

*Journal of*

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# **INDUSTRIAL TECHNOLOGY**

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*Volume 27, Number 1 - January 2011 through March 2011*

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Peer-Refereed Article  
Applied Research

**KEYWORD SEARCH**

***Manufacturing  
Metrology  
Plastics/Polymers  
Quality Control***



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# Flow Length Measurement of Injection Molded Spirals Using a Flatbed Scanner

By Dr. Martin P. Jones, Dr. Richard N. Callahan, and Dr. Richard D. Bruce

## ABSTRACT

This paper describes the potential of using flatbed scanners for a wide variety of dimensional measurements critical in the manufacturing of parts. A detailed example is presented on the measurement of thermoplastic spiral specimens. Some researchers use a spiral mold as a benchmark to assess the flow optimization of injection-molded thermoplastics. The spiral's length is critical in determining optimization algorithms that control the temperature, pressure, and speed of injection. This paper describes a new method developed for the precise measurement of these molded spiral lengths using a common flatbed scanner and AutoCAD software. The researchers compared measurements taken with a flatbed scanner to that of a profile projector through a gage repeatability and reproducibility (GR&R) study. Results of the study showed that flatbed scanners can be used to measure objects to an acceptable level of repeatability and reproducibility.

## INTRODUCTION

On a volumetric basis, the production of polymers exceeds that of all metals combined. Thermoplastics comprise more than 70% of the polymer tonnage produced annually. Injection molding is the most widely used molding process for thermoplastics. Optimization of the mold injection process can result in significant cost-savings. As discussed in this paper, many researchers use a spiral mold as a benchmark to assess the flow optimization of thermoplastics. The spiral's length is critical in determining optimization algorithms that control the temperature, pressure, and speed of injection. However, the accuracy and precision of the flow length measurement methods have not been

adequately addressed in prior publications. Furthermore, the published methods ignore the shape of the spirals' freeze front, which can influence the flow length. The present paper describes a novel flatbed scanner method and its accuracy in measuring the flow length of injection molded spirals.

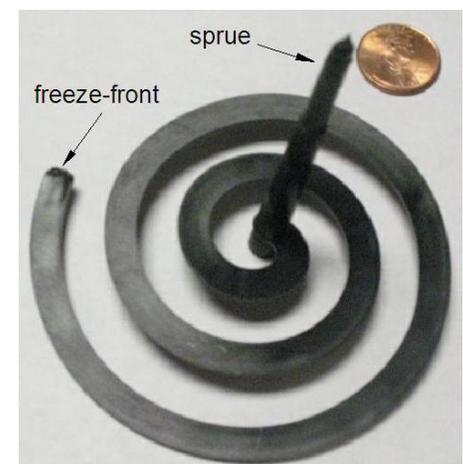
## Background

### Spiral molds

Compared to most thermoplastic products, the spiral mold cavity has a relatively simple geometry that can be used to mathematically model the flow of polymers during injection molding. They are also relatively easy to machine. The geometry of the spiral varies depending on the research objectives of a given study. Figure 1 shows a typical spiral specimen produced for the present study.

Some researchers have embedded multiple pressure sensors along the length of spiral mold cavity to assess the flow optimization (Clavería, Javierre, & Ponz, 2005). Others have

Figure 1. Typical thermoplastic spiral produced by injection molding.



used a single pressure sensor located at the junction of the sprue and spiral cavity (Wu, Zhang, Qu, & Xu, 2007). The pressure data and flow length in the spiral is used to calculate the viscosity of polymers under various injection parameters, such as temperature and injection speed. Using numerical modeling, the flow length and the freeze front profile in the spiral cavity can be predicted (Ilinca & Héту, 2007). It is generally acknowledged that flow length is a critical characteristic in optimizing injection molding for cost savings (Nguyen-Chung, Jüttner, Pham, & Mennig, 2008; Wu, Xu, Qu, & Zhang, 2006). However, the related published research does not reveal the method or accuracy of the measurement of the flow length.

