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Design and development of microwire feeder for laser applications

Amogh J. Shenoy

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DESIGN AND DEVELOPMENT OF MICROWIRE FEEDER FOR LASER APPLICATIONS

by

AMOGH JEEVAN SHENOY

A THESIS

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Approved by

Frank W. Liou
Joseph W. Newkirk
Xiaoping Du

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This thesis is presented in publication format and is divided into two separate papers. Pages 2 through 33 are to be published at American Society of Mechanical Engineering 2010 International Design Engineering Technical Conference for publication in *Design for Manufacturing and Life Cycle Conference* under the title, “Research and Development of Microwire Handling Devices”. Pages 34 through 68 are to be submitted for publication in the *American Welding Journal*, under the title, “Microwire Feeder for Laser Applications”.

ABSTRACT

This thesis focuses on the design and development of a microwire feeder for laser applications. The use of wire-feeders in laser welding and electrical discharge machining applications has been prominent which can handle wire of 0.25 mm and it can go up to 10.0 mm in other applications. Development of microwire handling devices is complicated and difficult due to its low buckling strength; the need for high accuracy for its use; and the harsh environment it is exposed to, in laser applications. This paper presents a systematic methodology for the design and development of a high-precision microwire handling device. This was done by dividing the microwire feeder into four basic sub-mechanisms: (1) feeding mechanism (2) transfer mechanism (3) precision guidance mechanism (4) adjustment mechanism and then integrating them to account for compactness, flexibility and precision. This microwire feeder is capable of handling wires as low as 0.05 mm in diameter. The device was experimentally tested for initial design failures, high precision, and repeatability. A case study on laser deposition is presented; where; a 316 stainless steel microwire of 0.125 mm diameter is fed into a melt pool of 0.2 mm. The wire feed and the traverse speed of the table is varied to achieve a uniformly distributed clad. The effect of wire feed and traverse speed is studied and a deposition process window is developed for future experimentation. Thus, the effectiveness of the microwire feeder in terms of accuracy and precision of delivering micro-diameter wires to very small melt pool sizes without damaging the wire is experimentally verified.

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1. INTRODUCTION

The use of metallic wire as a deposition medium in the field of laser manufacturing is gaining popularity, but the number of feasible industrial application is still growing. Compared to powder, wire as a medium for deposition, has much lower material cost and high material efficiency. But due to the lack of ready availability of microwires of different sizes and materials, powder deposition has been more popular.

The development of this microwire handling device was initiated to effectively feed wire of microdiameters to a mini-laser deposition machine in Laser Aided Manufacturing Process Laboratory, which required a high precision wire feeding equipment. The mini-laser deposition machine for which the microwire feeder is developed has a small melt pool of 0.2 mm with high power density and is significantly less expensive than its larger counter parts. This microwire feeder can handle wires sizes as low as 0.05 mm diameters. The development of this system was to target increased acceptance of laser deposition technology, by reducing the cost and using metallic wire as the means for deposition.

The first section provides details about the methodology and systematic approach towards the development of microwire handling devices, where the device is built and tested for its initial design, high precision and repeatability. The second section provides details about the design and embodiment of the microwire feeder used for effective laser deposition of metallic wires in min-laser deposition.

PAPER

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I. RESEARCH AND DEVELOPMENT OF MICROWIRE HANDLING DEVICES

Amogh J. Shenoy
Laser Aided Manufacturing Process Laboratory
Department of Manufacturing Engineering
Missouri University of Science & Technology
Rolla, Missouri 65409
Email: ajs5g8@mst.edu

Frank W. Liou
Laser Aided Manufacturing Process Laboratory
Department of Manufacturing Engineering
Missouri University of Science & Technology
Rolla, Missouri 65409
Email: liou@mst.edu

Shyam Barua
Laser Aided Manufacturing Process Laboratory
Department of Manufacturing Engineering
Missouri University of Science & Technology
Rolla, Missouri 65409
Email: sbrc3@mst.edu

ABSTRACT

This paper focuses on the research and development of wire handling devices for microdiameter wires of various sizes. Microsized wires and tools are gaining importance in aerospace technology, medical device manufacturing and in the semiconductor industry. Development of microwire handling devices is complicated and difficult due to the size of the wire and the need for high accuracy for its use. The aim of this work was to develop a compact, robust, and highly precise device. This paper presents a systematic methodology for the development of a high-precision microwire handling device. The device can accurately feed wires ranging as low as 0.05 mm in diameter. The wire handling device must satisfy the following three criteria: (1) it must continuously feed wire without slippage and kinking; (2) it must ensure repeatability with great accuracy; (3) and it must handle wire of various sizes. The device was experimentally tested for initial design failures, high precision, and repeatability. A practical example for laser deposition is presented here to illustrate the effectiveness of the proposed approach.

Keyword: microwire, wire handling, precision guiding, design methodology

1. INTRODUCTION

New processes are being developed in rapid prototyping and manufacturing each year [1]. The use of metallic wire for manufacturing applications has become common, used in aerospace and car manufacturing over the years. As a deposition medium in the field of laser manufacturing, metallic wire is gaining popularity, and the number of feasible industrial applications is still growing [2]. Until now, however few scientific projects have addressed microwire handling devices for use in small-business applications. Thus, this work sought to develop a compact, robust, and high-precision wire handling device applicable to all manufacturing industries.

In direct laser deposition (DLD), powder is delivered to the laser generated melt pool, which melt the powder and solidifies after cooling. Manufacture of three-dimensional prototype parts is possible by overlapping multiple individual tracks. So far, the widespread use of metallic wire as a deposition medium has been limited; about 80% of the application is laser welding and there have been only a few studies of the basic phenomena of laser cladding with wire feeding [2]. Compared to powder, wire as a medium for deposition, has much lower material cost and high material efficiency. But due to the lack of ready availability of microwires of different sizes and materials, powder deposition has been more popular.

Wire handling devices are used in welding, electrical discharge machining, and laser applications. These devices can handle wire 0.25mm in diameter, [3] and other applications can use wire up to 10.0 mm in diameter [4]. Wires with larger diameter are comparatively easy to handle due to their rigidity [3]. The raw material for microwire is purchased in coil form; thus the residual stresses always remain in the wire [5]. As a result, a robust handling mechanism is crucial to keep the wire taut for accurate feeding. Microwires are difficult to handle due to their tendency of kink and slip. To eliminate these issues; this work used a rigid pinch roller mechanism to feed the wire without slippage [6], a hypodermic needle with 4 degrees of freedom provided precision guidance. The equipment was tested its initial design failures, and its critical components were analyzed. It was also tested for precision, accuracy, repeatability, and reliability. Finally the device was applied in laser deposition to demonstrate its capabilities.

2. GENERAL APPROACH FOR DEVELOPING MICROWIRE HANDLING DEVICES

This section describes a general approach to the development of microwire handling devices. It provides a general overview of the development process and analyzes the initial design for accuracy, precision and reliability as shown in Figure 1.

The major issue of this wire handling device is to feed a small diameter stiff wire, continuously to a very small melt pool [7]. The problem to be solved was to ensure adequate force on the small diameter wire, without damaging it for continuous operation. For this it was essential to have a simple feeding mechanism which would impart the necessary force on the wire to continuously feed the wire without damaging it. Another important consideration is the poor compressive strength of microwire under the axial loading condition existing on the output side of a wire feed device. To reduce this problem to a minimum, the position of any such device must be as near the melt pool as possible. To reduce these problems, it was required to make a compact, robust and high precision wire feeder, which is capable of continuously feeding microdiameter wires to desired location with high precision and can be easily mounted for various applications.

By the theory of wire straightening, it should be possible fundamentally, to straighten the wire and feed accurately with a three-roller straightening unit [7]. The fact that this fails in practice is owed generally to fluctuation in initial bend of the wire, material of the wire, size of the melt pool. Thus, to avoid this problem and develop a simple, compact and high precision microwire feeder; the unit was divided into four different sub-mechanisms: feeding mechanism, transfer mechanism, precision guidance mechanism and adjustment mechanism. A feeding mechanism ensures smooth feeding of wire without slip, a transfer mechanism ensures the transfer of wire smoothly and without deformation, a precision guidance mechanism that feeds the wire to the desired location and an adjustment mechanism that accommodates wires of various diameters. These four mechanisms were integrated to develop the microwire feeder.

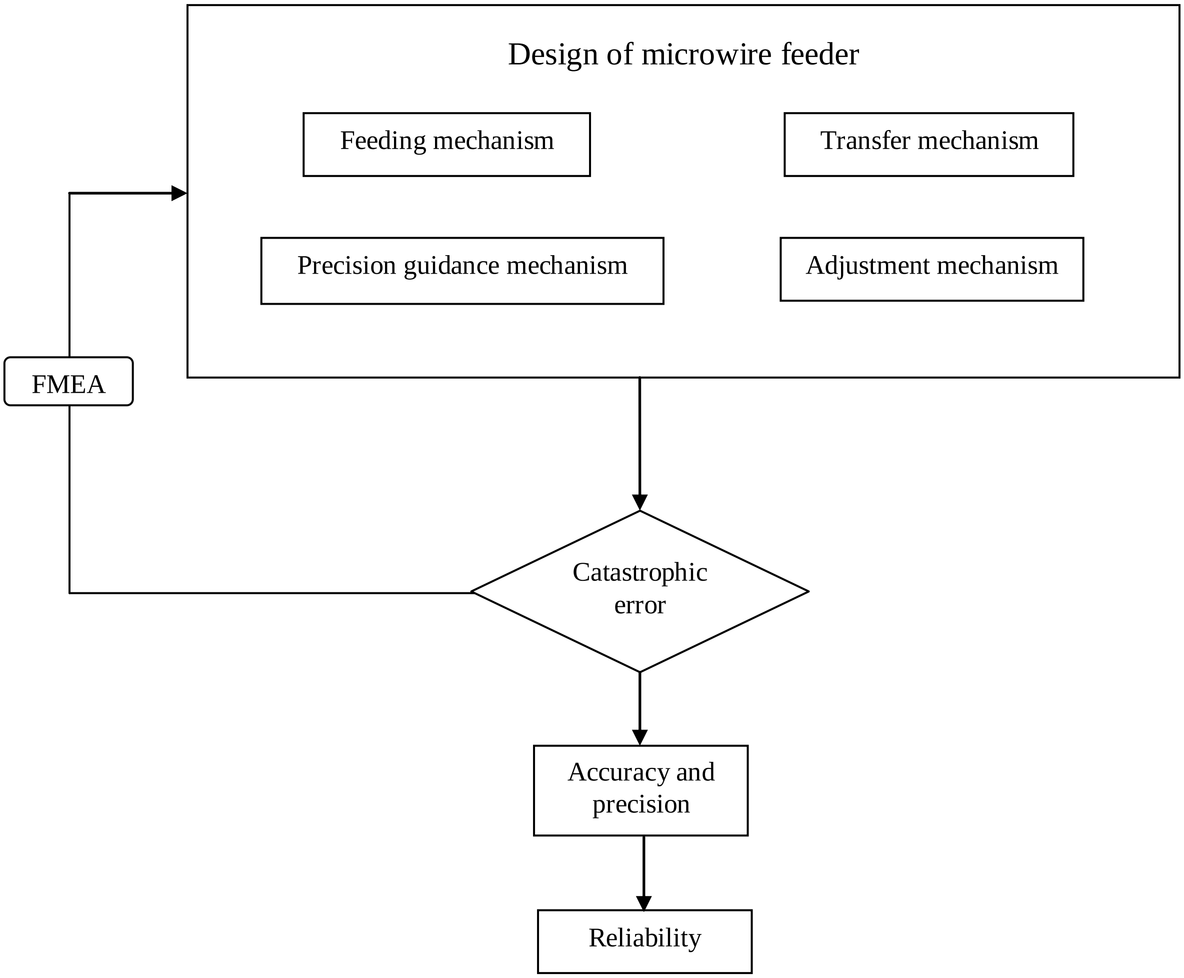

Figure 1. Approach for developing microwire handling devices

Design engineers often lack the time required to develop an accurate reliability assessment for a new design; therefore, a "build and test" approach to product development often replaces the preferred "analysis and test" methodology [8]. At the initial design stage, cost and reliability are tied primarily to manufacturing. The function of the device was to smoothly feed the wire without interruption to the desired location with high precision; failure to do so was termed as a catastrophic error. Identifying these failures at initial design stage was a critical aspect of Failure mode effect and analysis (FMEA). The FMEA analysis was divided into two primary process functions: (1) Setup; and (2) Feeding. The setup process function was analyzed to check for the ease of setup of the equipment, reduce changeover time, avoid initial kinks in the wire and to ensure adequate grip in the wire for smooth feeding. The feeding process function was analyzed to facilitate the primary function of the device; which; was to continuously feed the wire with high precision to a desired location. Thus, all the critical functions of the device were addressed by these two FMEA processes. FMEA was also used in the initial design stages to test the equipment for various failures and to determine the criticality of each component. This process informed the modification of critical components and the selection of materials for the various parts of the equipment. This analysis also would provide as the basis for calculation of the reliability of the equipment.

