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David Taylor Research Center

Bethesda, MD 20084-5000

DTRC-SME-91-51 July 1991

Ship Materials Engineering Department

Research and Development Report

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An Optical Roughness Sensor for the Real Time Determination of Spray Formed Preform Quality

by

Rochelle D. Payne

Angela L. Moran

Craig J. Madden

Paul Kelley

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CONTENTS

FIGURES

TABLES

An Optical Roughness Sensor

for the Real Time Determination of Spray Formed Preform Quality

Rochelle D. Payne, Angela L. Moran,

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ABSTRACT

As part of the intelligent processing efforts in spray forming technology at David Taylor Research Center, a laser stripe sensor has been implemented to monitor preform characteristics. The preform surface roughness data is measured in real time and the correlation to preform quality in terms of porosity levels is assessed. The laser stripe method is not a direct indicator of quality but can be used with other sensors and advanced control techniques for control of the spray forming process.

ADMINISTRATIVE INFORMATION

This report was prepared under Work Unit 1-2812-921 of the Submarine Materials Block. The program manager for this task is Mr. Ivan L. Caplan, DTRC, Code 0115.

INTRODUCTION

The spray forming process improves on many aspects of alloy production. It can be much more economical than both conventional processing and powder metallurgy and can yield a fully dense material when process parameters are set correctly. However, the process is not well understood and there is no clear correlation between spray formed preform quality and processing parameters for all materials. As a result, the determination of the optimal processing parameters can be an extensive trial and error process.

In an effort to avoid this time consuming process and to make the process more reproducible, the spray forming group at the David Taylor Research Center is implementing real time sensing of preform temperature, rate of growth and quality. The objective of this program is to develop sensor and control technology to monitor critical process conditions and to modify parameters during the process to produce components with desired qualities. This objective has been divided into two phases. In the first phase, sensors and controls were developed to monitor and correct simulated process conditions. In the second phase, selected sensors and controls will be combined with actuators for integration with DTRC equipment. Spray forming control strategies have been presented in detail in (1). The emphasis in this paper is on the application of these strategies towards the use of a laser stripe sensor for the calculation of root mean square (RMS) preform surface roughness. The objective of this study is to correlate this calculation of roughness with the preform quality.

BACKGROUND

Spray forming is a relatively new processing technique in which a stream of molten metal is atomized by an inert gas, producing a spray of liquid droplets. These droplets are cooled by the atomizing gas and accelerate towards a substrate where they consolidate to form a near fully dense deposit. The spray formed product is similar to the powder metallurgy product in that it has a rapidly solidified, grain-refined microstructure with limited segregation. However, unlike powder metallurgy, spray forming is free from the time consuming and costly steps of powder production, storage and handling, sintering and hot consolidation. Recent work at David Taylor Research Center evaluated the feasibility of utilizing (Osprey) spray forming to produce a variety of alloys including nickel base alloys, steel, bronzes and copper-base alloys for military applications. An extensive study of Alloy 625 indicated that the spray formed materials had equivalent or superior properties to the conventionally and powder metallurgy processed materials at a reduced production cost (2).

SENSOR CONFIGURATION

Although the benefits of spray forming are numerous, the process requires more sophisticated control technology than is currently provided. This control technology must be developed in order to achieve the level of reliability and reproducibility necessary for widespread commercialization. Relationships between primary process parameters and indicators of final part quality which can be sensed and controlled in real time must be established. It is known that an experienced spray forming operator will visually observe the surface roughness and the rate of growth of the preform to determine preform quality. If an operator wishes to alter the quality of the preform based on these two visual properties, he may change the appropriate process parameters before the run has finished.

It is possible to observe surface roughness and rate of growth through advanced sensing techniques as well. However, there are limitations because the depositing material is not solid and because of the harsh environment inside the chamber which is due to temperature variations, gas flow, metal particles, splats and movements of the manipulator. An optical sensor was chosen as it can observe the spraying of the material from outside the chamber through a glass window.

The optical sensor consists of an argon laser, a CCD video camera, acquisition and enhancement software, roughness determination software and an error accommodation provision. An argon laser was selected so that band-pass filtering could be implemented to attenuate the thermally induced radiation of the preform. In addition, the wavelength of the argon laser (514.5 nm) was within the sensitivity range of the CCD camera. The camera provides a spatial resolution of 0.065 cm in wavelength and 0.015 cm in amplitude. The laser is expanded by a zoom line projector into a long thin stripe and projected onto the depositing preform along the preform horizontal radius. The positioning of the laser stripe along this radius is done to reduce interference from the spray and the overspray. This image is captured by the CCD video camera placed at an angle of about 55 degrees to the laser-preform line (see figure 1).

The camera is adjusted so that it can capture the entire spray width. The video of a run will show a flat stripe that slowly builds to a maximum on one side of the screen while the other side remains at the minimum. This allows image analysis through the entire deposition zone from the inside diameter to the outside diameter. These conditions were derived for tubulars formed on a 10.2 cm diameter mandrel. These tubulars were never more than 38.1 cm in length and had wall thicknesses of approximately 2.5 cm.

IMAGE ENHANCEMENT AND ANALYSIS

Once the image has been recorded, a commercially available image analysis board captures and digitizes a frame. The image analyzer then decides whether the intensity of the laser stripe is sufficient to differentiate it from the background. If the laser stripe does not have sufficient intensity, the frame is discarded. If the laser stripe has sufficient intensity, the relative time is recorded and processing continues. Using a 3x3 kernel, the analyzer performs a vertical edge enhancement. Each row of pixels of this enhanced image is analyzed to find the location of the laser stripe. Occasionally during this line-by-line analysis, the computer will be unable to locate the laser stripe for a particular line. In this case, the line is disregarded but the information in the rest of the frame is kept. The result of the analysis is an array of data describing the location of the laser stripe on the screen.

This array of data is then filtered by a high-pass infinite impulse response (IIR) digital filter and a finite impulse response (FIR) digital filter. The filtered data is used in the calculation of the root mean square (RMS) value of the waveform. The RMS value can also be calculated over a user defined area (throughout this report, this area is 40 pixels wide) giving the roughness of a portion of the laser stripe at a given location. The above technique was used to generate RMS values for five spray forming runs with varying process parameters. This data is then compared with the preform quality.

METALLURGICAL ANALYSIS

The five runs analyzed in this study were tubulars made of Alloy 625. The properties of the runs were deliberately varied in order to get a variety in quality of preforms. After each run, a sample was cut lengthwise from the preform as shown in figure 2. Analysis was performed using a LECO 2001 image analysis system to quantitatively measure porosity. Porosity data was taken every millimeter from the inner diameter of the sample to the outer diameter in 1 cm increments the entire length of the preform. Areas were classified according to group definitions as cold porosity, banding, near fully dense or high density or hot porosity. All decisions about classifications of areas were based on the porosity values, the optical appearance of the microstructure and judgements based on experience.

Cold porosity is created when the liquid fraction of the spray is too small to fill interstices in the preform. In the microstructure, cold porosity usually forms on the inner diameter and exhibits prior particle boundaries and presolidified particles (see figure 3a). In this study, cold porosity was defined as porosity above 1% with the appropriate microstructure. Banding occurs when the time between rotations over a particular area allows the surface to solidify. When the particles in the spray hit mostly solid material, they tend to form either cold porosity or bounce off the preform completely. Banding is usually observed near the inner diameter, adjacent to the cold porosity (see figure 3b). Hot porosity occurs when the liquid fraction of the spray is large and viscosity is lowered. Although the mechanism is not completely understood, nitrogen becomes trapped in the viscous preform (see figure 3c). Hot porosity is not as common as cold porosity or banding, but is usually observed near the outer diameter of a preform. Sound areas were defined by porosity measurements well below 1% with appropriate microstructure. From the porosity information, profiles of the cross-section of each preform were derived (see figures 4 - 8).

Minimizing porosity is one of the requirements for producing a quality preform. However, it is difficult to eliminate porosity completely because the ID material is quenched by a room temperature mandrel which results in ID cold porosity. Maximizing the volume of fully dense material will reduce the amount of machining that is necessary. Therefore, a material that contains a large volume of near fully dense material is considered a good quality material. In contrast, a material with equivalent layers of banding and near fully dense has less usable area, requires more machining and is therefore poorer in quality.

RESULTS AND DISCUSSION

An objective of this analysis is to test the experienced operator's belief that perceived roughness of the preform surface is an indication of preform quality while taking into account the other information available to the operator.