#### *Dimensional measurement using flatbed scanners*

Researchers have used flatbed scanners for the measurement of a wide range of objects. While there has been significant research analyzing the grayscale of flatbed scanned images, mostly in the medical field (see for example Rampado, Garelli, & Ropolo, 2010), the present paper is focused on the measurement of length. Other research using flatbed scanners to measure length-related aspects of objects fall mainly in three categories: construction, food science, and manufacturing.

Construction research based on flatbed scanners have been used to measure the amount and size distribution of porosity in concrete and mortars (Miriello & Crisci, 2006; Peterson, Carlson, Sutter, & Van Dam, 2009; Zalocha & Kasperkiewicz, 2005). Among the essential criteria for proper porosity sizing was the selection of gray-level thresholds of the images. These researchers concluded that flatbed scanners are a low-cost and convenient alternative to stereoscopic microscopes for some porosity measurements.

Similarly, food science researchers have used flatbed scanners to measure the size distribution of rice and wheat grains (Paliwal, Borhan, & Jayas, 2004; Van Dalen, 2004). Algorithms were

developed to automate the inspection of these cereals based on scanned images. Shahin and Symons (2001) developed a neural network system using flatbed scanned images to classify lentils by texture and other characteristics. Their system resulted in a 90% classification agreement with human grain inspectors.

The use of flatbed imaging in manufacturing research has a broader range of applications than in the construction and food science categories. Korin, Larrainzar, and Ipin (2008) measured the crack lengths of steel SE(B) specimens (single edge loaded in bending) using a flatbed scanner. Ng (2008) developed a flatbed scanner method to inspect light-emitting diodes for encapsulation defects. Igathinathane, Melin, Sokhansanj, Bi, Lim, Pordesimo, and Columbus (2009) used flatbed images to determine dust particle size distributions produced in industrial environments. Kee and Ratnam (2009) developed a flatbed method to measure the diameters of fine wires used in electronics. Yakovlev and Safonov (2009) used a flatbed method to quantify the void distribution in manufactured foam-rubber.

For the above five studies, the critical calibration parameter for object sizing was the selection of the gray-level threshold. Calibration of flatbed scanners is the main topic of some previous research. Poliakov, Poliakov, Fedotova, and Tsvetkov (2007) developed precise glass rulers for the calibration of flatbed scanners used to digitize astronomical plates. Kangasraasio and Hemming (2009) studied the various sources of measurement uncertainties associated with flatbed scanners. A source of uncertainty not addressed in their paper was variation due to human error but is addressed in the present paper.

Automated measurement was conducted in all the above papers using flatbed scanning methods. In the present paper, the measurements are essentially made by humans interacting with software and the flatbed acquired images.

#### **Purpose**

The goal for the present research was to develop and demonstrate the capability of a new measurement method based on flatbed scanning that can provide accurate, precise, and relevant data to guide the optimization of thermo-plastic mold injection. Furthermore, the researchers sought to use equipment and software that are commonly available even at small engineering companies. The measurement capability of the method was assessed through a gage repeatability and reproducibility (GR&R) study. The GR&R provided baseline data for future development of automated measurement. The precision of the method was compared to that obtained using a profile projector. It was expected that the new method would have precision within the same order of magnitude as that of a profile projector based on similar measurement applications using flatbed scanners.

#### **METHOD**

##### **Specimens**

Over one thousand specimens were produced by using a Toyo Plaster Ti90G2 molding machine to inject molten high-density polyethylene into a two-plate spiral mold cavity. Machine operating settings were varied to produce a variety of spiral lengths and freeze-front profiles: barrel temperature from 380 to 420 °F, injection pressure from 300 to 1200 psi, and injection speed from 10 to 20 inches/second. The nominal dimensions of the spiral cavity channel were 0.25 inch in width, 0.0625 inch in depth, and 30 inch in length. Ten specimens were selected for measurement to represent a wide variety of lengths and profiles.

