

Thermal Response of Aluminum Engine Block During Thermal Spraying of Bores: Comparison of FEA and Thermocouple Results

Klaus-Peter Heinig, David A. Stephenson, and Timothy G. Beyer
 Ford Motor Company

ABSTRACT

Thermally sprayed coatings have been used in place of iron bore liners in recent aluminum engine blocks. The coatings are steel-based, and are sprayed on the bore wall in the liquid phase. The thermal response of the block structure determines how rapidly coatings can be applied and thus the investment and floor space required for the operation. It is critical not to overheat the block to prevent dimensional errors, metallurgical damage, and thermal stress cracks. This paper describes an innovative finite element procedure for estimating both the substrate temperature and residual stresses in the coating for the thermal spray process. Thin layers of metal at a specified temperature, corresponding to the layers deposited in successive thermal spray torch passes, are applied to the substrate model, generating a heat flux into the block. The thickness, temperature, and application speed of the layers can be varied to simulate different coating cycles. The temperature field in the block is calculated using a transient thermal analysis with convective cooling on exposed surfaces. The stresses in the coating are computed using a residual stress relaxation method. Computed temperature fields are compared to thermocouple measurements from two V8 blocks sprayed using the Plasma Transferred Wire Arc (PTWA) process at the Ford Essex Engine Plant. Measured and computed peak temperatures agree well. The application of the procedure to eliminate a prototype thermal stress crack and to the investigation of torch paths is described.

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1. INTRODUCTION

Thermally sprayed coatings have been used in place of cast iron bore liners in a number of low and high volume aluminum engine block applications [1, 2, 3, 4, 5, 6, 7, 8]. Reported advantages of the coatings include weight reduction, improved heat transfer, improved packaging, and friction reduction. The coatings, which are steel based, are applied in the liquid phase by a plasma torch. It is desirable to minimize the time required to coat a bore, especially in high volume applications, to minimize investment in spray cells. This can be done by increasing the deposition rate, but since the liquid metal spray imparts substantial heat to the block, the block thermo-structural response must be considered to avoid dimensional errors, metallurgical damage, and thermal cracks.

This paper describes an innovative CAE method for calculating substrate temperatures and coating residual stresses for thermally sprayed engine bores. The method is validated using thermocouple measurements from Ford 5.2l V8 blocks sprayed using the Plasma Transferred Wire Arc (PTWA) process. The production process is briefly described in [Section 2](#). The CAE method and thermocouple measurements are described in [Sections 3](#) and [4](#). Agreement between measured and computed results is discussed in [Section 5](#). The application of the method to the resolution of a prototype thermal cracking issue and to torch path studies is discussed in [Section 6](#).

2. PROCESS DESCRIPTION

The coating of cylinder bore walls is a multi-step process to ensure proper adhesion of the thermal spray material to the aluminum bore wall [1]. In the Ford 5.2l V8 process, the cylinder bores are mechanically roughened using an interpolated milling process to provide an interlock for the thermal spray material to build upon [9,10]. Coating is done using the PTWA process ([Figure 1](#)), in which a wire feedstock is continuously fed into a heat source, where the material becomes molten or partially molten. An arc is formed between the non-consumable tungsten cathode and the consumable wire anode. Gas (argon and hydrogen) flowing around the arc forms the plasma. The particles are further atomized and propelled onto a prepared substrate by a stream of compressed air. Due to the high kinetic energy, the particles flatten when they impinge on the surface of the substrate; the heat transfer between the flattened particles and the substrate causes a rapid solidification [4]. These flattened particles build up a lamellar coating in and around the mechanically roughened bore surface. Repeated passes with the rotating torch will build layers of material to reach the desired thickness required for the product ([Fig.2](#)). The 5.2l V8 is a low-volume product machined on an existing flexible CNC system, and requires a relatively thick coating due to the tolerance stack-up of the existing process sequence for lined blocks. The coated cylinder is finished by rough boring followed by honing.

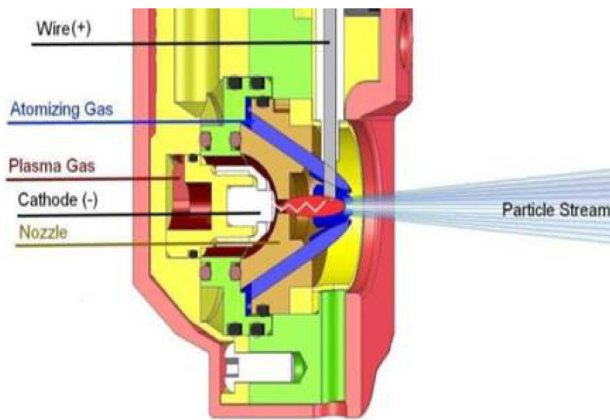


Figure 1. Cross section through a Plasma Transferred Wire Arc (PTWA) torch head.