The percentage of near fully dense area for each sample was calculated (table 1) by estimating the amount of near fully dense areas from figures 4-8 and dividing by the total areas. Using this information, a close optical inspection of the samples and information obtained from the run process parameters, each run was classified as "good" or "poor" based on the percent dense area.

The observation of trends in the moving average RMS data for runs C (good), D (poor) and E (very poor) (see figures 11-13) reveals that there is a difference in the RMS values between the different quality runs. The poorest run, E, has the lowest trends in RMS values and the best run, C, has the largest trends in RMS values. An average run, D, has intermediate trends in RMS values. This apparent correlation leads to the conclusion that the laser stripe sensor is able to quantitatively observe the difference between good and poor runs. However, at this time the laser stripe RMS value is not a perfect predictor of preform quality. Run A, which is shown in figure 9, has indications of very poor quality while its RMS values start off low and increase to a level that indicates intermediate quality. Another average run, B (figure 10), has RMS values that are close to or lower than those of run A. Following the logic outlined above, the RMS data would lead us to conclude that run B was a very poor run when it is actually good.

It has not yet been determined whether specific changes in the RMS value correspond to specific defects in the preform. A goal of the intelligent processing program is to integrate the laser stripe information with other inputs into a fuzzy logic controller. This fuzzy logic controller can successfully use sparse or "fuzzy" information such as surface roughness or other process parameters.

The fuzzy logic controller will be able to determine the real-time quality of a preform based on a set of rules. This set of rules will associate a certain range of values for a given parameter with a qualitative judgement of preform quality (i.e. "good" or "poor"). The range of values that correspond to a specific quality will be developed and evolved as the surface roughness database increases with use.

Final decisions about preform quality are based on the inputs of several sensors which will increase the controller's accuracy. When several of the sensors indicate that the preform is "poor" in quality, the fuzzy logic controller will first decide that the preform is "poor" and will then make appropriate adjustments in process parameters to improve the quality of the preform.

CONCLUSIONS

A laser stripe technique was developed for the real-time sensing of spray formed preforms. It was determined that a loose correlation can be inferred between preform quality and laser stripe RMS data. This sensor works best when the quality of the preform is either extremely poor or extremely good. However, when combined with other sensor input into a fuzzy logic controller, the laser stripe surface roughness can help the controller predict the quality of the preform in a variety of preform qualities.

ACKNOWLEDGEMENTS

This program is sponsored by the Office of Naval Technology. The authors wish to express their appreciation to program sponsors, Mr. James Kelly, Mr. Marlin Kinna and Mr. Ivan Caplan. The technical participation of Allen Matteson is gratefully acknowledged as well as the guidance provided by Dr. Robert Cammarata of the Johns Hopkins University. Thanks are extended to Steve Szpara, Al Brandemarte, Bob Mattox and Tom Queen for their technical assistance.

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1. Moran, Angela L. and Dawn R. White, "Developing Intelligent Control for Spray Forming Processes," JOM, 42 (7) (1990), pp. 21-23.

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Table 1. Process parameter data and percentage of fully dense area for runs A-E.

Run	Dense Area (cm^2)	Total Area (cm^2)	Percent Dense	Melt Size (kg)	Gas/Metal Ratio (kg/kg)	Melt Superheat (C)	Qualitative Description
A	0	21.5	0	15.9	0.43 (min)	N/A	very poor
B	12.7	15.6	81	15.2	0.29	1480	good
C	15	16.5	91	15.8	0.255	1483	good
D	7.7	18.8	41	16.2	0.36	1490	poor
E	0	20.3	0	15.6	0.55	1491	very poor

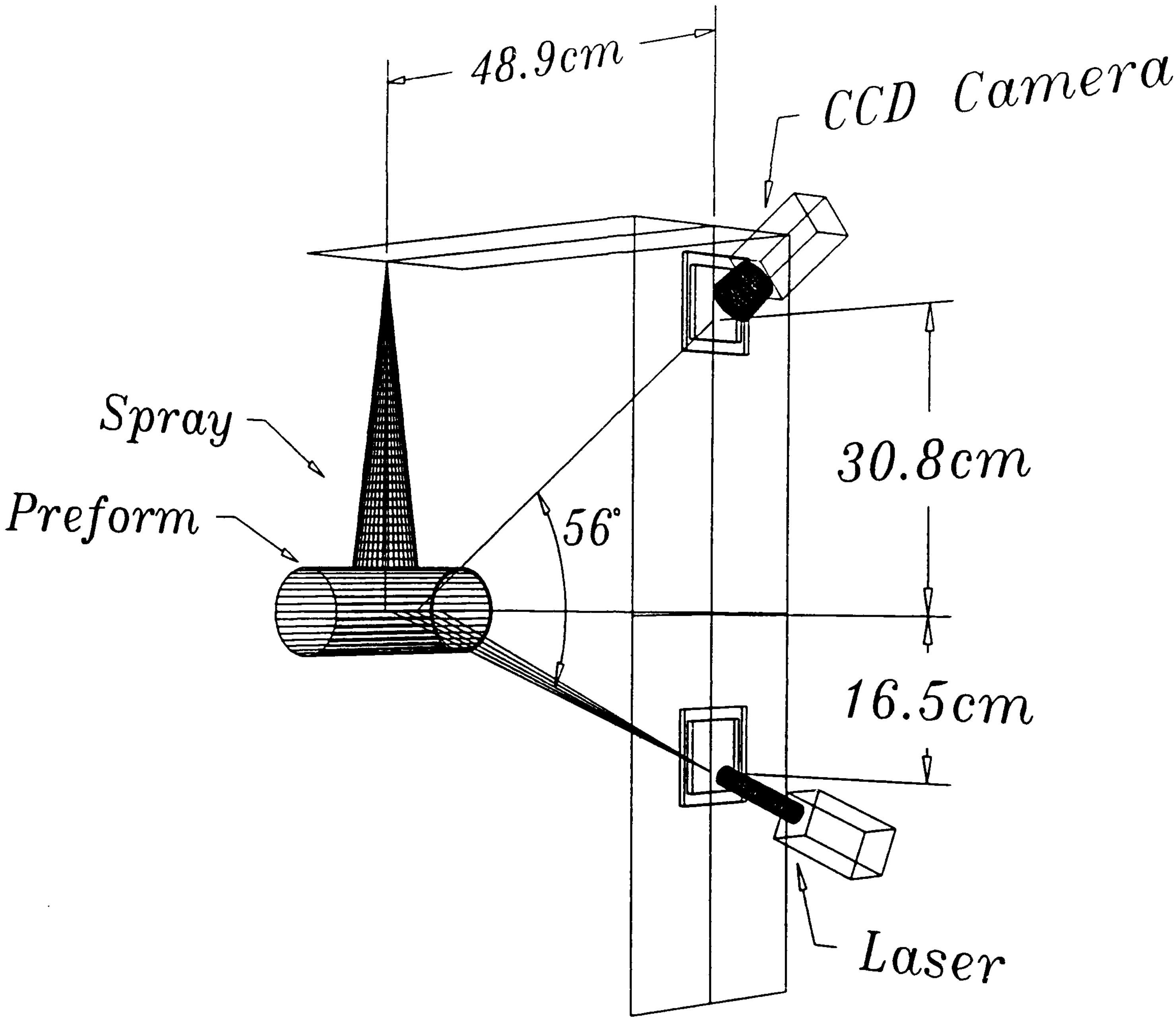


Figure 1. Set up of laser stripe with respect to preform and camera.