After application of FMEA, the design was tested for precision and accuracy, through the application of regression analysis. This approach ensured that the device would be sufficiently precise. To ensure repeatability and continuous operation of the system, a reliability test was also performed.

3. BASIC MECHANISMS OF MICROWIRE HANDLING DEVICES

Figure 2 shows the design of a typical microwire handling system. The system combines the feeding, transfer, and precision guidance mechanisms with flexibility for handling wires of varying microdiameters. Most important parameter for handling microwires is the elimination of slip and kinks in the wire.

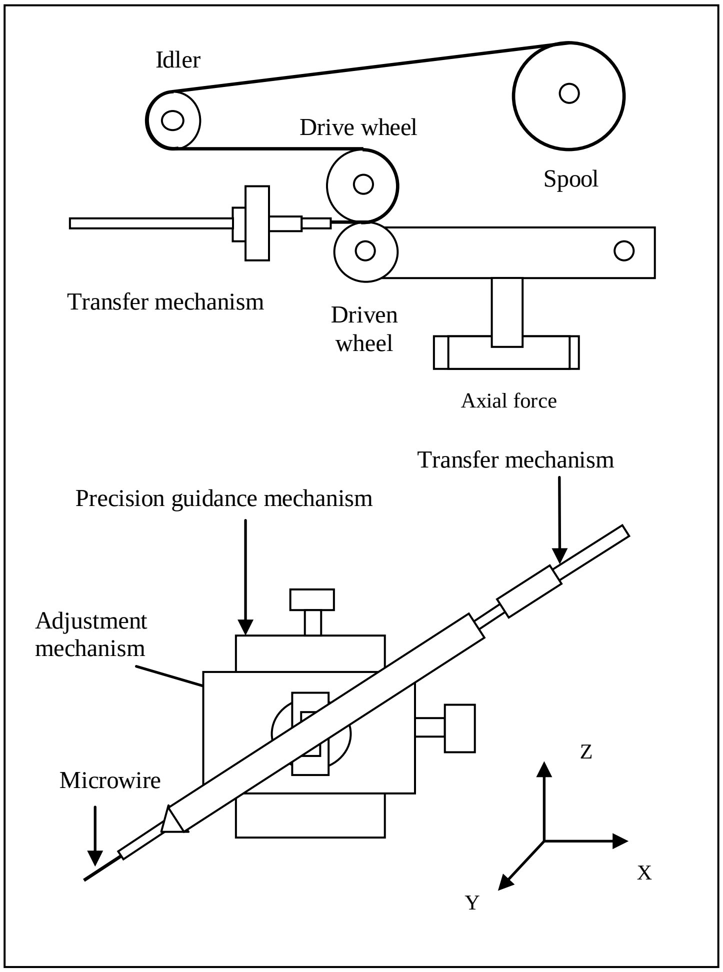

Figure 2. Typical design of a microwire handling device

3.1 Feeding Mechanism

A feeding mechanism feeds the wire continuously from the spool to the desired location with no slippage or deformation in the wire. It must impart the necessary axial and frictional force to keep the wire in tension. Due to the very small diameter of the wire, this mechanism should keep the wire taut at all times. The force applied should not deform the microwire. The larger the diameter of the wire, the easier it is to handle due to its rigidity. This work used rollers to pull/push the wire through the various components of the system [6]. The alignment of the wire as it enters the rollers is crucial to the performance of the system. The feeding mechanism should be able to accommodate a range of wire diameters.

3.2 Transfer Mechanism

The transfer mechanism provides the necessary flexibility to separate the feeding mechanism from the precision guidance mechanism. The wire must to be routed through to a precision guidance mechanism through a transfer conduit. This conduit must have a low coefficient of friction, and it must be wear resistant and structurally sound [3]. The conduit is typically a pliable outer tube with a diameter larger than that of the wire. An advantage of separating the feeding mechanism from the precision guidance mechanism is ease of maintenance and repair in an industrial environment. The transfer mechanism allows flexibility in the installation of the precision guidance mechanism; depending on the application requirements.

3.3 Precision Guidance Mechanism

To guide the wire precisely to a particular position, a rigid guide member is required with a diameter almost equal to the wire to minimize position error due to swaying of the wire within the guide member. The conduit used in the transfer mechanism should snugly fit with the guide member to ensure smooth transfer of the wire. The guide member should be adjustable in various axes to feed the wire to the desired location. Angular adjustment required in certain applications and is, therefore recommended to ensure precision guidance.

3.4 Adjustment Mechanism

So that, handling devices can handle microwire of various diameters, flexibility is necessary. Parts should be designed to be interchangeable depending on the diameter of wire. Thus the entire system is designed keeping in mind the change in the performance requirements.

4. ANALYSIS OF MICROWIRE HANDLING DEVICES

This section explains the importance of analysis of the system for its initial design, accuracy and precision, and repeatability and reliability are highlighted. The overview of the tools required for the assessment of the system is discussed below.

4.1 Failure Mode Effect and Analysis

FMEA is an engineering technique used to identify and prioritize potential problems in a system, design or process [9]. FMEA was used here during the initial design phase to analyze the reliability of both the development process and the microwire device itself. Critical factors affecting the continuous operation of the system were examined and the modifications were made to reduce or eliminate problems. The performance of each component was evaluated accordingly. This analysis facilitated the selection of material for each component. It highlighted design flaws and determined the criticality of each part. A risk priority number (RPN) methodology was used to analyze the risk associated with potential problems identified during The RPN is given by the following equation:

$$RPN = \mathrm{Occ} \times \mathrm{Sev} \times \mathrm{Det} \tag{1}$$

where; *Occ* represents the likelihood or occurrence of failure, *Sev* is the severity of the failure effect, and *Det* is the likelihood that the problem will be detected before the product reaches the end user.

4.2 Accuracy and Precision

The precision of a measurement system, also called reproducibility or repeatability, is the degree to which repeated measurements under unchanged conditions show the same results [10]. Regression analysis was used here to evaluate the precision of the system at varying motor speeds. This input speed of the motor was converted to the theoretical length of the wire to be fed by the system. This theoretical length was then compared with the observed experimental length to determine the error in the system. This was done to verify the linearity of the system. The theoretical length of the wire for a specified time is by simple regression analysis equation:

$$L(t) = \beta_0 + \beta_1 T \tag{2}$$

where, L represents the length of the wire in inches and T represents a specified unit of time in min

$$\beta_1 = \frac{\sum LT - \langle \sum L \sum T | n \rangle}{\sum T^2 - n\bar{T}^2} \tag{3}$$

$$\beta_0 = \bar{L} - \beta_1 \bar{T} \tag{4}$$

where; β_0 and β_1 are regression analysis constant, $\bar{L}$ represents the average length of wire to be fed and $\bar{T}$ represents the average time required to feed the wire.

4.3 Repeatability and Reliability

Reliability is the ability of a system or component to perform its required functions under stated conditions for a specified period of time. Process reliability assessment is an integral part of product development [11]. Identifying potential failures is a critical step in assessing reliability. The reliability of a component or a system at a given time t is calculated by cumulative normal distribution as follows:

$$R(t) = P(T > t) = [1 - P(T < t)] \sim N\ (\mu, \sigma^2) \tag{5}$$

where T represents a continuous random variable denoting time to failure, t represents a specified input time for failure, and μ is the mean time for failures, and σ^2 is the standard deviation of failures. Further the average number of failures per interval time is calculated as:

$$\mu = \frac{\sum_{i=1}^{n} a}{n} \tag{6}$$

where a is the sum of all the time to failure and n is the total number of failures

$$\sigma^2 = \frac{1}{n} \sum_{i=1}^{n} (a_i - \ \mu) \tag{7}$$

where a_i is sum of all time to failure and n represents the number of failures occurrence during the experiment.

5. CASE STUDY

This section describes the design methodology for the development of a microwire handling device with emphasis on the four mechanisms described above. Figure 2 shows a schematic for the development of a typical microwire handling device.

5.1 Feeding Mechanism

In this mechanism, the wire was wound on a spool and rigidly mounted on the base plate. The initial tension in the wire was determined by applying a known force to keep the wire taut and thus prevent it from kinking. A V-groove idler was used to change the direction of the wire and impart the necessary friction force required to avoid slippage. A stepper motor connected to a microprocessor-based controller allows both continuous and pulse feeding. The pinch roller was the driving mechanism for the system; it ensured continuous feeding of the wire. The roller was made of polyurethane and mounted on a shaft of a stepper motor and a V-groove steel bearing pinched together by means of a spring holder. The feeding mechanism was analyzed by breaking the system down into its various components and determining the forces required in the system to keep the wire taut and prevent it from slipping and kinking.

5.1.1 Initial Tension. The initial tension was necessary to hold the wire taut. The spool holding the wire was mounted on the base plate with the support of friction brakes that imparted the force necessary to determine the tension in the string. The tension T_1 required to keep the wire taut can be calculated by attaching a known mass, M, causing the spool to roll as shown in Figure 3.

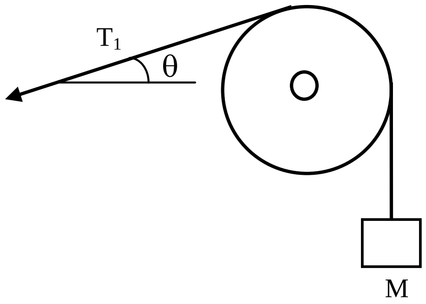

Figure 3. Microwire spool holder

Based on the free body diagram (FBD) of Figure 3, the initial tension T_1 is given by:

$$T_1 = \frac{M}{\sin\theta} \tag{8}$$

where θ represents the angle of inclination between wire and horizontal surface.