##### **Equipment and Software**

A Hewlett-Packard Scanjet 5590 was utilized to capture the images at 4800 dots per inch (dpi) and 256 level gray-scale. This particular scanner was chosen because it was a common office model used at the researchers' university. The 4800 dpi resolution translates to a pixel size of about 0.0002 inch. To reduce image file size and process time, only the last inch of the spirals were

scanned; each resulting in a six mega-byte file acquired within one minute. No post-scan processing was performed on the images such as contrast enhancement. Images were imported into AutoCAD 2009 for measurement of the spirals using line and arc construction tools within this software. The review of literature supported this application. The measurements were performed at an AutoCAD scale factor of 0.05 (20X magnification). This scale factor enabled the cursor to be moved across the image at a resolution of 0.0001 inch. The computer used to acquire and measure the images was a laptop running a 2.4 GHz Intel processor and with a 14 inch display screen.

Similar measurements were obtained using a Mitutoyo PH-14LS profile projector with a QM-Data200 digital readout device. A 20X magnification objective lens was used to measure all specimens. The translational micrometers of the projector system had a resolution of  $\pm 0.00005$  inch. Both through-transmission and reflection modes of this system were simultaneously used to measure the spirals.

Calibrations of both the profile projector and flatbed measurement systems were checked against a NIST traceable gage block. The 0.300 inch gage block was manufactured by F. V. Fowler, Inc., certified to be within +0.000008 to -0.000004 inch of the nominal value.

### Procedure

#### Flatbed scanning

Figure 2 shows a scan of the longest spiral produced. Note that there are reference lines (ridges) at approximately one inch segments along the spiral. The reference lines were machined as grooves into the spiral cavity for the purpose of providing a quick and rough estimate of flow length. Each segment's radius of curvature increases from the center sprue to produce the spiral geometry. The numbers in the figure identify the segments of the spiral and the last number indicates where the freeze-front stopped. Here the freeze-front stopped in segment 26 of the cavity. Measurement of the end segment's length was always made relative to the end reference line. Therefore

Figure 2. Scan of a spiral showing segment numbering convention used.

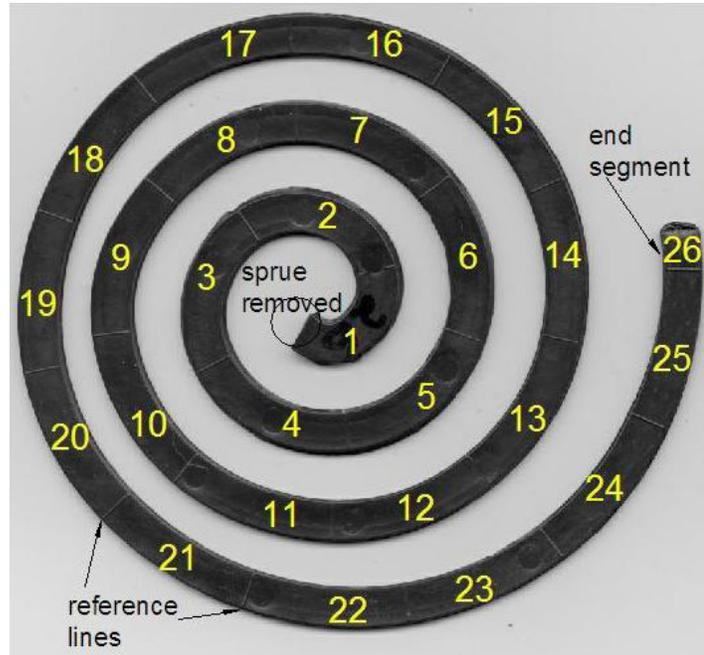
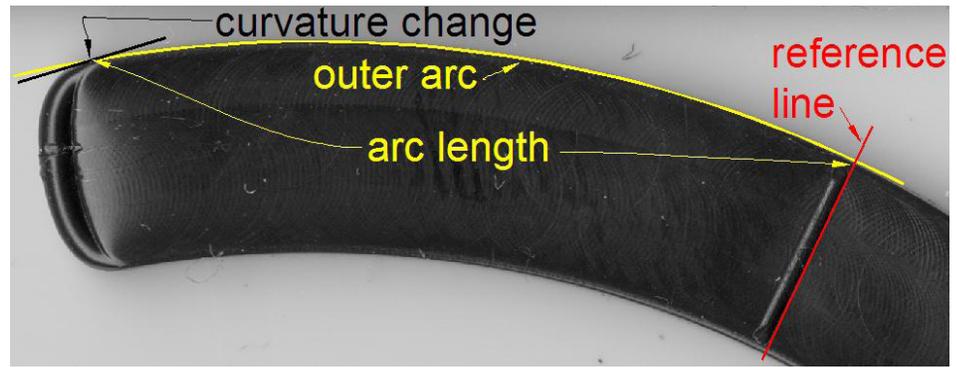


