece temperature, we have advocated a heat transfer model approach, and have modified the discussion section accordingly. As the temperatures are recorded at various stages of the process directly from the blank, the data from the DAQ is complimentary and serves to inform a process model.