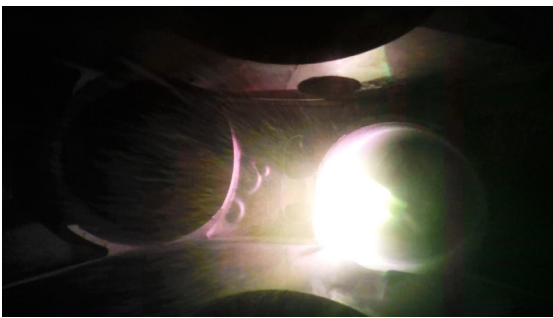


Figure 2. Torch spraying bore 5 as seen from below.

3. CAE METHOD

For a better understanding of the PTWA process described in section 2, a CAE methodology of the process has been developed based on the Finite Element Method [11]. In order to capture the thermal and mechanical effects during and after spraying, a 2-step approach was chosen to decouple and simplify the problem (Fig. 3).

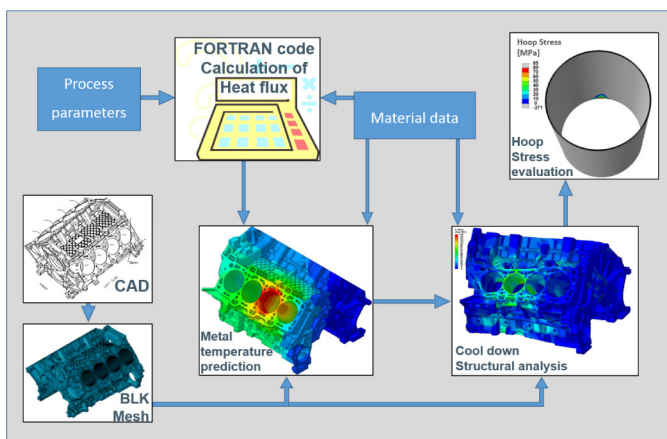


Figure 3. Flow chart of the CAE methodology.

In a first step, the thermal behavior is analyzed by a transient metal temperature prediction using process parameters and different material properties. The second step is a structural analysis of the cool down event of a specific bore to ambient temperature using the thermal results from step one as thermal boundary conditions. Here the

assumption is, that at the end of the coating of a bore there are no residual stresses in the PTWA due to the fact that each new spraying pass is annealing the layer before. The cool down analysis calculates the residual stresses in the PTWA and the base engine block. These stresses are analyzed in terms of hoop stress in the PTWA coating. The magnitude of the tensile hoop stresses is correlated to the probability of coating cracks. The location of positive hoop stress is often identical with coating cracks found in the real engine block. Possibly critical regions of the bore can be identified from results from either step. With the help of the CAE-simulation, the process parameters and also the engine block design itself can be virtually varied and modified to find the best coating without costly prototype builds.

In this paper we will focus on the thermal simulation part and its correlation with real world thermocouple measurements. Knowing the metal temperatures as accurately as possible is crucial for a realistic structural simulation. As shown in the flow chart (Figure 3) the basis of the simulation is the 3D-CAD model of the engine block. The block will be meshed for a finite element analysis with a commercial meshing tool. This mesh contains a solid element mesh for the base engine block and shell meshes for the PTWA coating. Additionally it has to contain predefined areas for convective and forced cooling and, as a result of the calibration done with thermocouple measurements, special areas where PTWA is deposited unintentionally but with a significant influence on the temperature response of the system.

In an early stage of the methodology development, the PTWA layers itself were also modeled as solid elements as depicted in Fig. 4. A tube of the layer thickness and the temperature of the spray droplets is brought into contact with the block. Heat flux is enabled and the transient temperature calculation starts. On the outer surface of that tube, air cooling is activated. After the time for a pass, all temperatures are saved and the next tube is brought into contact with the previous one, where the air cooling is deactivated and natural convection activated. This continues until the end of the process for all bores. Spraying strategies with small layer thicknesses and many passes cannot be simulated this way because of the huge model size. Small layer thicknesses imply small finite element sizes to be in the limits for the elements aspect ratio. This approach is not suitable for producing a flexible and versatile solution.

Therefore a FORTRAN routine has been developed to calculate the amount of energy transferred into the bore wall within each spraying step. It is using the process and material parameters shown in Table 1 and the bore dimensions diameter and height. With this information it calculates the mass of the added layer and, with the droplet temperature and the specific heat of the PTWA material, the heat flux into the bore. The program creates a loading history which will be added to the simulation input deck. The transient thermal simulation performed with this input deck using ABAQUS as solver calculates the time dependent metal temperature evolution during the PTWA spraying process. Using the bore numbering convention shown in Fig. 5, post-processing of the simulation results deliver temperature-time curves as shown in Fig. 6 for locations where thermocouples were mounted as discussed in the next section. As expected temperatures increase for later bores due to block heating from spraying previous bores.