Figure 3. Outer rule identification of end segment (arc) length of spiral specimen.



this method focuses on small relative changes to the length of the spiral.

Two different rules defining the end segment's length were created for the flatbed scanning system. The first rule (termed "Outer") was created to imitate and, thus be comparable to, the measurement procedure used with the profile projector system. The second rule (termed "Offset") defining the end segment's length was created to enable more repeatable measurements by employing AutoCAD drawing tools not available with the profile projector system.

Figure 3 illustrates the Outer rule which

identifies the end segment's length as being the outer arc from the beginning of the reference line to where the spiral starts to deviate from its radius of curvature. The researchers completed the following steps in AutoCAD to find the arc length:

1. Drew a line along the reference line.
2. Extended that line past the outer arc with the "lengthen" tool.
3. Used the "arc 3-point" tool to select three points on the outer arc of the last segment.
4. Extended the resulting arc using the "lengthen" tool such that it overhung beyond the reference line and the freeze-front.

5. Drew a line through the point at which the spiral started to deviate from the drawn arc.
6. Used the “trim” tool to remove the overhang to the deviation point and to the reference line.
7. Selected the trimmed arc and obtained its arc length from the “properties” table.

Each of the ten specimens was measured three times in random order using the above rule. The average and range for each specimen was calculated and is presented. Also, the average of the ranges and average of the averages were calculated and are presented.

Figure 4 illustrates the Offset rule which identifies the end segment’s length as being the middle arc from the beginning of the reference line to where the arc intersects the freeze-front. The researchers completed the following steps in AutoCAD to find the arc length:

- Drew a line along the reference line.
- Extended that line past the outer arc with the “lengthen” tool.
- Used the “arc 3-point” tool to select three points on the outer arc of the last segment
- Used the “offset” tool to draw an arc midway along the spiral’s length; offset distance was always set to 0.1224 inch shorter than the radius of outer arc.
- Extended the resulting offset arc using the “lengthen” tool such that it overhung beyond the reference line and the freeze-front.
- Drew a line through the point at which the offset arc crossed the freeze-front.
- Used the “trim” tool to remove the overhang to the freeze-front point and to the reference line.
- Selected the trimmed arc and obtained its arc length from the “properties” table.

Each of the ten specimens was measured three times in random order using the above rule. This was repeated by two other appraisers. Training of the appraisers is discussed later. Calcula-

Figure 4. Offset rule identification of end segment (arc) length of spiral specimen.