5.1.2 Angle of Wrap. The wire from the spool was then passed over a nylon idler, which induced adequate tension in the wire due to the frictional force. The angle of wrap is the angle of contact between the steel wire and the idler. The higher the angle of wrap, the higher was the frictional force. The angle of wrap can be changed by changing the angle of inclination, which is the angle made by the wire between spool and idler with the horizontal surface. The angle between the idler and spool was determined by the amount of force required to keep the wire taut, as calculated in Equation 8. This angle was found experimentally to be suitable in the range of 150°-180°.

Based on the FBD of Figure 4,

$$T_2 = T_1 \cos\theta \quad (9)$$

where T_2 represents tension in the wire after it passes through idler

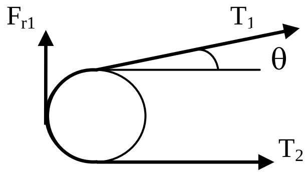

Figure 4. Mechanical idler

The friction force F_{r1} between the wire and nylon idler is given by

$$F_{r1} = \mu_{s1} T_1 \quad (10)$$

where µs1 is the coefficient of static friction between the nylon and the wire material.

As indicated by FBD of Figure 3, the friction force can also be calculated by

$$F_{r1} = T_1 \sin\theta. \quad (11)$$

The coefficient of static friction between the nylon idler and the wire is calculated as

$$\mu_{s1} = \frac{F_{r1}}{T_1} \quad (12)$$

This value should lie within the range of the coefficient of friction between the nylon and the wire material, and thus satisfy the frictional force required to keep the wire taut.

5.1.3 Frictional Force. A polyurethane foam was rigidly mounted on a shaft to act like a roller, coupled with a stepper motor that was used as the drive wheel mechanism to feed the wire. The controller connected to the stepper motor was capable of both pulse and continuous feeding. The shaft was coated with polyurethane due to the high static friction of polyurethane with steel surfaces [12]. Polyurethane ensured an adequate grip so that the wire could be fed continuously without slippage. The friction force required for the drive wheel was provided by the V-groove steel bearing which imparted an axial spring load on the roller. The FBD in Figure 5 shows the force analysis on the drive wheel mechanism.

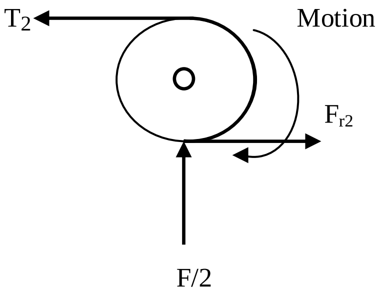

Figure 5. Drive wheel mechanism

As indicated by FBD of Figure 5, the frictional force F_{r2} between the drive wheel and the driven wheel is given by

$$F_{r2} = \mu_{s2} \frac{F}{2} \tag{13}$$

where $\mu s2$ equal to 0.6-0.9 is the coefficient of friction between polyurethane and steel bearing, and *F/2* is the axial load applied by the bearing.

The friction force F_{r2} is equal to the tension T_2 in the wire after it passes through the idler. Thus from Equation (13), we know the value of μ_{s2} should lie within the range of the coefficient of friction between polyurethane and steel.

5.1.4 Axial Load. The pinch roller comprised a unidirectional steel bearing mounted on a pivot and spring arrangement applies an axial load to the polyurethane-shaft roller. A very fine V-groove was made in the center of the roller bearing with a precision diamond cutter. Roller bearing is selected due to its high strength and resistance to wear over V-groove bearing. This groove maintained the alignment of the wire during feeding. A helical compression spring applied the force required to feed the wire without slippage.

As suggested in Figure 6, the axial force F applied on the helical spring can be calculated by compressing the spring with a known mass and measuring its deflection. This compressive force prevents the wire from slipping off the pinch roller arrangement and ensures rigid contact between the polyurethane roller and the steel bearing. The minimum force F required to ensure continuous feeding of the wire was determined experimentally. Assuming uniform distribution of the load in the pivot-bearing arrangement, the force on the bearing is the axial force divided by two. This force is responsible for maintaining rigid contact between the pinch rollers and thus minimizing slippage.

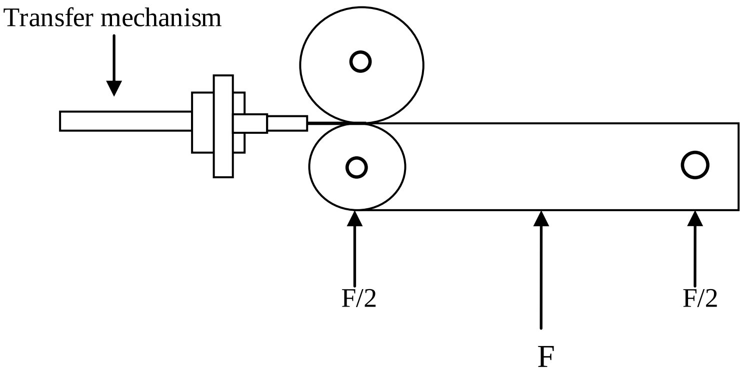

Figure 6. Pinch roller mechanism

5.2 Transfer Mechanism

A polytetrafluoroethylene (PTFE) tube was used to transfer the wire from the pinch roller to the hypodermic needle. This Teflon material has very low friction [12] and thus prevents deformation in the wire. The tube was rigidly held in a barb hose adapter which mounted on the base plate in such a way that the tube was aligned with the center of the V-groove bearing. This arrangement ensured smooth transfer of wire to the hypodermic needle as it emerged from the pinch rollers, preventing slippage and deformation. The PTFE tube can vary in size according to the size of the hypodermic needle to ensure sung fit. To feed a wire with a diameter of 0.1 mm through a hypodermic needle of outside diameter 3.0 mm, a PTFE tube with an inside diameter of 3.048 mm or 0.12 inch is appropriate. The inner diameter of the tube depends on the outer diameter of the hypodermic needle because a snug fit between the needle and the tube is necessary for smooth transfer of the wire. A heat shrink tube was coated on both ends of the PTFE tube to provide structural support and avoid resistance during feeding.

5.3 Precision Guidance Mechanism

A hypodermic needle was used to guide the wire, because such needles have low friction and are available with small inner diameters. Linear guide-ways with three degrees of freedom were used to guide the wire to the desired location. The size of the hypodermic needle can vary according to the size of the wire, to ensure smooth transfer of wire and have minimum frictional force with the inner wall of the needle during continuous operation. For example a hypodermic needle with an inside diameter of 0.125 mm and an outside diameter of 3.0 mm was used to feed wire with a diameter of 0.1 mm. This particular needle was selected for its small inner diameter and its thick wall features that prevent deformation of the inner wall. This needle also limited the maximum deflection of the wire from the central axis to minimize positioning errors and ensure a smooth feed with minimum frictional force. Linear guide-ways were used to orient the collet-needle arrangement along the X, Y, and Z axes.

5.4 Adjustment Mechanism

The hypodermic needle was encompassed in a mechanical collet capable of accommodating needles of various outside diameters. To feed a wire of 0.05-1.0 mm in diameter, the only change necessary would be the hypodermic needle and the PTFE tube. The collet can hold needles with outer diameters of 2-5 mm. The needle is held such that a very small portion of it is suspended at either end of the collet to minimize the cantilever effect. This arrangement makes the feeding precise and flexible for various applications. A clamp was machined with angle markers to permit changes in the angle at which feeding would take place. This clamp was then mounted on the Y-axis of the linear guide-ways to hold the collet-needle arrangement rigidly. This arrangement provides 4 degrees of freedom in X-Y-Z axes and an angular adjustment for guiding the wire to the desired location.

These four mechanisms were integrated to construct a microwire handling device that feeds wire continuously without slippage or deformation and that can accommodate wires of various sizes. Thus the design methodology followed the principle of “analysis and test” for pre-determined design requirements.

6. RESULTS

This section presents the result of experiments that demonstrate the effectiveness of the microwire handling device. The performance of the system was evaluated using 316L stainless steel wires of 0.1 mm, 0.125 mm, 0.5 mm and 1.0 mm. A copper wire of diameter 0.05 mm was used to check the performance of the system, due to the lack of availability of steel wire of that size. It was observed that the feeding of wires of larger diameters was much easier due to the rigidity of the wire. Thus wires of larger diameter were ran for considerably less time, as the focus was on handling microsized wires. To handle wires of different sizes, only the PTFE tubing and the needle ought to be changed. Thus the FMEA, regression analysis, and reliability test were performed on a 316L stainless steel microwire of diameter 0.1 mm, due to its ready availability and its use in practical applications of laser deposition.

6.1 Failure Mode Effect and Analysis

Wires of various diameters were run continuously for 8 hrs, which represents a standard shift. The major part of this analysis was done with 316 stainless steel microwire of diameter 0.1 mm due to its availability. This schedule permitted design changes during the initial design phase. The risk priority number (RPN) was calculated and the actions necessary to improve system performance were determined. After modification, the device was tested again and a new RPN recorded. The appendix provides a detailed list of the experiments. The modifications made to eliminate errors greatly reduced the RPN, as indicated in Figure 7.

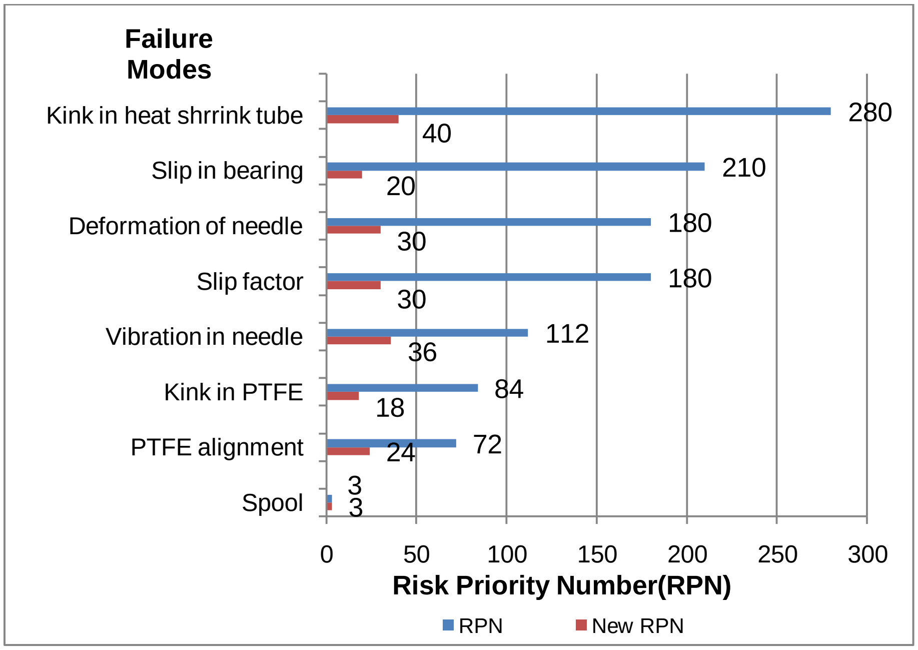

Figure 7. Reduction IN RPN by FMEA analysis

6.2 Accuracy and Precision

Regression analysis was used to determine the precision and accuracy of the device. The theoretical length of wire to be fed was calculated in inches per second based on the step angle of the stepper motor and based on the drive wheel diameter. The device was tested at various speeds for 20 minutes and each set was repeated 5 times, to verify experimentally the precision and linearity of the system. The setup was designed to compare the actual length of wire delivered to the theoretical length. Table 1 shows the results with an almost constant error of 5% for various motor input speeds. Figure 8 shows that the system is linear.