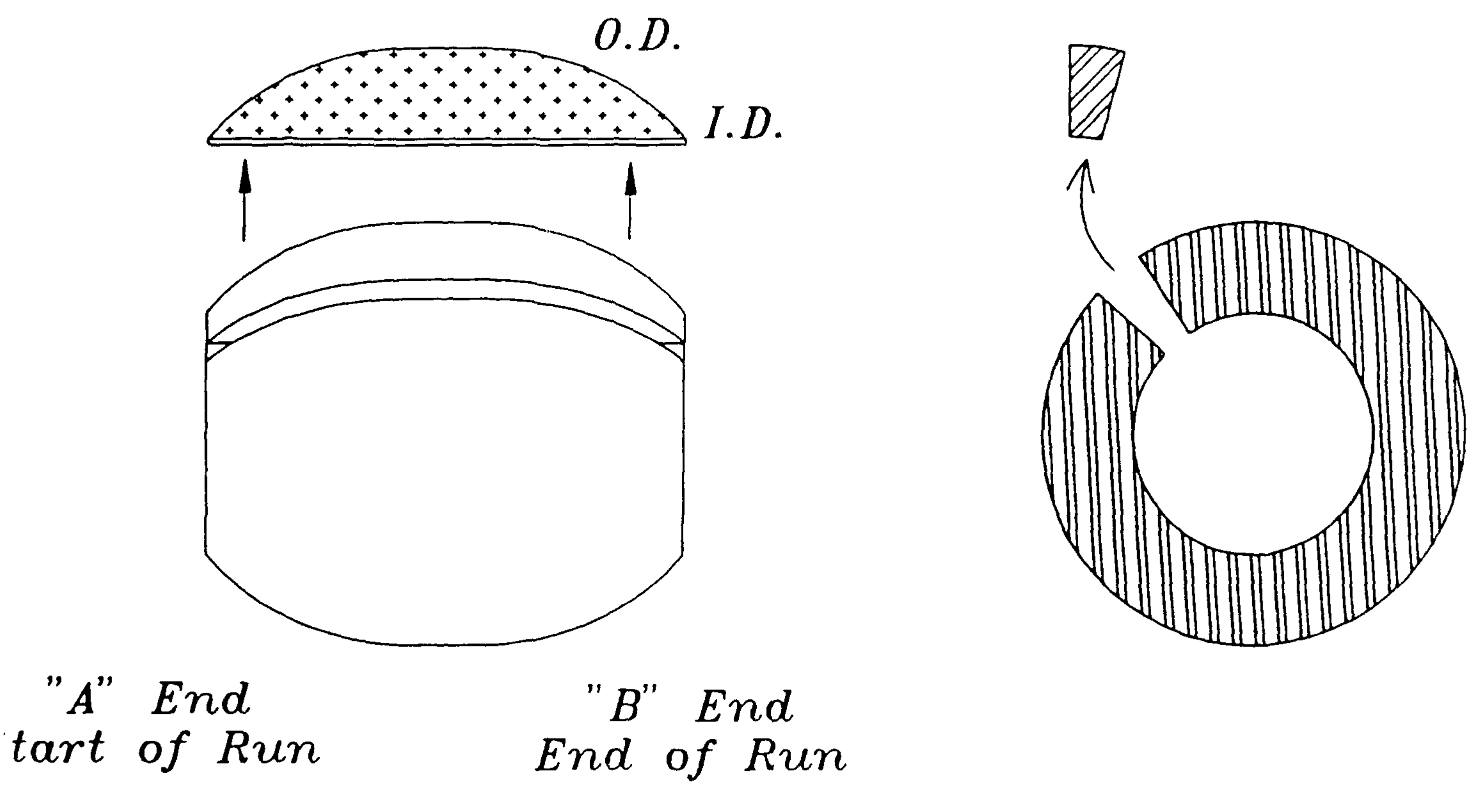
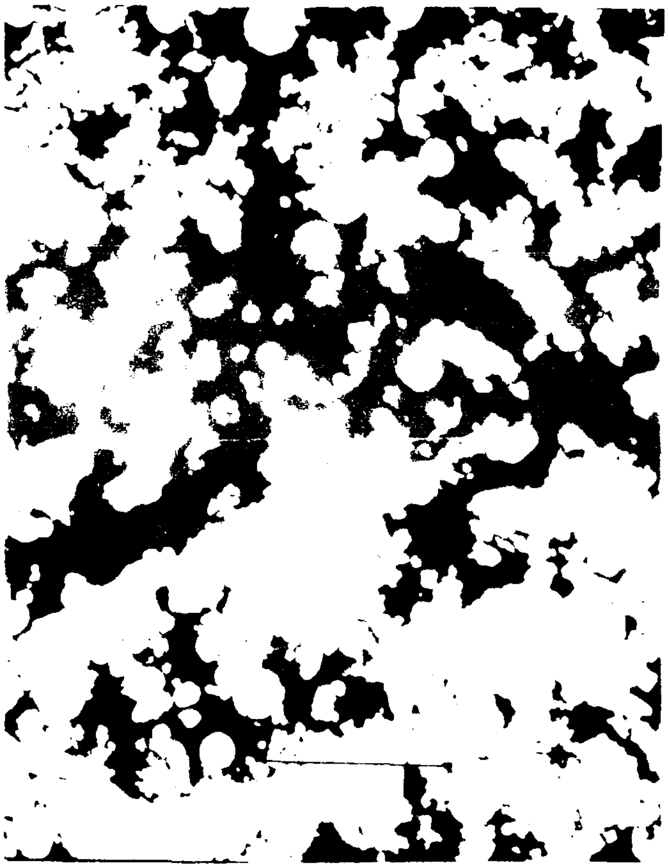
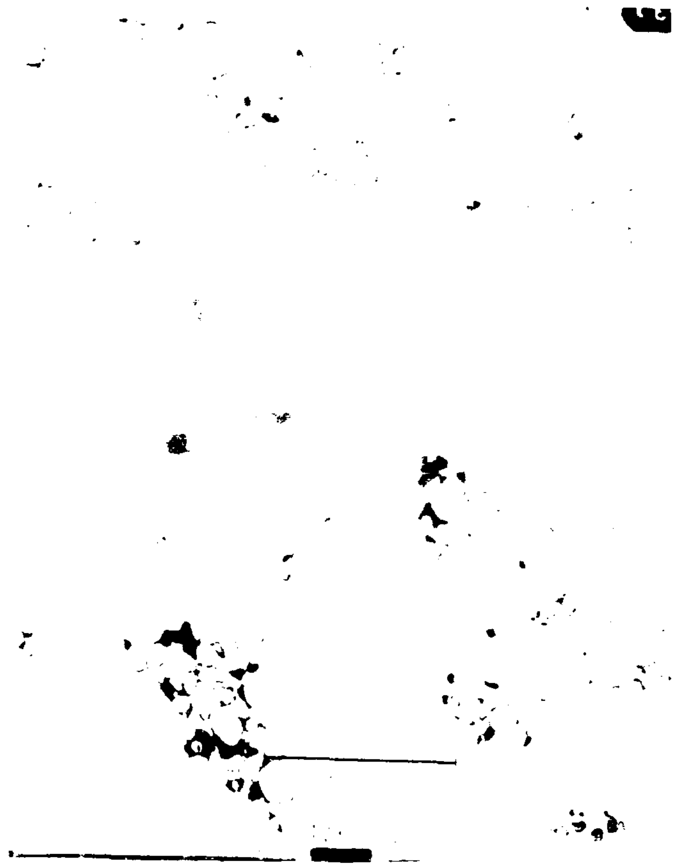


Figure 2. The configuration of the samples as they are taken from the preform. Samples are taken lengthwise to get information from all times in the run.