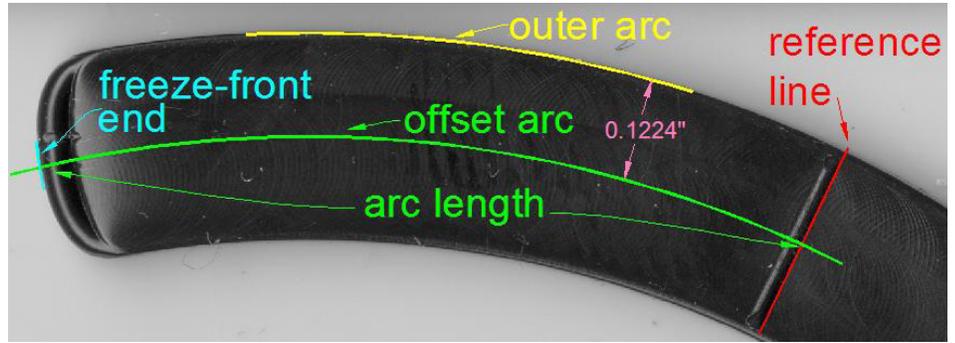
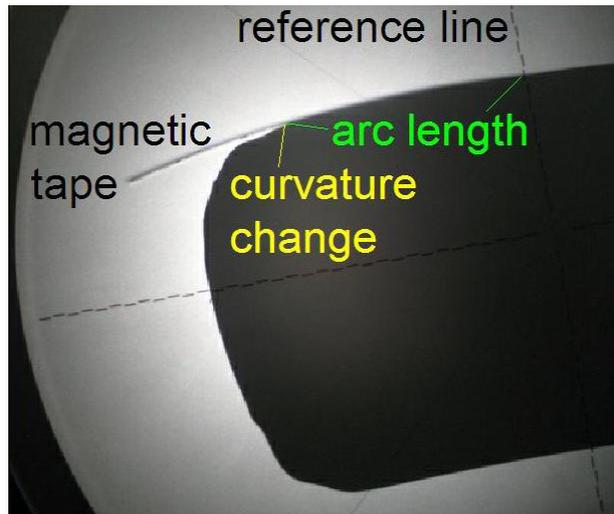


Figure 5. Photograph of profile projector screen showing identification of end segment (arc) length of spiral specimen.



tions and analysis of this data was based on the procedure for a GR&R study as below described.

#### Profile projector

As previously mentioned, a profile projector was utilized as an alternative measurement device. Data obtained from the projector was compared to the data obtained from the flatbed scanner. Of the two rules described above, the Outer rule was more readily adaptable and comparable to the profile projector. Since the profile projector used did not have the ability to draw arcs on its screen, a thin strand of plastic (cassette magnetic tape) was draped over the end segment as shown in Figure 5. This simulated the arc overhang drawn on the scanned images using AutoCAD. The end segment’s length was identified as being the outer arc from

the beginning of the reference line to where the spiral starts to deviate from the strand. The researchers followed the following steps to find this arc length:

- Aligned one axis of the projector screen’s crosshairs along the end reference line.
- Moved the x, y micrometer translation stages; located and recorded the coordinates where the outer arc and the axis crossed.
- Located and recorded the point coordinates at which the spiral and strand deviated.
- Located and recorded a third point’s coordinates on the outer arc that was about equidistant from the deviation and reference line points.
- Entered the coordinates of the above three points into AutoCAD using the “arc 3-point” tool.
- Selected the drawn arc and obtained

its length from the “properties” table.

Each of the ten specimens was measured three times in random order using the above rule. The average and range for each specimen was calculated and is presented. Also, the average of the ranges and average of the averages were calculated and are presented.