Table 1. Regression analysis

Feed-rate	**Motor**	**Observed Length**	**Average Length**	**% Error in feed**
Inch/Sec	steps/min	Inch	Inch	
0.025	3036	15	14.3	4.9%
0.05	1518	30	28.5	5.0%
0.075	1012	45	42.7	5.0%
0.1	759	60	57.0	5.0%
0.125	607	75	71.2	5.1%

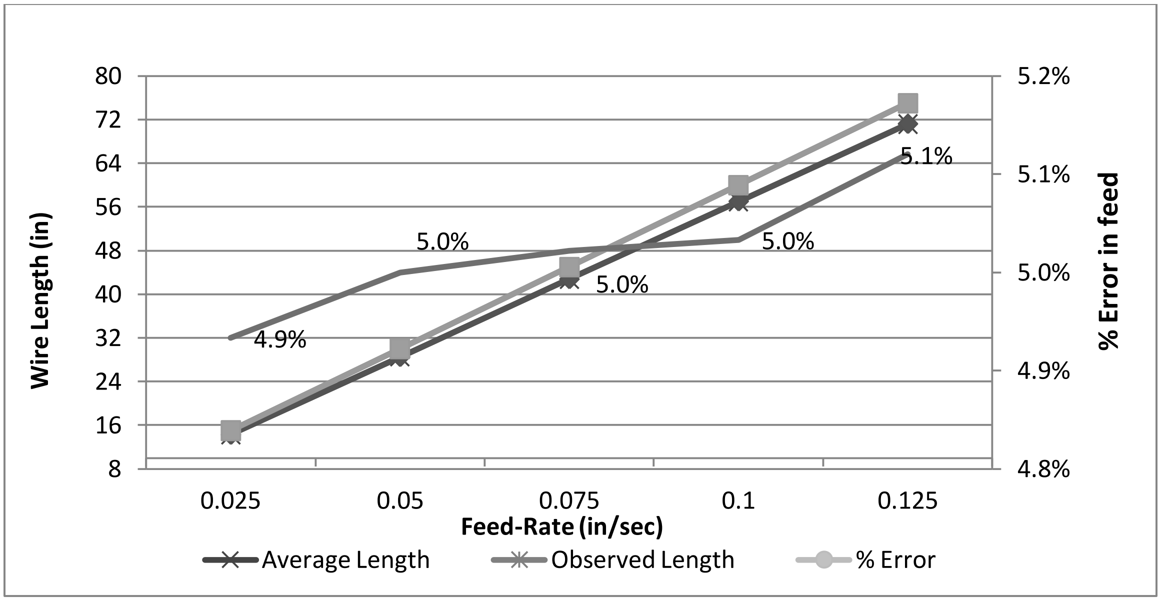

Figure 8. Precision feeding analysis

A constant error of 5% was observed indicating that the system to be linear and very precise. To ensure the accuracy, required for the system, the controller input was adjusted to compensate for the constant error introduced in the system. Thus high accuracy and precision of the system was achieved.

6.3 Repeatability and Reliability

The experiment was set up to run continuously, for 8 hours. The test was repeated for a total of 720 hours of operation. Failures occurred when feeding stopped or when the precision of the system was compromised.

Thus, occurrence data in the FMEA results (appendix) were used instead to calculate the number of failures. Six failures were observed; they are listed in the appendix. These failures were termed as catastrophic failures, which would affect the primary function of microwire handling device which is to feed the wire continuously to a desired location. The times for these failures were recorded and were used as a basis for calculation of mean time to failure and standard deviation of the experiment [13]. All the failures occurred in repairable products and required only minimal time to repair.

The specified time for which the reliability of the system was calculated was 8 hours, as it signifies an entire shift. Normal distribution was used to calculate the reliability of the system. Using the *Occ* data in the FMEA results, the reliability of the system over an 8 hours/shift was calculated using Equation (5), (6), and (7) and found to be 96.5 %. Thus the system was experimentally tested and verified to be 96.5% reliable for continuous operation of 8hrs/shift.

6.4 Practical Application for Laser Metal Deposition

Laser metal deposition is an additive process that uses an energy source, such as a laser to melt metal powder or wire onto a substrate. This experiment used a single diode laser with a wavelength of 808 nm for laser deposition of metals. The material of deposition was 316L stainless steel wire with a diameter of 0.125 mm. The laser had a focal length of 25 mm, and the melt pool size was 0.2 mm. The substrate was a steel plate of 1.75 mm thickness. The wire handling device was set up to feed the wire to the melt pool with the help of precision guide-ways and a digital microscope with a 200X zoom. A computer numerical control table was used to controls the motor which moves the substrate along the x- and y-axes. [14].

Figure 9, shows the deposition of microwire of 0.125 mm by hand feeding the wire, which was done by placing the wire flat, on the substrate. It can be seen that, the deposition is not uniform and it was not easily repeatable. Moreover the need for accuracy and precision required for laser deposition is high as the melt pool size is limited to 0.2 mm. It required a microwire handling device which would not only ensure a continuous uniform deposit, but would also ensure high repeatability. As shown in Figure 10, a continuous uniform cladding was obtained using the microwire of the same size as for hand feeding, which helped in further analysis and study of the deposition by forming a continuous uniform clad. Thus an effective deposition was achieved for this process by means of a microwire handling device.

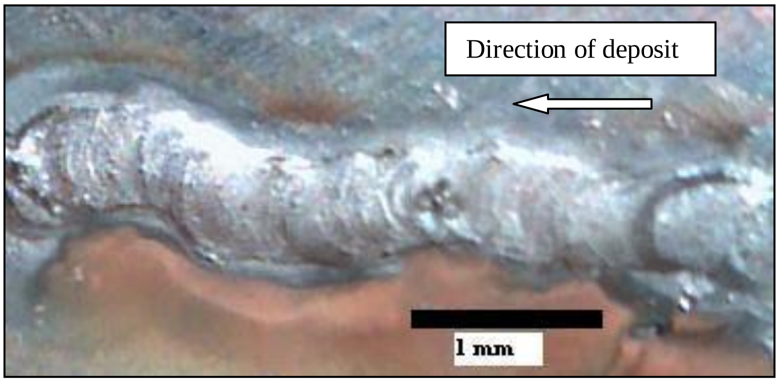

Figure 9. Laser deposit of 0.125 mm stainless steel wire on mild steel substrate by hand

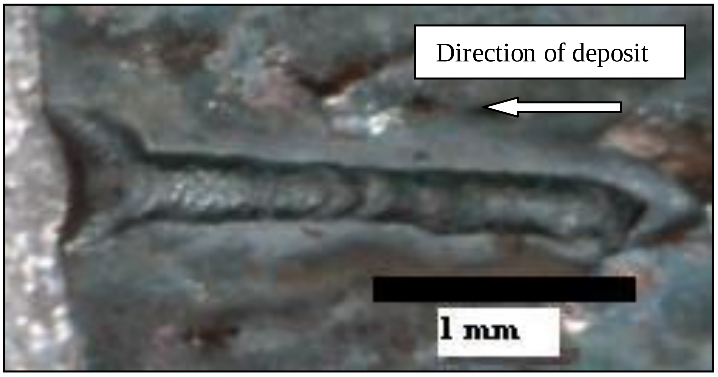

Figure 10. Laser deposit of 0.125 mm stainless steel wire on mild steel substrate by microwire handling device

7. CONCLUSION

This work developed a microwire handling device capable of accommodating wires 0.05-1.0 mm in diameter. Such wires are difficult to handle due to their low buckling strength. The microwire handling device was tested for precision and was found to be 95% precise. The reliability of the system was verified by normal distribution and the system was found to be 97% reliable. Thus the system was designed to feed wire continuously without slippage or kinking to ensure repeatability and accuracy; it was also designed to accommodate wires of various sizes. The device was applied to the laser metal deposition process to demonstrate its effectiveness for practical use. The results show the validity and competitiveness of the methodology for the development of microwire handling devices to feed wires of microsize diameters effectively to desired locations for laser applications.

ACKNOWLEDGEMENTS

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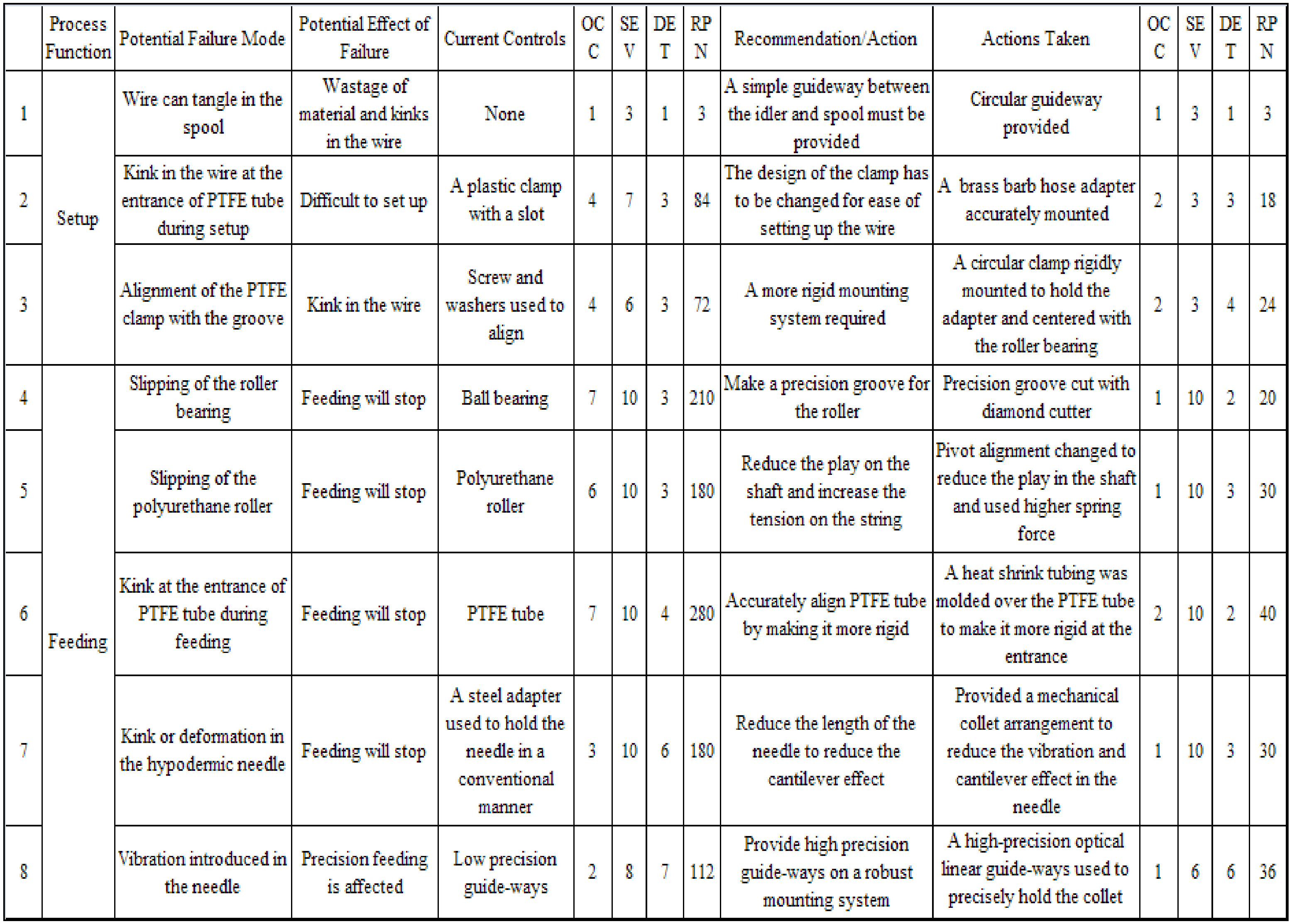
Appendix: FMEA Experimental Analysis