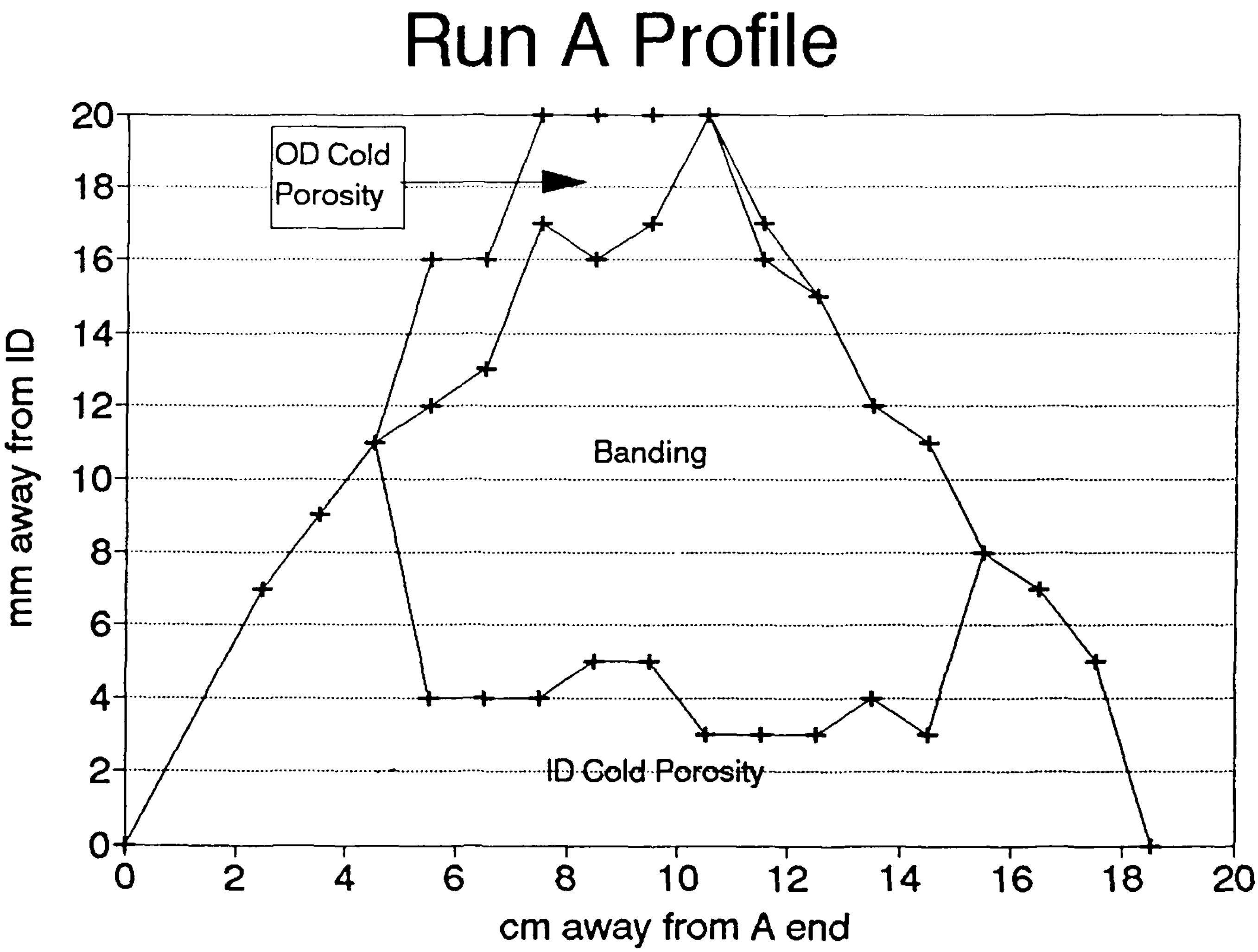



Figure 4. Profile of sample taken from run A.

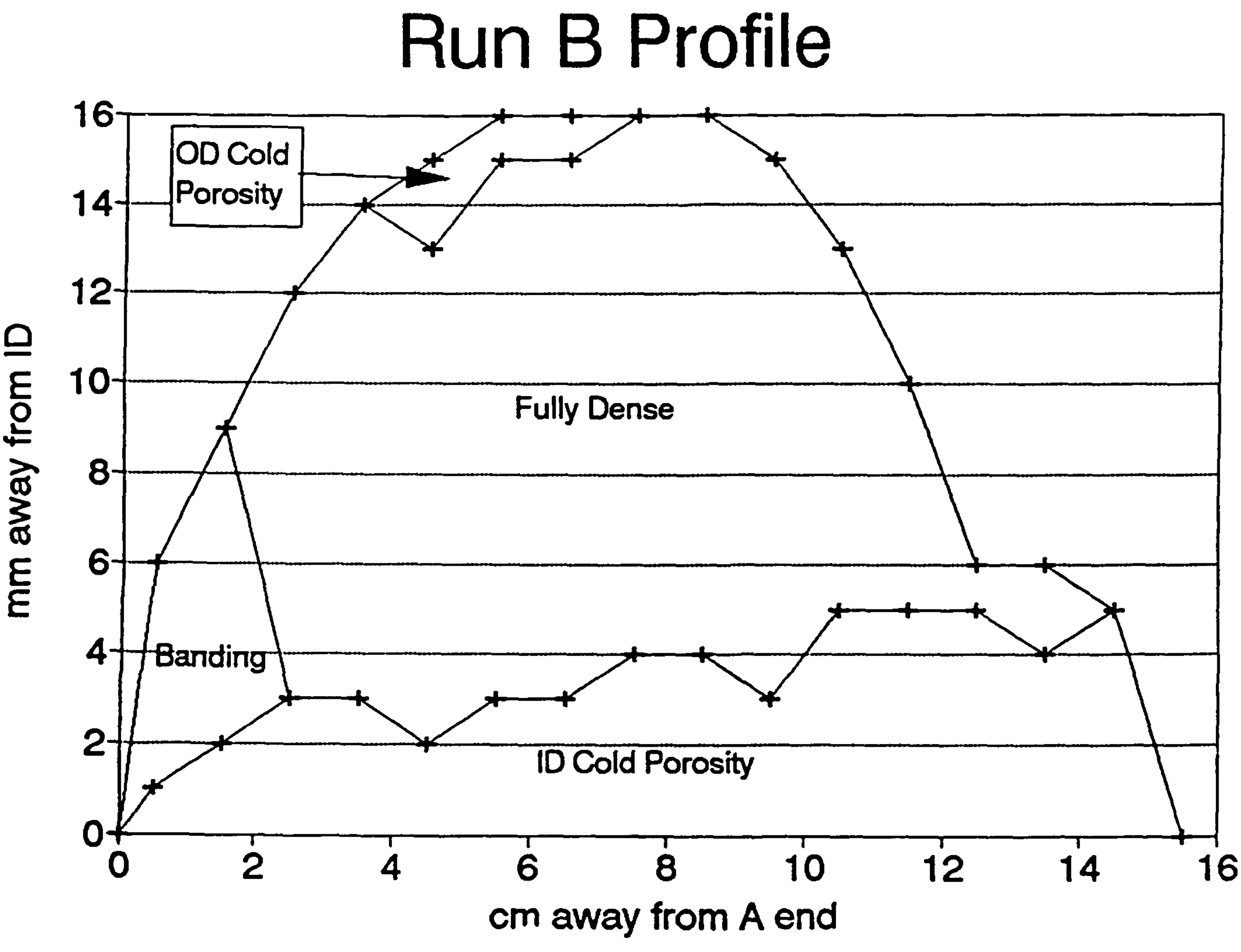


Figure 5. Profile of sample taken from run B.

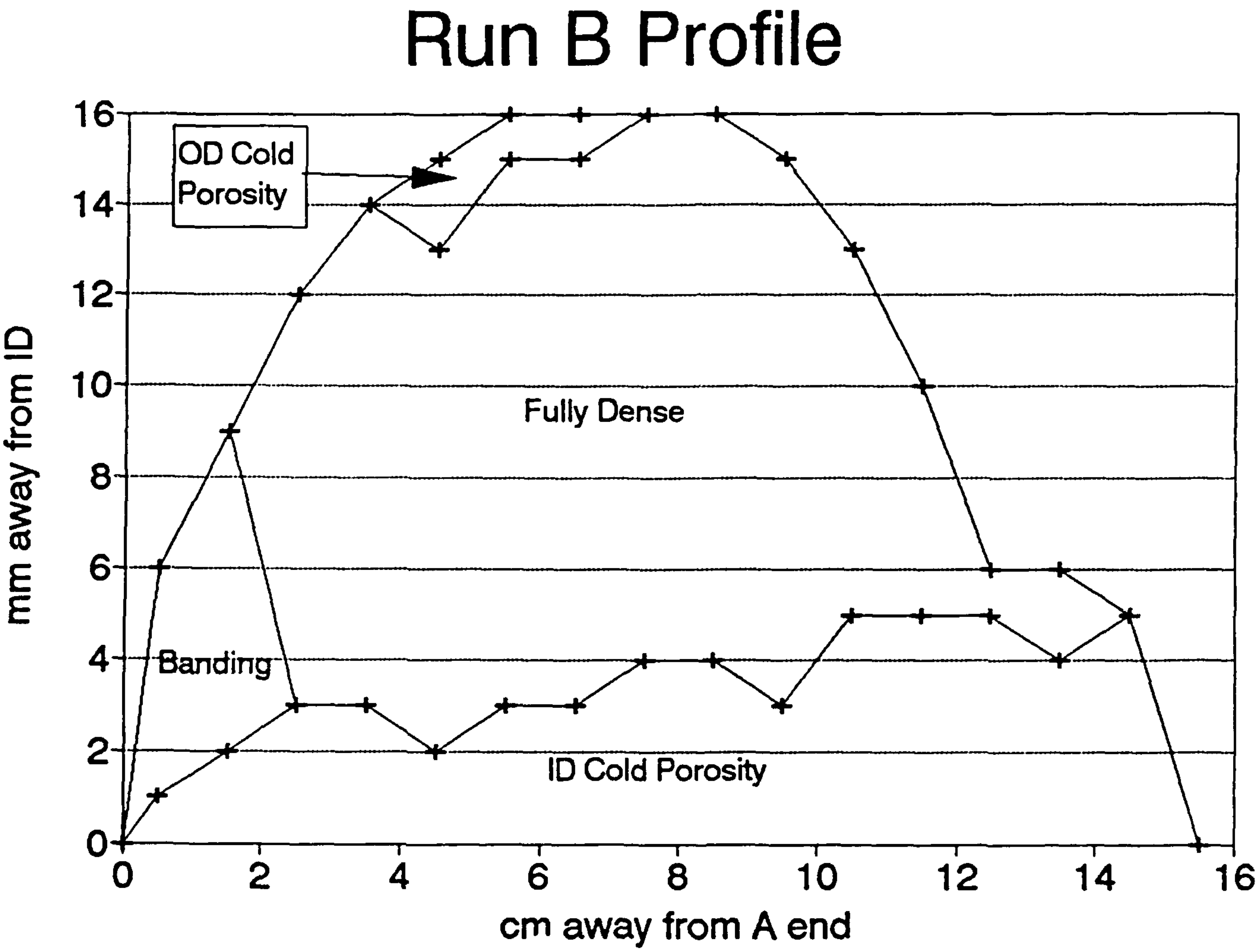


Figure 5. Profile of sample taken from run B.