*Gage repeatability and reproducibility (GR&R)*

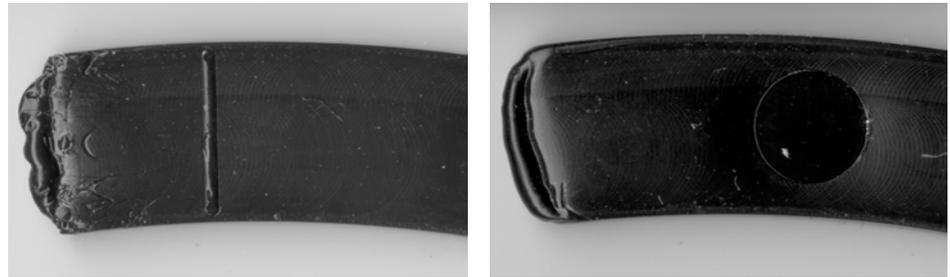
The present GR&R study followed the procedure suggested in *Measurement Systems Analysis* (AIAG, 2002). Three appraisers, ten specimens, and three trials were chosen for the study of the spiral length measurement based on the Offset rule (see Figure 4). The ten specimens were chosen to represent a variety of segment lengths and freeze-front profiles that might present challenges to the measurement system. Figure 6 shows two of the freeze-front profiles that illustrate the variability of freeze-front profile shapes. Two of the appraisers (“B” and “C”) had no experience using AutoCAD prior to the present GR&R study. They received approximately one half hour of training to learn the eight steps of applying the Offset rule. Each appraiser measured each specimen three times (trials) in random order. Each measurement took about 5 minutes to complete and record.

**RESULTS AND DISCUSSION**

**Calibration**

Ten scanned measurements of the nominal 0.300 inch gage block resulted in an average of 0.30159 inch and standard deviation of 0.000099 inch. Similarly, ten measurements using the profile projector resulted in an average of 0.29995 inch and standard deviation of 0.000161 inch. Therefore, the average difference between the scan and projector measurements is about 0.55%. The projector average falls within its 0.00005 inch resolution of the nominal value, which indicates accurate measurement. However, the scan average is not within its 0.0002 inch resolution of the nominal value.

**Figure 6. Scans of two end segments showing wide variation of profile shapes.**



**Table 1. End Segment’s Length using Outer Rule (in inches)**

Specimen number	Segment position	Scanner		Projector		Difference in averages
		Average	Range	Range	Average	
1	7	1.05100	0.00223	0.00223	1.04303	0.00797
2	8	0.44083	0.00734	0.00734	0.43678	0.00404
3	10	0.91948	0.00502	0.00502	0.93356	0.01408
4	11	0.84584	0.00763	0.00763	0.83112	0.01472
5	14	0.36011	0.00129	0.00129	0.35129	0.00883
6	15	1.00457	0.00414	0.00414	1.01183	0.00725
7	17	0.41489	0.00544	0.00544	0.41521	0.00032
8	18	0.95944	0.00196	0.00196	0.96039	0.00095
9	21	0.29696	0.00120	0.00120	0.31177	0.01481
10	22	0.69565	0.00346	0.00346	0.68685	0.00880
Averages of all specimens		0.69888	0.00397	0.00397	0.69818	0.00818

The difference between the scan average and nominal value is about 0.53%. This indicates a systematic error of scan measurements that are slightly larger than the true value of the object. The standard deviations of the scan and projector measurements indicate both have about the same repeatability.

Outer Rule Measurements

Following this Outer rule, the end segments’ lengths were measured using both a flatbed scanner and a profile projector system. Table 1 shows the ranges and averages for each specimen based on the measurement system used. The average of the averages for the scanner is 0.69888 inch whereas for the projector it is 0.69818 inch; a difference about 0.09%. This indicated that

the scanner measurements are slightly larger than those of the projector, which agrees with the calibration measurements of the gage block. However, the average of the ranges for the scanner is about 3.9% higher than that for the projector.

Offset Rule Measurements

The above results enabled comparison of measurements between two systems, while the results for the GR&R study enabled comparison among three appraisers. Table 2 shows the ranges and averages for each specimen based on the appraiser. The average of all appraisers is 0.71361inch and the average maximum difference among appraisers is 0.00048 inch for a given specimen; a difference of about 0.07%. Translated