	Process Function	Potential Failure Mode	Potential Effect of Failure	Current Controls	OCC	SEV	DET	RPN	Recommendation/Action	Actions Taken	OCC	SEV	DET	RPN
1	Setup	Wire can tangle in the spool	Wastage of material and kinks in the wire	None	1	3	1	3	A simple guideway between the idler and spool must be provided	Circular guideway provided	1	3	1	3
2		Kink in the wire at the entrance of PTFE tube during setup	Difficult to set up	A plastic clamp with a slot	4	7	3	84	The design of the clamp has to be changed for ease of setting up the wire	A brass barb hose adapter accurately mounted	2	3	3	18
3		Alignment of the PTFE clamp with the groove	Kink in the wire	Screw and washers used to align	4	6	3	72	A more rigid mounting system required	A circular clamp rigidly mounted to hold the adapter and centered with the roller bearing	2	3	4	24
4	Feeding	Slipping of the roller bearing	Feeding will stop	Ball bearing	7	10	3	210	Make a precision groove for the roller	Precision groove cut with diamond cutter	1	10	2	20
5		Slipping of the polyurethane roller	Feeding will stop	Polyurethane roller	6	10	3	180	Reduce the play on the shaft and increase the tension on the string	Pivot alignment changed to reduce the play in the shaft and used higher spring force	1	10	3	30
6		Kink at the entrance of PTFE tube during feeding	Feeding will stop	PTFE tube	7	10	4	280	Accurately align PTFE tube by making it more rigid	A heat shrink tubing was molded over the PTFE tube to make it more rigid at the entrance	2	10	2	40
7		Kink or deformation in the hypodermic needle	Feeding will stop	A steel adapter used to hold the needle in a conventional manner	3	10	6	180	Reduce the length of the needle to reduce the cantilever effect	Provided a mechanical collet arrangement to reduce the vibration and cantilever effect in the needle	1	10	3	30
8		Vibration introduced in the needle	Precision feeding is affected	Low precision guide-ways	2	8	7	112	Provide high precision guide-ways on a robust mounting system	A high-precision optical linear guide-ways used to precisely hold the collet	1	6	6	36

Table: FMEA experimental analysis

II. MICROWIRE FEEDER FOR LASER APPLICATIONS

Amogh Shenoy and Frank Liou

Laser Aided Manufacturing Process Laboratory

Department of Manufacturing Engineering

Missouri University of Science and Technology

Rolla, Missouri 65409

Email: ajs5g8@mst.edu; liou@mst.edu

ABSTRACT

This paper focuses on the design and development of a fine microwire feeder for laser applications. The use of metallic wires as a medium of deposition has been widely used in aerospace and car manufacturing industries. These micro sized wires are also gaining importance in medical and semi-conductor industries. The use of wire-feeders in laser welding and electrical discharge machining applications has been prominent. There are devices used in laser applications which can handle wires from 0.25 mm to 10.0 mm in diameter. The handling of microsized wire in laser application is often considered difficult due to its low buckling strength exposure to harsh environment. The primary function of the microwire feeder described in this paper was to feed wires of varying microdiameters to a desired location with high accuracy and precision for laser aided manufacturing processes. This can be designed by dividing the microwire feeder into four basic sub-mechanisms: (1) feeding mechanism; (2) transfer mechanism; (3) precision guidance mechanism; (4) adjustment mechanism. These sub-mechanisms are integrated to account for compactness, flexibility and precision. This microwire feeder is capable of handling wires as low as 0.05 mm in diameter. The precision and accuracy of the device was experimentally tested prior to its practical application. A case study on laser deposition was presented, where a 316 stainless steel microwire of 0.125 mm diameter was fed into a melt pool of 0.2 mm. The wire feed and the traverse speed of the table were varied to achieve a uniformly distributed clad. The effects of wire feed and traverse speed were studied and a deposition process window was developed for future experimentation.

1. INTRODUCTION

In industrial manufacturing, the application of the laser beam as a tool has been popular in aerospace and automotive industries. Laser application allows batch as well as individual production and it has a wide range of applications from welding, and cutting to direct metal deposition. To facilitate the requirements of these wide ranges of application is what drives the development of system components such as wire feeders and sensor systems for automation for laser aided manufacturing processes.

The use of metallic wires as a deposition material in the field of laser manufacturing is gaining popularity, and the number of feasible industrial applications is still growing.[1] Until now few scientific works have been reported on microwire handling devices being used in small business applications, due to the high cost associated with laser manufacturing processes. In direct laser deposition (DLD), powder or wire is delivered to the laser generated melt pool, which melts the powder and solidifies after removal of the laser. Manufacture of three-dimensional prototype parts is possible by overlapping multiple individual tracks.[2] So far, the widespread use of metallic wire as a deposition medium has been limited; about 80% of the application is laser welding and there have been only a few studies of the basic phenomena of laser cladding with wire feeding.[3] Compared to powder, wire as a medium for deposition, has a much lower material cost and high material efficiency. But, due to the lack of availability of microwires of different sizes and materials, powder deposition has been more popular.

The use of wire feeders in laser welding and electrical discharge machining applications has been prominent. There are devices which can handle wires from 0.25mm[4] to 10 mm in diameter.[5] These wire feeders were used in high power laser applications with melt pool sizes varying from 0.5 – 4 mm. The initial cost associated with this laser technology is very high, which limits its application mainly to aerospace and automotive industries. These micro sized wires are gaining importance in the medical and semi-conductor industries. The development of this microwire handling device was initiated to effectively feed microdiameter wires to a mini-laser deposition machine which requires a high precision wire feeding equipment. The mini-laser deposition machine for which the wire feeder was developed has a small melt pool spot size of 0.2 mm and is significantly less expensive than its larger counter parts. The development of this system was targeted to increase acceptance of laser deposition technology, by reducing the cost and using metallic wire as a medium for deposition. Thus, a compact, robust, cost-efficient, and high precision microwire feeder was developed which is capable of handling microwires of sizes as low as 0.05 mm effectively.

2. BASIC DESIGN OF MICROWIRE FEEDERS

The major issue of the wire feeder is to feed a wire of an unusually small diameter and springy nature, continuously to a very small melt pool. The problem to be solved was to ensure adequate force to grip the small diameter wire, without damaging it during continuous operation. It was essential to have a simple feeding mechanism which would impart the necessary force on the wire to continuously feed the wire without damaging it. Another important consideration is the poor buckling strength of the microwire under the axial loading condition existing on the output side of the wire feed device. To minimize this problem, the position of the feed rolls must be as close to the melt pool as possible. Moreover, the size of the wire feeding unit is important, as it has to be mounted around the laser application, which would require fixture modifications and high setup and changeover time. To resolve these problems, a compact, robust and high precision wire feeder was required, which could continuously feed microdiameter wires to the desired location with high precision and require minimal fixture changes.

2.1 Roller Design

For handling and orientation of microdiameter wires, it is important to guide the wire accurately to the desired location. The straightening of these wires is not as important as guiding them accurately. But, it is important to determine the number of rollers required for straightening the wire to avoid bird-nesting and to keep the wire taut at all times. To determine the minimum number of rollers required for the application, the initial bend and yield point of the wire are considered to be the most important product parameters.[6] Yield points are determined by tensile testing various wire sections. The initial bend range is easy to determine by using a simple measurement of the original condition of several wire sections. To determine the initial bend K_a, it suffices to measure the camber of the wire over a random but fixed reference length. Figure 1 shows the schematic for measurement of the camber, where it can be measured by placing a fixed reference length of wire on a flat surface and against a straight edge. The greatest distance between the straight edge and the wire is the maximum camber and the least distance between them is the minimum camber. Calculation of initial bend is given by Equation (1) [6]

$$K_a = \frac{2h}{\left(\frac{l}{2}\right)^2 + h^2} \tag{1}$$

where;

$K_{a\,(max/min)}$ = Maximum/minimum initial bend in the wire

l = fixed reference length

$h_{(max/min)}$ = Maximum/minimum initial camber in the wire

The maximum values of initial camber $h_{(max)}$ yield the maximum initial bend $K_{a\,(max)}$. The same relationship applies for the minimum values.

With the values of the bends and yield points, it is possible to determine the minimum number of rollers, which is verified by the following equation[6]

$$2.0 < \left[RA = \frac{\frac{1}{K_{a\,max}} - \sqrt{\frac{1}{{K_{a\,max}}^{2}} - \frac{l^{2}}{4}}}{\frac{1}{K_{a\,min}} - \sqrt{\frac{1}{{K_{a\,min}}^{2}} - \frac{l^{2}}{4}}} + \frac{R_{p\,0.2\,max}}{R_{p\,0.2\,min}} \right] \leq 2.9 \tag{2}$$

where, $R_{p\,0.2\,(max/min)}$ = Maximum/minimum yield point at $R_{p\,0.2}$

If the value of RA < 2; the minimum number of rollers to be used is 3 rollers. If the value of RA is, 2.0< RA≤ 2.9, then the minimum number of rollers can be calculated by the following equation[6]

$$RB = \{(RA - 2) \times 10 + 4\} \tag{3}$$

According to the above equations, the minimum number of rollers required for the microwire feeder, was experimentally determined to be three rollers by the above equations. Based on the theory of wire straightening, it should be possible fundamentally, to straighten the wire and feed accurately with a three-roller straightening unit.[6] The fact that this becomes difficult in practical applications, is owed generally to fluctuation in the initial bend of the wire, the wire material, and tolerances of precision feeding. Thus, to avoid this problem and develop a simple, compact and high precision microwire feeder, after determining the minimum number of rollers, the unit can be divided into four different sub-mechanisms: feeding mechanism; transfer mechanism; precision guidance mechanism and adjustment mechanism. Moreover, limiting the device to three-rollers, helps to make it compact and considerably smaller in size, which helps it to be mounted around the laser application and requires minimal fixture modifications, ease of setup, reduces changeover time and makes it cost effective.

2.2 Feeding Mechanism

A feeding mechanism supplies the wire continuously from the spool to the desired location with no slippage or deformation in the wire. It must impart the necessary axial and frictional force to keep the wire in tension. Due to the very small diameter of the wire, this mechanism should keep the wire taut at all times. The force applied should not deform the microwire. The larger the diameter of the wire, the easier it is to handle due to its rigidity. Rollers were used to pull/push the wire through the various components of the system. The alignment of the wire as it enters the rollers is crucial to the performance of the system. The feeding mechanism should be able to accommodate a range of wire diameters.

Figure 2 shows the prototype of the feeding mechanism in which the wire was wound on a spool and rigidly mounted on the base plate which was connected to a torque motor. The initial tension in the wire was determined by applying a known force to keep the wire taut and thus preventing it from kinking. A V-groove idler can be used to change the direction of the wire and impart the necessary friction force required to avoid slippage. A stepper motor connected to a microprocessor-based controller allows for both continuous and pulse feeding.[7] The pinch roller was the driving mechanism for the system; which ensured continuous feeding of the wire. The roller was made of polyurethane and mounted on a shaft of the stepper motor and a V-groove steel bearing pinched together by means of a pivot-spring holder.