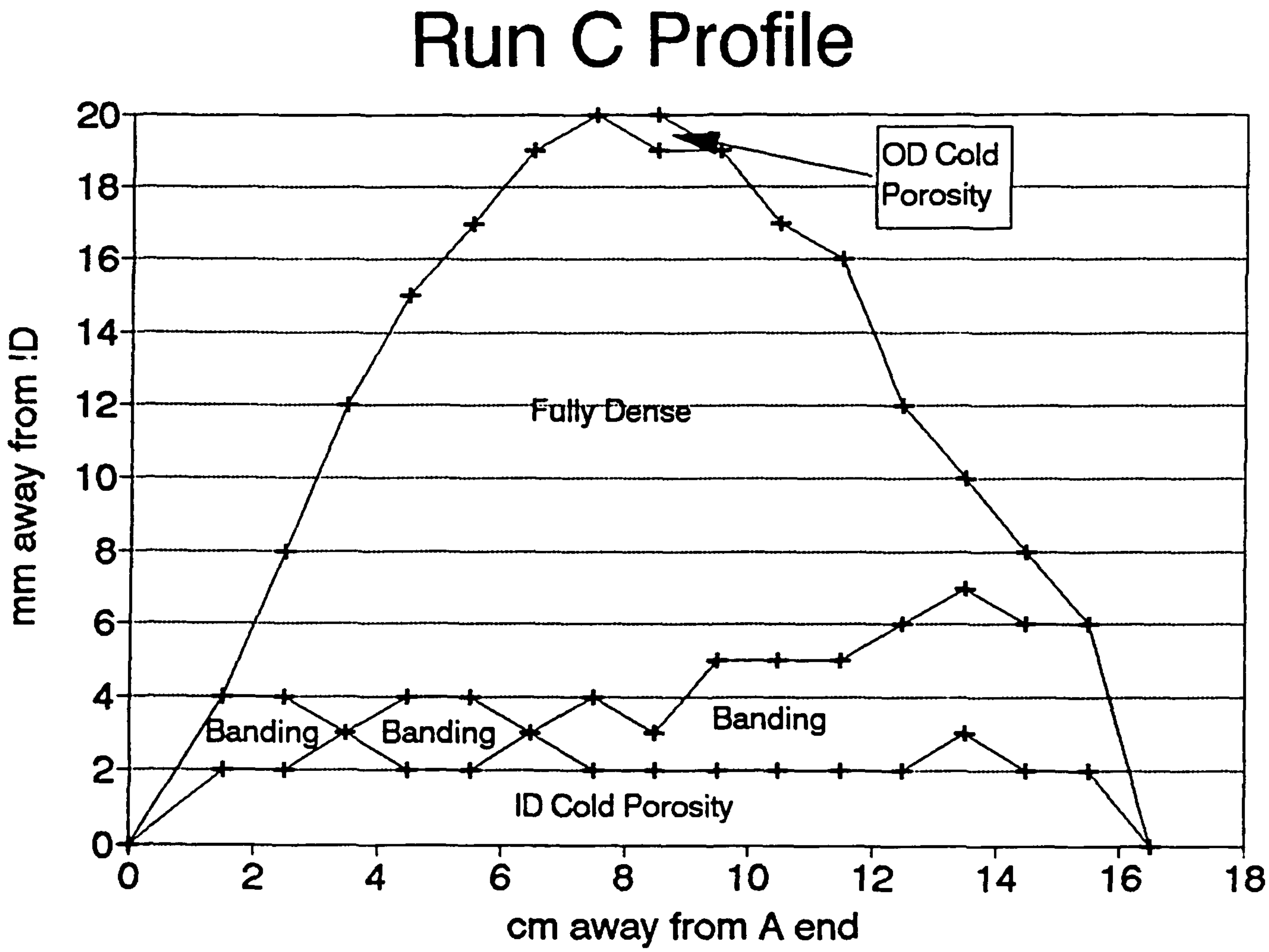


Figure 6. Profile of sample taken from run C.

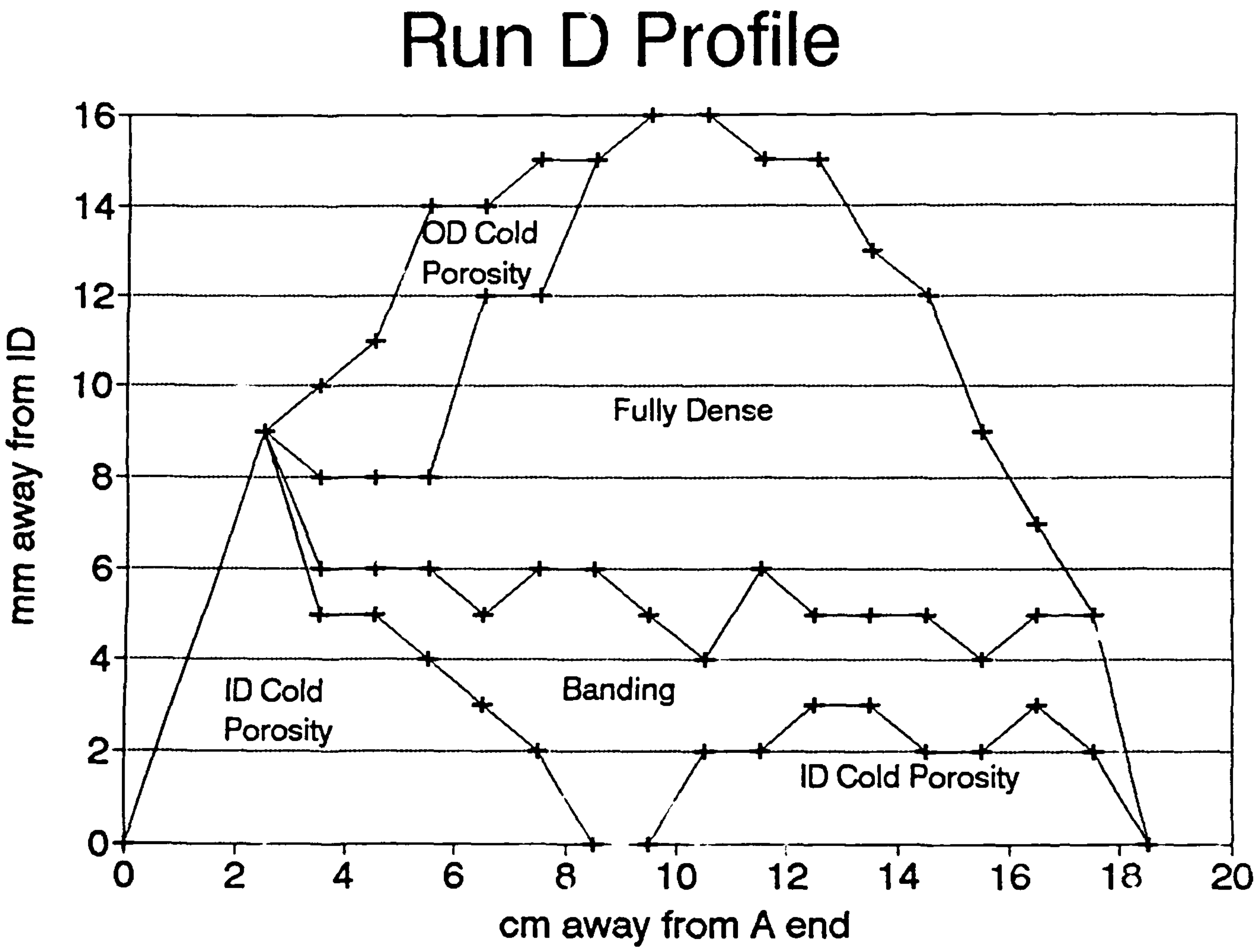


Figure 7. Profile of sample taken from run D.