**Table 2. End Segment's Length using Offset Rule (in inches)**

Spec. num.	Seg. pos.	Appraiser						Maximum difference in averages
		A		B		C		
		Range	Average	Range	Average	Range	Average	
1	7	0.00013	1.00642	0.00015	1.00610	0.00040	1.00666	0.00056
2	8	0.00031	0.46075	0.00031	0.46040	0.00029	0.46067	0.00035
3	10	0.00004	0.91903	0.00074	0.91820	0.00056	0.91884	0.00083
4	11	0.00018	0.84070	0.00021	0.84034	0.00012	0.84036	0.00036
5	14	0.00017	0.40088	0.00044	0.40056	0.00042	0.40084	0.00032
6	15	0.00027	1.01596	0.00044	1.01564	0.00053	1.01584	0.00033
7	17	0.00004	0.45751	0.00041	0.45713	0.00012	0.45723	0.00037
8	18	0.00022	0.96192	0.00008	0.96116	0.00032	0.96141	0.00075
9	21	0.00079	0.35448	0.00020	0.35415	0.00020	0.35460	0.00045
10	22	0.00037	0.72047	0.00058	0.72000	0.00038	0.72005	0.00047
Averages of all Specimens		0.00025	0.71381	0.00036	0.71337	0.00033	0.71365	0.00048

in terms of dpi, this means the appraisers differ among one another on an average of about two pixels for a given specimen. Referring again to Table 2 for the Offset rule measurements, the average of one appraiser is 0.69888 inch with an average range of 0.00412 inch for a given specimen; or about 0.59%. Based on the definitions of the Offset and Outer rules, it was expected the Offset rule would yield longer end segment measurements since almost all of the specimens had convex freeze-fronts. It was also expected that measurement variation would be less for those from the Offset rule since the end of the freeze-front was more readily identifiable by the appraisers than a change in radius of curvature.

In terms of a GR&R study, Table 3 below is used to evaluate the capability of using a flatbed scanner to measure spiral length. Generally, the gage system is acceptable if the GR&R is under 10% according to the Automotive Industry Action Group (2002). As one can see in Table 3, the measured R&R percentage (0.143%) is well below this require-

**Table 3. GR&R Results of Offset Rule Measurements**

Measurement category	Inches	Percent
Repeatability: equipment variation (E.V.)	0.00096	0.089
Reproducibility: appraiser variation (A.V.)	0.00119	0.111
Part Variation (P.V.)	1.07148	100
Repeatability & Reproducibility (R&R)	0.00153	0.143
Total Variation (T.V.)	1.07148	

ment. Also note that the repeatability and reproducibility are close in value to each other, indicating the measurement variation is due equally to the equipment and appraisers. The part variation of 100% is a desired result since it indicates that the specimens selected represent full variation of the process.

**CONCLUSIONS**

This research demonstrates that flatbed scanners can be used to measure objects with a high degree of precision comparable to that of a profile projec-

tor. While there are some drawbacks to the method, they are outweighed by its advantages.

The method uses software (AutoCAD) and equipment (scanner) that technology-based companies commonly own. The method is easy to learn and to apply with accuracy: the gage capability study shows very little difference in performance of the AutoCAD experienced and inexperienced appraisers, which can be attributed, in large part, to the ability of the appraisers to imme-

diately see their drawn arcs and adjust their technique (learning feedback). Also, since the drawings are archived, a supervisor can review appraiser performance and re-train on specific steps as needed. The present flatbed scanning measurement method can be adapted through computer-automation for high production rate measurement.

The main disadvantage of using flatbed scanners is that the measurement area must be flat. The narrow depth of field of the scanner prohibits obtaining sharp images of object features beyond about one-tenth of an inch above the glass platen. Further, there is about a half percent error in the accuracy of the measurement, although this could be reduced by applying a scaling correction factor.

The present research presents further research opportunities for improving the measurement method. To reduce the scan time and file size requirements, lower scanner dpi and gray levels would need to be investigated, which will establish criteria for automated measurements. Another approach would be to compare different makes/models of scanners, especially those with higher resolutions. It might also be possible to extend the height above the glass platen where measurements could be made acceptable. Most likely this will require application of image enhancement software. It is anticipated that a wide range of industries will continue to find an increasing variety of measurement applications for flatbed scanners. As this paper shows, appropriate measurement criteria will need to be developed to obtain accurate and precise data for new applications of this method.

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