2.2.1 Angle of Inclination

As shown in Figure 3, the angle of inclination is the angle of contact between the steel wire and the idler. The wire from the spool was passed over an idler, which induced adequate tension in the wire due to the frictional force. The lower the angle of inclination, the higher the frictional force. The angle of inclination can be changed by the wire between spool and idler with the horizontal surface. The angle between the idler and spool was determined by the amount of force required to keep the wire taut without damaging it. This angle was found experimentally to be suitable in the range of 10°-30°.

2.2.2 Pinch Roller Mechanism

As seen in Figure 3, the pinch roller is the drive wheel mechanism of the wire feeder. The material used for the drive and driven wheel is critical as it has to ensure adequate grip on small diameter wires without damaging them. The drive wheel also has to account for the change in the sizes of wire and accordingly adjust the imparted pressure on the wire. In some wire feeders a capstan wheel is used as the drive wheel mechanism,[4] which makes the system bulky due to the size of the capstan.

To reduce the size of the microwire feeder, polyurethane foam was mounted on the motor shaft, which acted as the drive wheel for the system, and a bearing with a precision V-groove was used as the driven wheel. Polyurethane foam is used because it has a high coefficient of friction with steel. The V-groove was provided for the self-alignment of the wire, during feeding. Axial load is applied on the polyurethane shaft roller by means of a compressive spring. This arrangement also prevents the deformation of the wire and ensures an adequate grip which is required to avoid slippage of the wire.

2.2.3 Precision Grooved Rollers

As shown in Figure 3, a precision grooved roller is the key to continuously feed the wire without kinking or damaging it. It is also required to self-align the wire which reduces slippage of the wire to a great extent. The groove designs generally include V-groove style, radius-groove style and a special shaped groove to suit some applications.[7] A radius-groove roller is best suited for the straightening application because it has a high durability, but is limited to the size of wires it can handle. A special shaped groove requires custom production as per the requirement of the laser application and wire shape and size, with accurate tolerances and diameter. Standard V-groove is the most cost effective and is the most common with a wide range for handling wires of different sizes, for which the same rollers can be used. The limitation in V-groove is the high wear that occurs at contact points during continuous operation.

In the microwire feeder, a radial-groove roller is modified into a V-groove roller with the help of a precision diamond cutter. This is done because of the extreme small size of the wire and the V-groove is cut in the radial roller bearing, which helps in the self-alignment of the wire, provides the flexibility of using multiple wires and has high durability.

2.2.4 Force Analysis

Figure 4, shows the free body diagram (FBD) of the feeding mechanism, required for force analysis of the system. The spool which held the wire was mounted on the base plate with the support of friction brakes that imparted the force necessary to determine the tension in the string. The tension T_1 required to keep the wire taut can be calculated by attaching a known mass, M, causing the spool to roll. Based on the free body diagram (FBD) in Figure 4, the initial tension T_1 is given by:

$$T_1 = \frac{M}{\sin\theta} \tag{4}$$

where θ represents the angle of inclination between the wire and horizontal surface

The wire from the spool was then passed over a nylon idler, which induced adequate tension in the wire due to the frictional force. The angle between the idler and spool, which is the angle of inclination, was determined by the amount of force required to keep the wire taut, as calculated in Equation 4. This angle was found experimentally to be suitable in the range of 10°-30°. Based on the FBD in Figure 4,

$$\mathrm{T}_2 = \mathrm{T}_1 \cos\theta \tag{5}$$

where T_2 represents tension in the wire after it passes through the idler

The friction force F_{r1} between the wire and nylon idler is given by:

$$F_{r1} = \mu_{s1} T_1 \tag{6}$$

where μ_{s1} is the coefficient of static friction between the nylon and the wire material. As indicated by the FBD in Figure 4, the friction force can also be calculated by

$$F_{r1} = T_1 \sin\theta. \tag{7}$$

The coefficient of static friction between the nylon idler and the wire is calculated as

$$\mu_{s1} = \frac{F_{r1}}{T_1} \tag{8}$$

This value should lie within the range of the coefficient of friction between the nylon and the wire material, and thus satisfy the frictional force required to keep the wire taut.

Polyurethane ensured an adequate grip so that the wire could be fed continuously without slippage. The friction force required for the drive wheel was provided by the V-groove steel bearing which imparted an axial spring load on the polyurethane shaft roller, assuming a uniform distribution of axial spring force F, the frictional force F_{r2} between the drive wheel and the driven wheel is given by:

$$F_{r2} = \mu_{s2} \frac{F}{2} \tag{9}$$

where μ_{s2} equal to 0.6-0.9 is the coefficient of friction between polyurethane and the steel bearing, and *F/2* is the axial load applied by the bearing, which is half of axial spring force applied assuming uniform distribution of the load.

The friction force F_{r2} is equal to the tension T_2 in the wire after it passes through the idler. Thus, from equation (9), we know the value of μ_{s2} should lie within the range of the coefficient of friction between polyurethane and steel

2.3 Transfer Mechanism

The transfer mechanism provides the necessary flexibility to separate the feeding mechanism from the precision guidance mechanism. The wire must to be routed through to a precision guidance mechanism through a transfer conduit. This conduit must have a low coefficient of friction, and it must be wear resistant and structurally sound. The conduit is typically a pliable outer tube with a diameter larger than that of the wire. The advantage of separating the feeding mechanism from the precision guidance mechanism is ease of maintenance and repair in an industrial environment. The transfer mechanism allows flexibility in the installation of the precision guidance mechanism, depending on the application requirements.

As shown in Figures 2 and 3, a polytetrafluoroethylene (PTFE) tube was used to transfer the wire from the pinch roller to the hypodermic needle. This material has very low friction[8] and prevents deformation in the wire. The tube was rigidly held in a barb hose adapter which was mounted on the base plate in such a way that the tube was aligned with the center of the V-groove bearing. This arrangement ensured smooth transfer of wire to the hypodermic needle as it emerged from pinch rollers, preventing slippage and deformation. The size of the PTFE tube can vary according to the size of the hypodermic needle to ensure a snug fit. To feed a wire with a diameter of 0.1 mm through a hypodermic needle with an outside diameter of 3 mm, a PTFE tube with an inside diameter of 3.048 mm or 0.12 inch is appropriate. The inner diameter of the tube depends on the outer diameter of the hypodermic needle because a snug fit between the needle and the tube is necessary for a smooth transfer of the wire. A heat shrink tube was applied on both ends of the PTFE tube to provide structural support and avoid resistance during feeding.

2.4 Precision Guidance Mechanism

For precision guidance of wire to a particular position, it requires a rigid guide member with a diameter almost equal to the wire being handled. This minimizes position error due to the swaying of the wire within the guide member. The conduit used in the transfer mechanism should have a snug fit with the guide member to ensure smooth transfer of the wire. The guide member should be adjustable in various axes to feed the wire to the desired location. Angular adjustment is also recommended as it may be required in certain applications.

Figure 5 shows the precision guidance mechanism of the microwire feeder, where, a hypodermic needle was used to guide the wire, because such needles have a low coefficient of friction with steel wires and are available with small inner diameters. Linear guide-ways were used to guide the wire to the desired location. The size of the hypodermic needle can vary according to the size of the wire. Linear guide-ways were used to orient the collet-needle arrangement along the X, Y, and Z axes and an angle bracket clamped on the Y-axis provided the necessary angular adjustment.

The selection of the hypodermic needle according to different wire sizes is critical for the smooth functioning of the microwire feeder. The selection becomes critical in applications, where the wire has to be fed into a very small melt pool, with minimal scope for error. A needle with a large inner diameter can hamper the accuracy of feeding and in the case of an inner diameter which is too small, the smooth feeding of wire is affected. Thus, it becomes very important to select the right size needle for the specified wire diameter. The hypodermic needle used in this application is a 316L stainless steel with a very high tolerance of +0.0125 mm. The wall thickness should be as large as possible, which helps to keep the inner surface of the needle intact without any deformation. A number of microwires were tested with various hypodermic needles, experimentally, to determine the smooth feeding of wire without any interruption. A good fit for wires of different sizes was determined experimentally as shown in Table 1.

From Table 1 it can be observed that the ratio between the diameter of the wire and the inside diameter of the hypodermic needle is fairly constant and within the range of 60% to 67%. Thus the needle diameter limits the maximum deflection of the wire from the central axis to minimize positioning errors and ensures smooth feeding of wire with minimum frictional force. This largely limits the deflection error of the wire at the output end, as the wire is constrained by the inner walls of the hypodermic needle.

2.5 Adjustment Mechanism

In order for the microwire handling devices to handle wire of different diameters, it is necessary to have flexibility in handling wires to account for the same. This involves design of interchangeable parts which can be changed according to the diameter of wire which needs to be handled. Thus, the entire system is designed keeping in mind the change in the performance requirements.

As shown in Figure 5, the hypodermic needle was encompassed in a mechanical collet capable of accommodating needles of various outside diameters. To feed a wire of 0.05-1 mm in diameter, the only change necessary would be the hypodermic needle and the PTFE tube. The collet can hold needles with outer diameters of 1-4 mm. The needle is held such that a very small portion of it is suspended at either end of the collet to minimize the cantilever effect. This arrangement makes the feeding precise and flexible for various applications. To hold the collet-needle arrangement rigidly, a clamp with machined markers permit changes in the angle at which feeding would take place. This clamp was then mounted on the Y-axis of the linear guide-ways. This arrangement provides 4 degrees of freedom for guiding the wire to the desired location.

These four mechanisms: feeding mechanism; transfer mechanism; precision guidance mechanism and adjustment mechanism are integrated together for development of the microwire handling device. The primary function of the device is to continuously feed the wire without slippage or deformation and be able to handle wires of various microdiameters is achieved by this integration.

3. MICROWIRE FEEDER TESTING

This section presents the experiments that demonstrate the effectiveness of the microwire handling device. The performance of the system was evaluated using 316L stainless steel wires of 0.1 mm, 0.125 mm, 0.5 mm and 1.0 mm. It was observed that the feeding of wires of larger diameters was much easier due to the rigidity of the wire. Thus wires of larger diameter were ran for considerably less time, as the focus was on handling microsized wires. Failure mode effect and analysis and regression analysis were performed on a 316 stainless steel microwire of diameter 0.1 mm, due to its ready availability and its use in practical applications of laser deposition.

3.1 Failure Mode Effect and Analysis

FMEA is an engineering technique used to identify and prioritize potential problems in a system, design or process. Critical factors affecting the continuous operation of the system were examined and the modifications were made to reduce or eliminate problems.[9] The performance of each component was evaluated accordingly. For this the wires of various diameters were run continuously for 8 hrs, which represents a standard shift. A risk priority number (RPN) methodology was used to analyze the risk associated with potential problems identified during The RPN is given by the following equation:

$$RPN = \mathrm{Occ} \times \mathrm{Sev} \times \mathrm{Det} \tag{10}$$

where; *Occ* represents the likelihood or occurrence of failure, *Sev* is the severity of the failure effect, and *Det* is the likelihood that the problem will be detected before the product reaches the end user.

The risk priority number (RPN) was calculated and the actions necessary to improve system performance were determined. After modification, the device was tested again and a new RPN recorded. The appendix section provides a summary of the experiment.

3.2 Accuracy and Precision

Regression analysis was used here to evaluate the precision of the system at varying motor speeds. This input speed of the motor was converted to the theoretical length of the wire to be fed by the system. This theoretical length was then compared with the observed experimental length to determine the error in the system. The theoretical length of wire to be fed was calculated in inches per second based on the stepper motor's step angle and based on the drive wheel diameter. The device was tested at various speeds, for a specified duration to experimentally verify the precision and linearity of the system. Table 2 and Figure 6 show the experimental results observed for the system with an almost constant error of 5% for different input speeds of the motor showing the system to be liner and precise. To ensure the high accuracy required for the system, the controller input was adjusted to compensate for the constant error introduced in the system. Thus high accuracy and precision of the system was achieved.