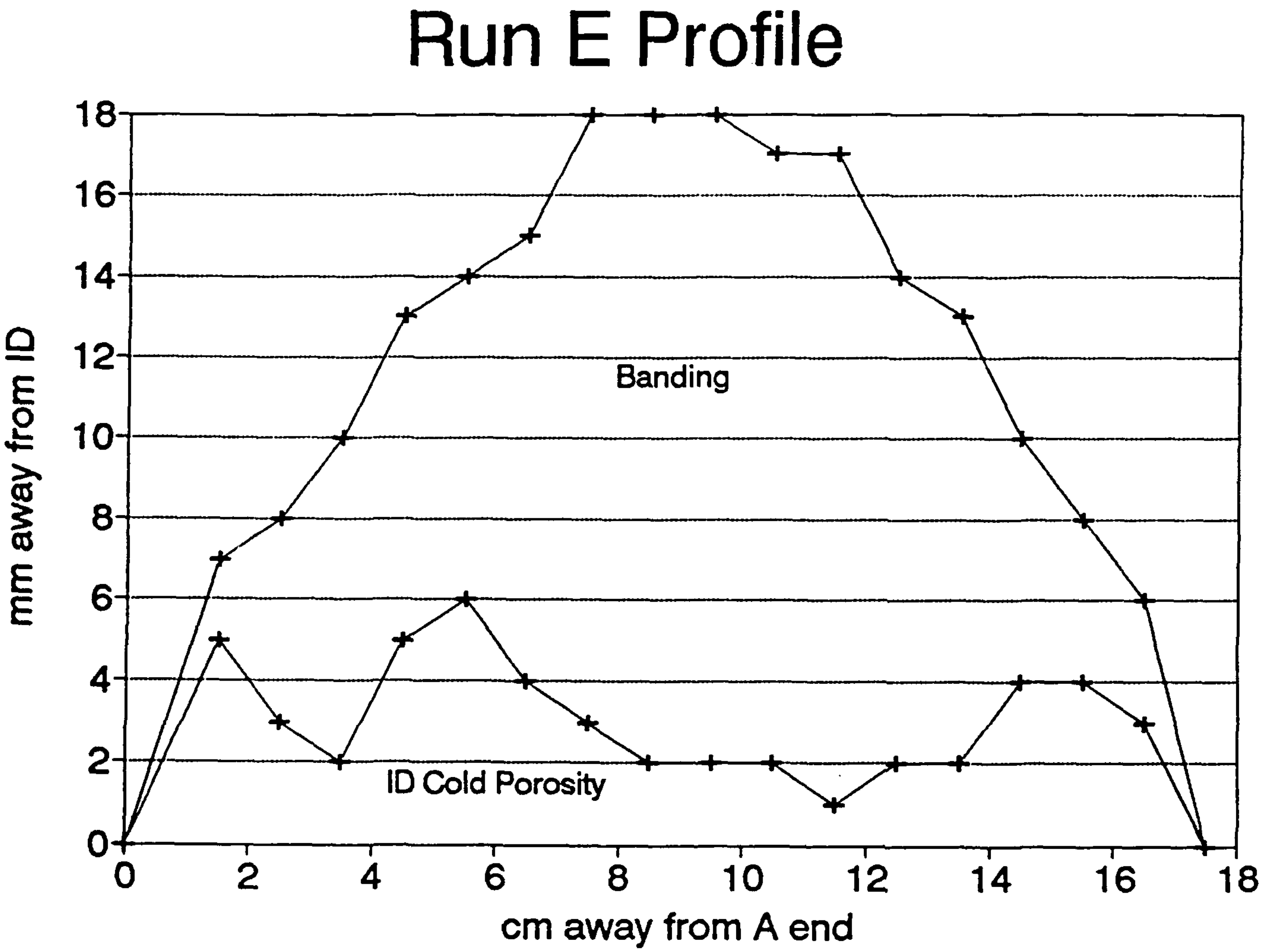


Figure 8. Profile of sample taken from run E.

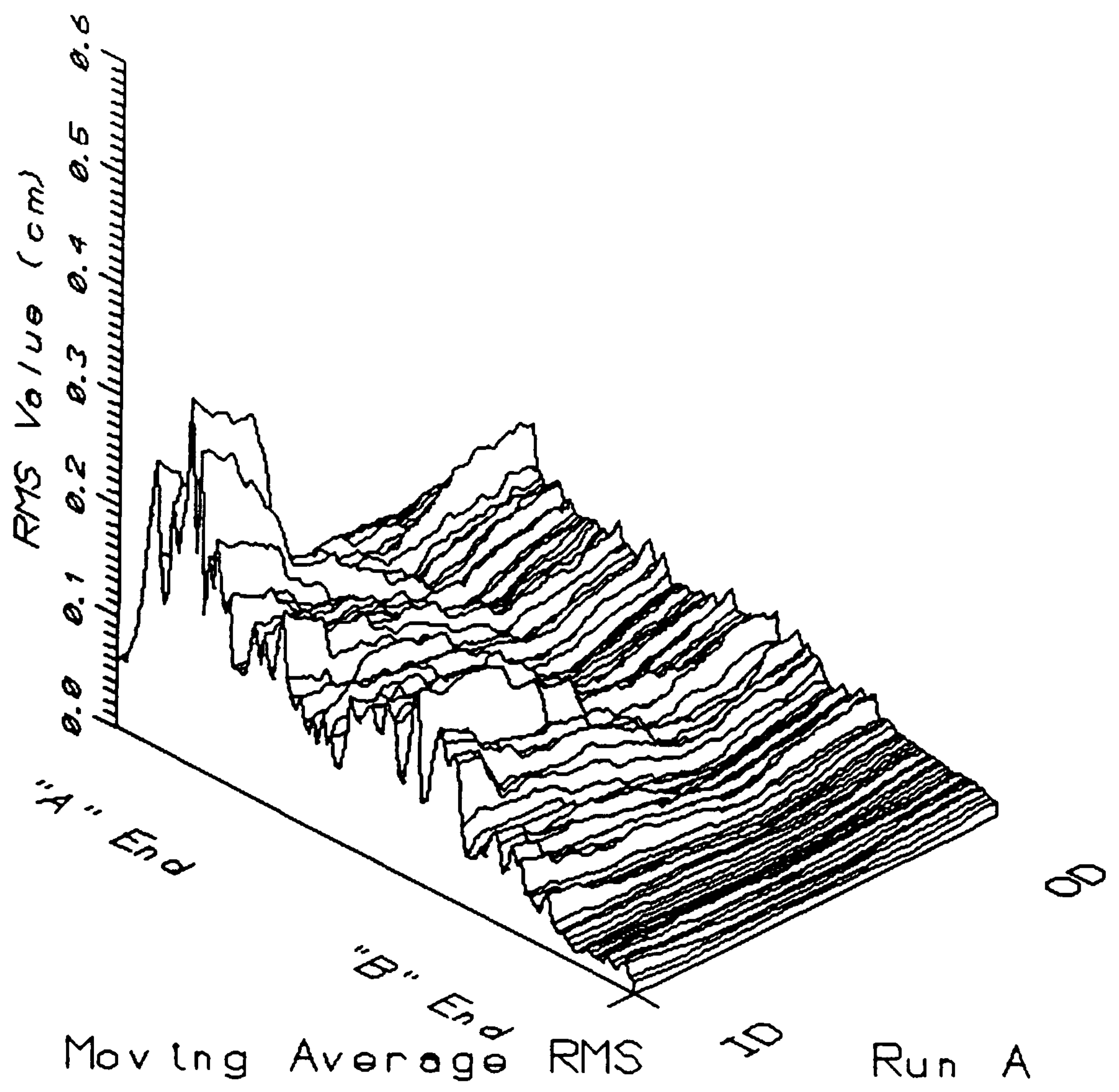


Figure 9. Moving average RMS value taken from a 40 pixel wide window in run A. Trends in this data are compared to the metallographic data.

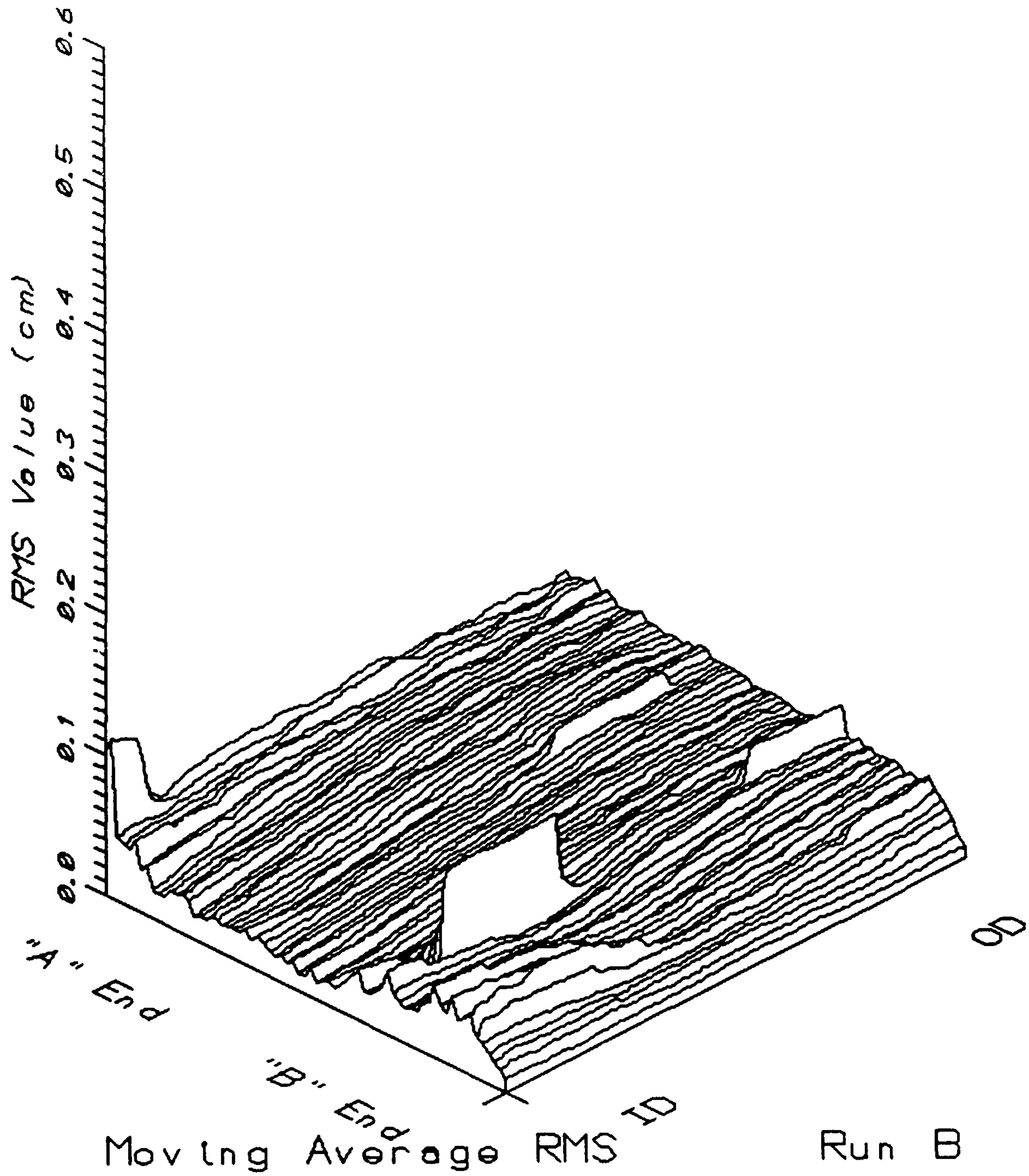


Figure 10. Moving average RMS value taken from a 40 pixel wide window in run B. Trends in this data are compared to the metallographic data.

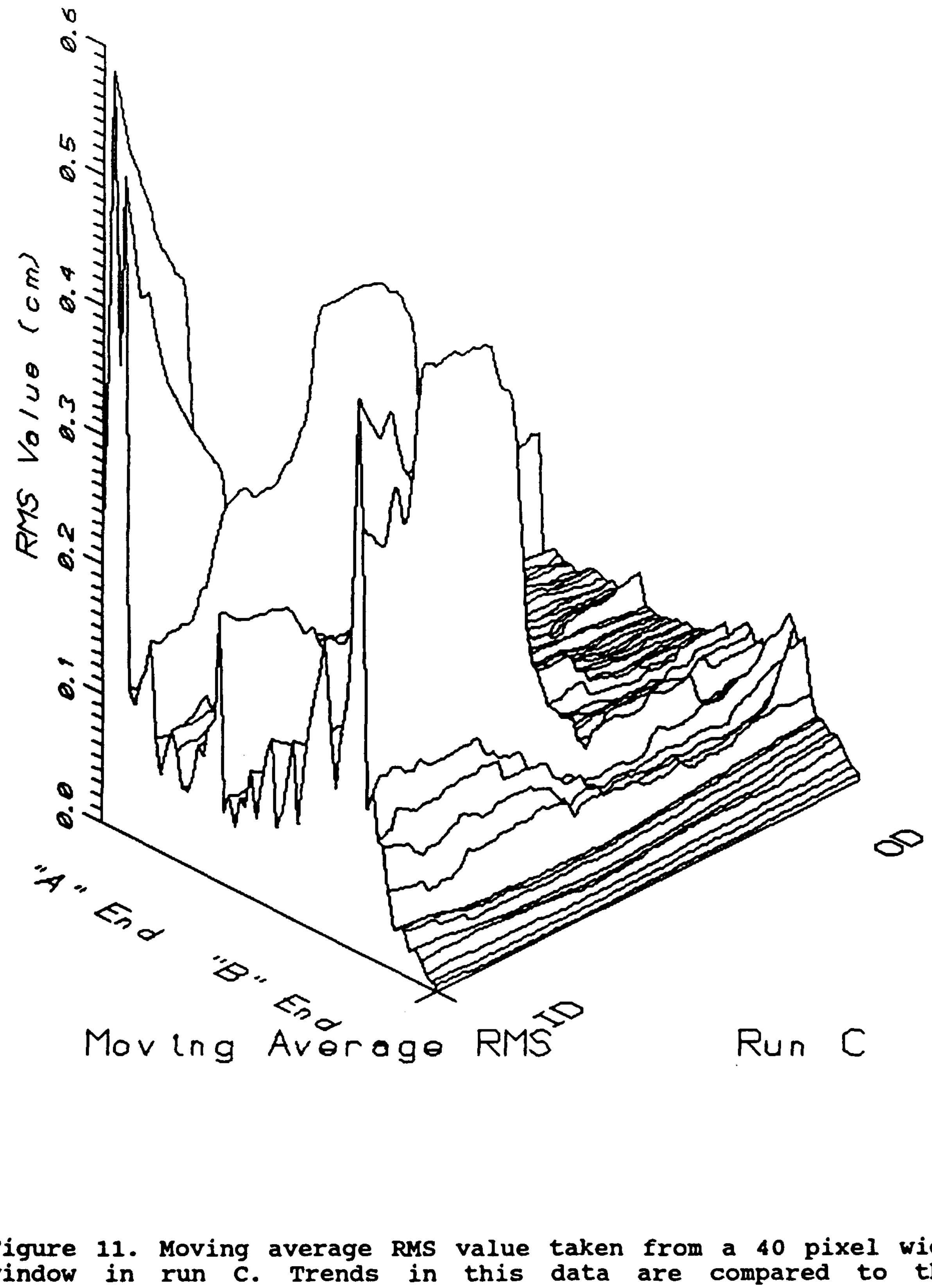


Figure 11. Moving average RMS value taken from a 40 pixel wide window in run C. Trends in this data are compared to the metallographic data.