4. CASE STUDY

The development of the microwire feeder was initiated to facilitate laser deposition of metals with wire as a medium of deposition. The mini-laser deposition machine in the Laser Aided Manufacturing Process laboratory is a single-diode, laser with high power density.

4.1 Mini-Laser Deposition System

As shown in Figure 7, the laser system is a single diode laser, emitting a wavelength of 808 nm and has approximately the same intensity. The laser beam has a focal length of 50 mm along the z-axis and the melt pool size is 0.2 mm when the laser beam is directed perpendicular on a 316 stainless steel substrate of a 5 mm thickness. The very small melt pool size is due to the fine spot of the laser which is 0.2 mm (200 microns), initiated the development of a fine microwire feeder which is capable of handling wires of very small sizes with high accuracy and precision. Moreover, the focal length of the beam is just 50 mm, which required the microwire feeder to be compact and robust. The experimental setup consists of a diode laser with a beam delivery system, a microwire feeder, and a computer numerically controlled (CNC) table for 3 axes; horizontal motion (x and y axis) and vertical motion (z axis). The microwire feeder, the single-diode laser, and the CNC table are controlled by a single controller unit, which helps to make it compatible and ensures high performance. The laser, feeder, and the CNC table are connected to a single power supply and are controlled by standard G and

M codes with modifications to allow for the deposition process. In addition, the system also includes:

- an air cooling system (top and base cooling plates)
- a 200X USB camera device to initially guide the wire accurately to the melt pool
- vision camera system developed for process observation and video capture
- an argon cover gas

This complete arrangement is the mini-laser deposition system used in the Laser Aided Manufacturing Process laboratory. The entire system is a table-top system, which requires a 5 foot by 5 foot space and is significantly less expensive than other laser deposition systems. However, the limitation of this system is that wire of various sizes of different materials is not readily available. Moreover, due to the extremely small melt pool size, it is limited to the size of parts that can be developed by this system. Due to the volume of wire fed in the melt pool is approximately equal to the size of the melt-pool itself, the volume causes a high fluctuation in heat dissipation.

4.2 Material

The wire used for deposition was 316 stainless steel wire with a 0.125 mm diameter and was chosen due to its resistance to oxidation and ease of availability for testing purposes. The laser beam was directed perpendicular to the substrate, made of mild steel with dimensions of 10 mm by 5 mm by 0.2 mm. This thin substrate was selected to study the effectiveness of the laser, parameters of the system, limitations of the process during deposition and to check the precision and accuracy of the wire-feeder.

4.3 Arrangement of the Experiment

The experimental arrangement was set up to feed the wire to the melt pool as shown in Figure 7. Front-feeding implies when the movement of the substrate is away from the feeder, this was chosen as it is considered to facilitate good clads.[5] The wire was oriented at an angle of 45 degrees from the horizontal surface of the substrate, with the help of an angle marker provided on the wire feeder. This arrangement was selected to study the efficiency of microwire feeding in laser deposition.[10]

4.4 Results and Discussion

During the feeding of the wire to the melt pool, it was observed that, the wire tends to melt and loosely sticks to the substrate rather than forming a good clad. This can be due to the high volume of wire entering a relatively small volume of melt pool, which chills the melt pool. To address this problem, a delay of 0.05 sec was set in the start of wire feeding by the controller, which ensured a continuous clad. The wire feed rate and traverse speed of the table are critical to achieve a good deposit. Thus, the traverse speed of the table and wire feed rate were varied at maximum constant laser power and observations were made during the experiment. In the mini-laser deposition system the wire is fed by the controller; thus, the wire feed rate is given as the ratio of wire fed by the microwire feeder per 0.5 inch of the travel of the table. This was done to ensure compatibility in feeding the wire and having an accurate response time. Table 3 shows the effect on the clad surface observed by varying the wire feed rate and traverse speed. The values outside the range of these speed and feeds were observed to be not suitable for the experiment. The qualitative analysis was done by observing the cladding surface under an optical microscope, and a continuous uniform clad was termed to be a good clad. Figure 8 (a), (b), and (c) show the three variations in cladding observed during the experiment. At a traverse speed of 1.5 inch/min and the wire feed of 0.5 inch/ 0.5 inch of table travel, a continuous uniform clad was observed, which is the best deposition as seen in Figure 8 (c).

Table 3 shows the effects of cladding at varying traverse speeds and wire feeds, as per experimental observation. The aim is to achieve continuous uniform deposition. Discontinuous deposits were observed when the wire fed to the melt pool was not adequate. It was also observed that when the wire was fed in excess, it tended to sway away from the melt pool due to resistance in the wire, which was termed as failed to melt in the table. The deposit in the non-uniform and uniform category is in our area of interest, where modifications can be made to facilitate a good uniform continuous deposit.

To verify the uniformity of the deposition obtained in Figure 8 (c), 5 points at equal intervals were selected on the deposit, and the width of the deposit was measured and compared to Figure 8 (b) as shown in Table 4. The standard deviation was calculated and found to be below 2% in uniform deposit as compared to 6.2% in non-uniform deposit.

From the results obtained in the experiment, a deposition process window was developed as shown in Figure 9. The dark square region in the figure indicated the parameters by which a good deposit was achieved, the deposition shown in Figure 8 (c) falls in this category. The grey square indicates the region where a continuous deposit was formed, but the deposition width is not uniform, as shown in Figure 8 (b). The circular region depicts the zone where the deposits were discontinuous, as shown in Figure 8 (a), and it defines the boundaries for experimentation.

During deposition of 0.25 mm 316 stainless steel wire on a 0.2 mm mild steel substrate, it was observed that the substrate tends to warp due to heat conductivity, which can be one of the reasons for non-uniform deposition of wire. Moreover, the scope of error being extremely small, it can also cause the wire to misalign itself during this process. It is also necessary to ensure that the surface is flat and the laser remains in focus, as the melt pool size can vary significantly, causing non-uniform deposition. These factors need to be taken into account, which can affect the deposition, for which the grey square region is defined in the deposition process window in Figure 9. This region is critical for further study. For further experiments, with varying traverse speed and wire feeds, the ratio of wire feed and traverse speed in the square region should be considered, for effective deposition. These show the effect of varying speed and wire feed rate on the deposition. Thus the effectiveness of the microwire feeder in terms of its accuracy and precision of delivering micro-diameter wires to a very small melt pool to achieve continuous uniform deposition is demonstrated.

5. FUTURE WORK

During the effective usage of the microwire feeder in practical application, there were no problems observed with feeding the microwire, which is the primary function of the device. But it was observed that the set up procedure for feeding the wire initially from the spool to transfer mechanism; varied largely on the expertise of the person running the experiment. This was due to the arrangement of the pivot-bearing and the transfer mechanism. The two components are independent of each other and during the setup for feeding the wire; it causes misalignment of the PTFE tube at the entrance of the pinch roller. Thus the development of a robust setup mechanism initiated the need for a second generation microwire feeder.

In the second generation microwire feeder, as shown in Figure 10, the basic mechanisms would remain the same, but the design would be modified for the ease of set up irrespective of the user expertise. The positioning of the spool, idler and the motor would remain unchanged, just with an addition of a guide clamp provided between spool and idler for support. The pivot-bearing arrangement and the transfer mechanism are modified and clamped to become a single unit, held by a pivot-clamp and spring arrangement. This would ensure accurate alignment required during setup. This design focuses on automation where the user can place the wire in the V-groove of the bearing and the motor would drive the wire through the PTFE tubing. This would help in reducing the setup time in applications which requires part manufacturing flexibility.

6. CONCLUSION

The design and development of microwire feeders, capable of handling microdiameter wires is often considered to be difficult due to its low buckling strength and high precision required for laser application usage. There are wire feeders which can feed wires as low as 0.25 mm diameter. Thus, the need for systematically developing a wire feeder capable of handling wires as low as 0.05 mm was initiated. In this paper, the design and embodiment of a fine microwire feeder for laser applications, capable of handling wires as low as 0.05 mm was discussed. This was done by integrating four different sub-mechanisms: feeding mechanism; transfer mechanism; precision guidance mechanism and adjustment mechanism. These mechanisms facilitated the compactness, flexibility and high precision requirements for varying laser applications. This microwire feeder was tested for its initial design failures and to select critical components for the system by using Failure mode effect and analysis, and its accuracy and precision was experimentally verified to be 95 % precise. A case study on mini-laser deposition was presented to verify the effectiveness of the microwire feeder, where a 0.125 mm wire was fed into a melt pool of 0.2 mm. The effect on deposition quality with varying wire feed rate and table traverse speed was studied to obtain a continuous uniform deposit. The results show standard deviation of deposition width between a uniform and non-uniform continuous deposit. Thus the validity and effectiveness of the microwire feeder in terms of its accuracy and precision of delivering micro-diameter wires to very small melt pool sizes in laser applications is experimentally verified.

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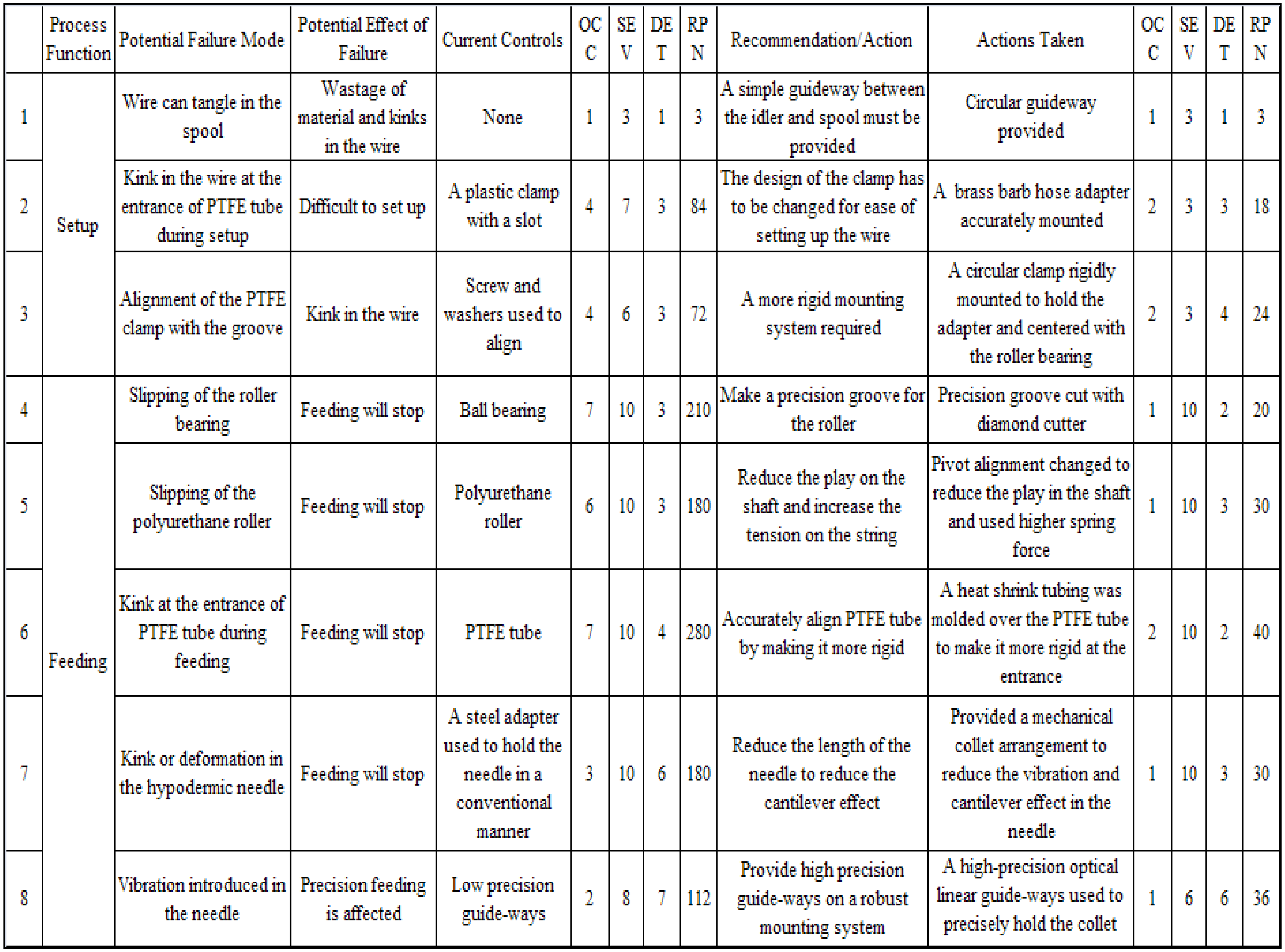
APPENDIX