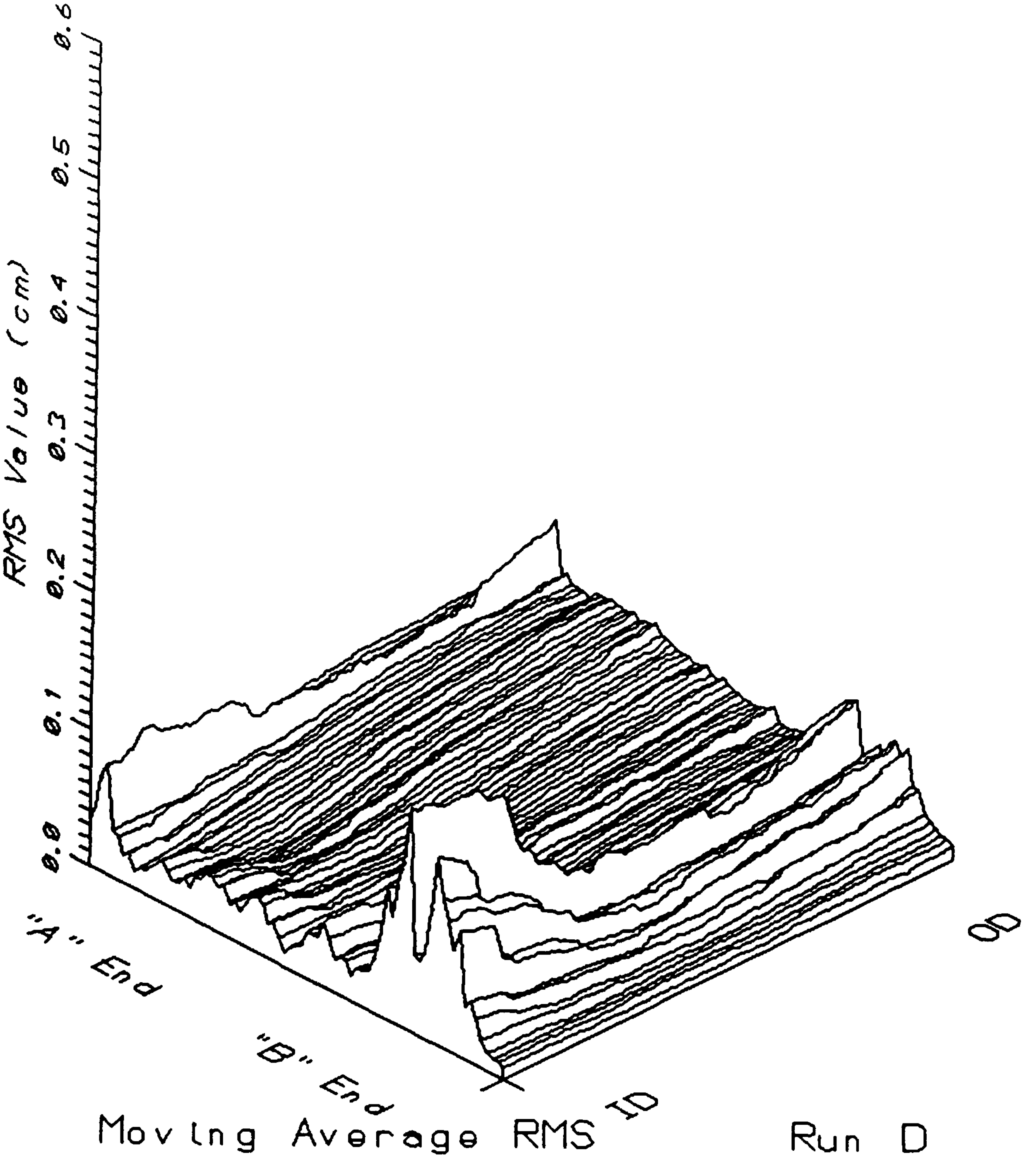


Figure 12. Moving average RMS value taken from a 40 pixel wide window in run D. Trends in this data are compared to the metallographic data.

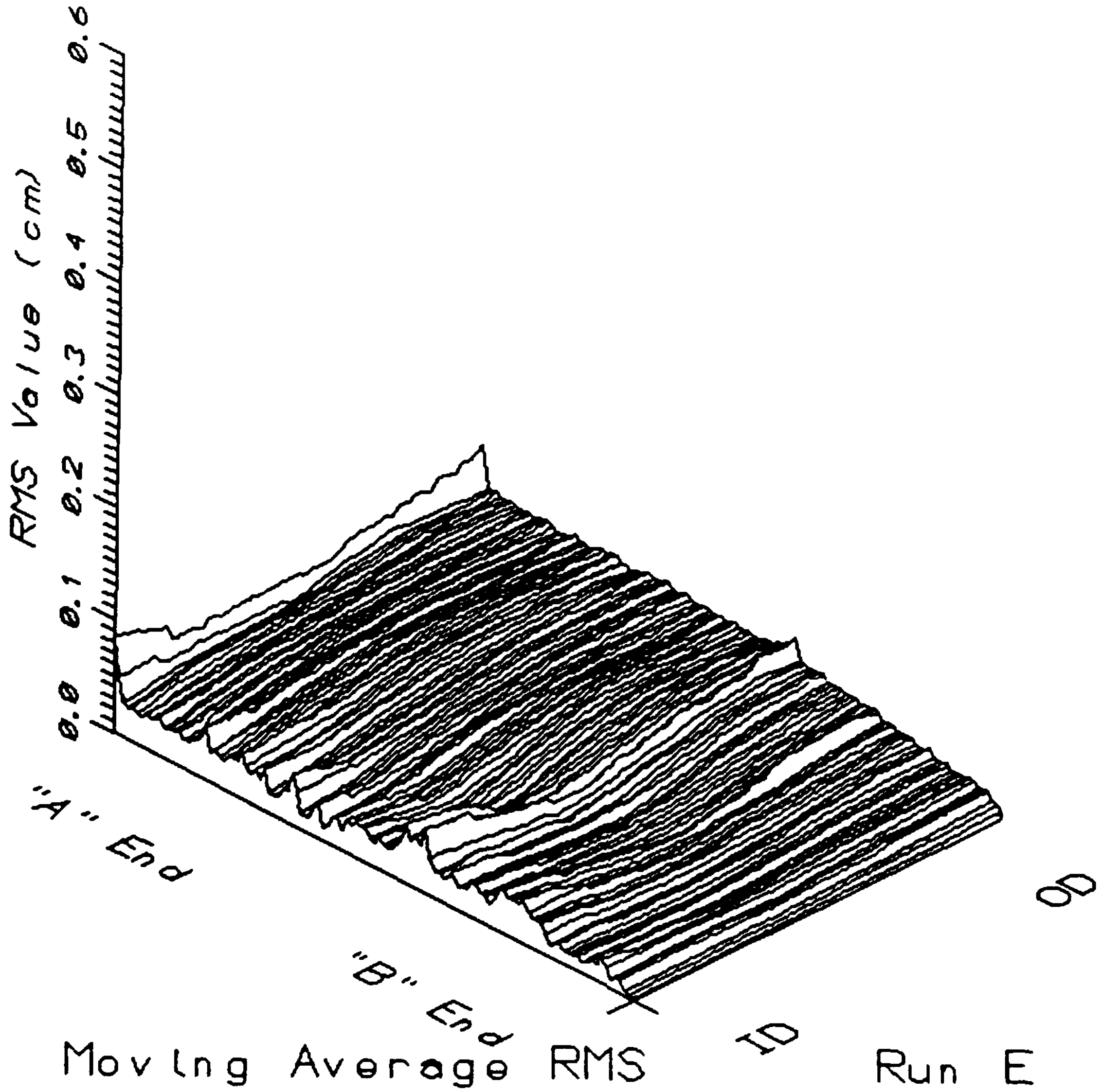


Figure 13. Moving average RMS value taken from a 40 pixel wide window in run E. Trends in this data are compared to the metallographic data.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
July 1991

3. REPORT TYPE AND DATES COVERED
Research & Development—Apr to Jul 1991

4. TITLE AND SUBTITLE
An Optical Roughness Sensor for the Real Time Determination of Spray Formed Preform Quality

5. FUNDING NUMBERS
1-2812-921

6. AUTHOR(S)
Rochelle D. Payne, Angela L. Moran, Craig J. Madden, Paul Kelley

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
David Taylor Research Center
Code 2812
Annapolis MD 21402–5067

8. PERFORMING ORGANIZATION REPORT NUMBER
DTRC–SME–91–51

9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Mr. Ivan Caplan
Code 0115, DTRC
Annapolis MD 21402–5067

10. SPONSORING /MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

As part of the intelligent processing efforts of the Spray Forming Technology Group at David Taylor Research Center, a laser stripe sensor has been implemented to monitor preform characteristics. The preform surface roughness data is measured in real time and the correlation to preform quality in terms of porosity levels is assessed. The laser stripe method is not a direct indictor of quality but can be used with other sensors and advanced control techniques for control of the spray forming process.

14. SUBJECT TERMS

15. NUMBER OF PAGES
28

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Same as report