	Process Function	Potential Failure Mode	Potential Effect of Failure	Current Controls	OCC	SEV	DET	RPN	Recommendation/Action	Actions Taken	OCC	SEV	DET	RPN
1	Setup	Wire can tangle in the spool	Wastage of material and kinks in the wire	None	1	3	1	3	A simple guideway between the idler and spool must be provided	Circular guideway provided	1	3	1	3
2		Kink in the wire at the entrance of PTFE tube during setup	Difficult to set up	A plastic clamp with a slot	4	7	3	84	The design of the clamp has to be changed for ease of setting up the wire	A brass barb hose adapter accurately mounted	2	3	3	18
3		Alignment of the PTFE clamp with the groove	Kink in the wire	Screw and washers used to align	4	6	3	72	A more rigid mounting system required	A circular clamp rigidly mounted to hold the adapter and centered with the roller bearing	2	3	4	24
4	Feeding	Slipping of the roller bearing	Feeding will stop	Ball bearing	7	10	3	210	Make a precision groove for the roller	Precision groove cut with diamond cutter	1	10	2	20
5		Slipping of the polyurethane roller	Feeding will stop	Polyurethane roller	6	10	3	180	Reduce the play on the shaft and increase the tension on the string	Pivot alignment changed to reduce the play in the shaft and used higher spring force	1	10	3	30
6		Kink at the entrance of PTFE tube during feeding	Feeding will stop	PTFE tube	7	10	4	280	Accurately align PTFE tube by making it more rigid	A heat shrink tubing was molded over the PTFE tube to make it more rigid at the entrance	2	10	2	40
7		Kink or deformation in the hypodermic needle	Feeding will stop	A steel adapter used to hold the needle in a conventional manner	3	10	6	180	Reduce the length of the needle to reduce the cantilever effect	Provided a mechanical collet arrangement to reduce the vibration and cantilever effect in the needle	1	10	3	30
8		Vibration introduced in the needle	Precision feeding is affected	Low precision guide-ways	2	8	7	112	Provide high precision guide-ways on a robust mounting system	A high-precision optical linear guide-ways used to precisely hold the collet	1	6	6	36

FMEA experimental analysis

Table 1. Selection of hypodermic needle according to wire diameter

Wire Dia (d)	Hypodermic Needle Inside Dia (D)	Wire/Needle Dia Ratio (d/D)
Mm	mm	(%)
0.05	0.08	62.5%
0.1	0.15	66.7%
0.125	0.2	62.5%
0.15	0.25	60.0%
0.2	0.3	66.7%
0.25	0.4	62.5%

Table 2. Microwire feeder precision testing at varying speeds

Feed-rate	**Motor**	**Observed Length**	**Average Length**	**% Error in feed**
Inch/Sec	steps/min	Inch	Inch	
0.025	3036	15	14.3	4.9%
0.05	1518	30	28.5	5.0%
0.075	1012	45	42.7	5.0%
0.1	759	60	57.0	5.0%
0.125	607	75	71.2	5.1%

Table 3. Effects on cladding at varying wire feed and traverse speeds

Traverse Speed	**Wire Feed**	**Surface Cladding Quality**
inch/min	inch/ 0.5 inch of travel	
2	0.25	Discontinuous
1.5	0.25	Discontinuous
2	0.375	Non-Uniform
1.5	0.375	Non-Uniform
2	0.5	Discontinuous
1.5	0.5	Uniform
2	0.75	Failed to Melt
1.5	0.75	Failed to Melt

Table 4. Deposition width of 0.125 mm 316 stainless steel wire on mild steel

Deposition	**Standard Deviation**
Uniform	1.9%
Non-uniform	6.2%

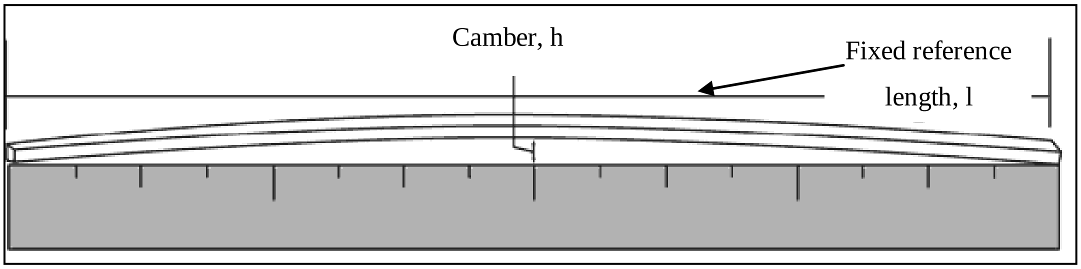


Figure 1. Calculation of camber in a circular wire

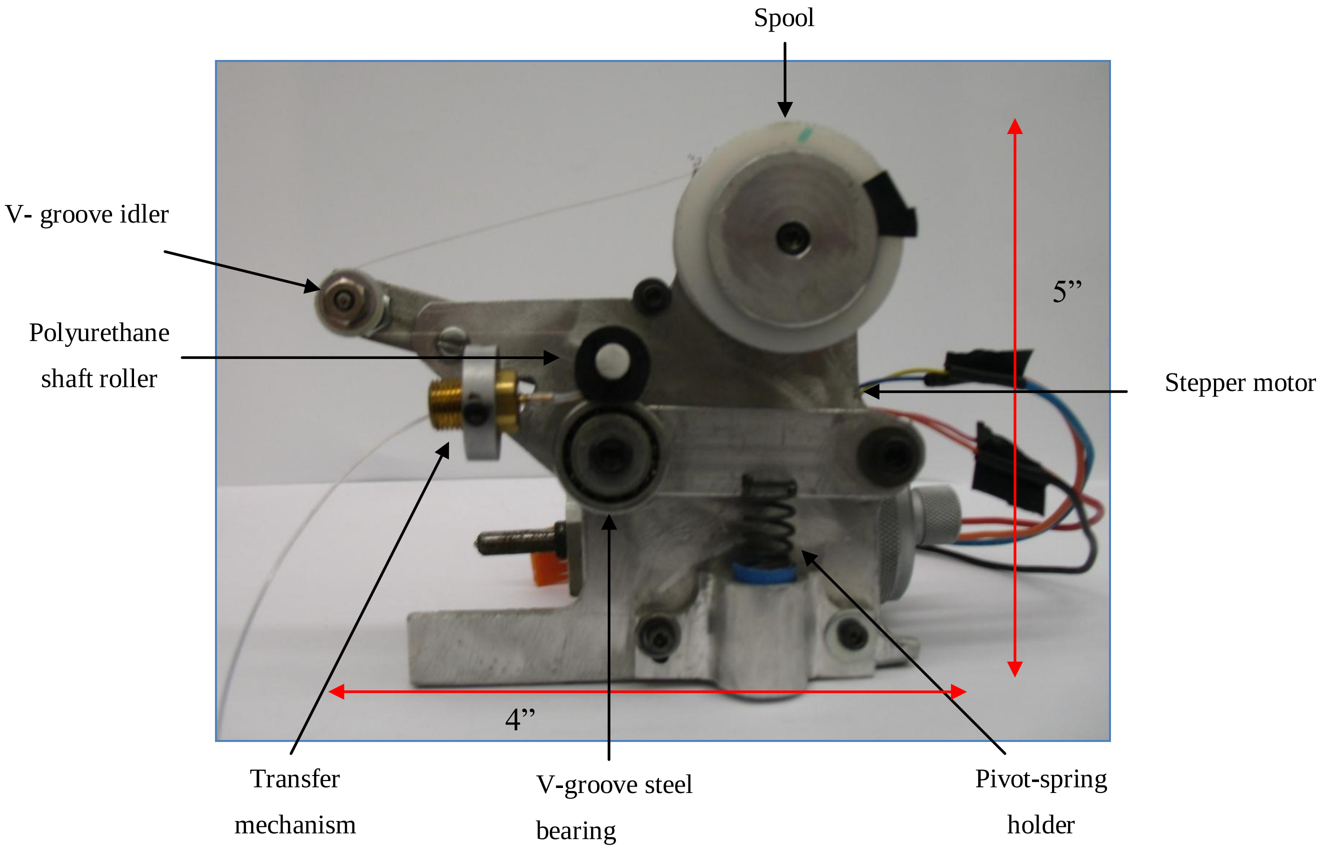


Figure 2. Prototype of microwire feeder

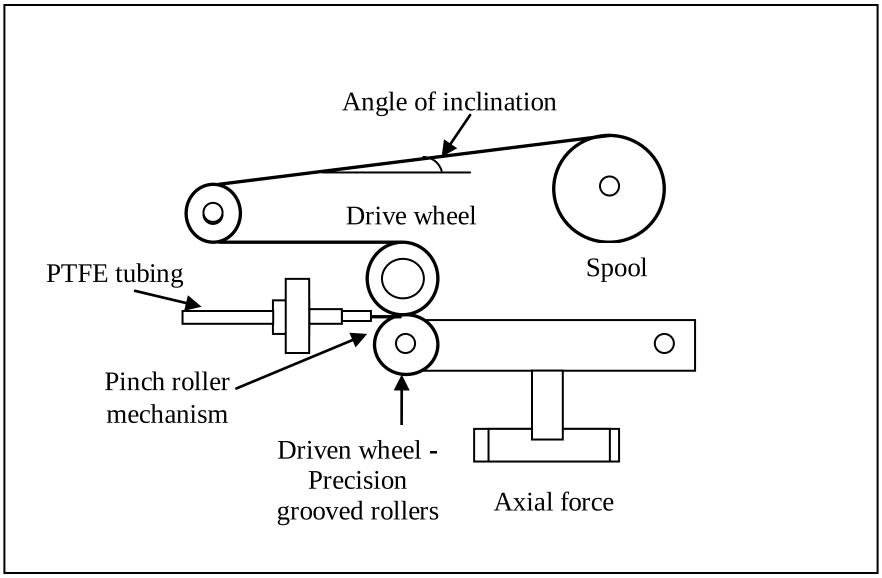


Figure 3. Basic feeding mechanism for microwire feeder

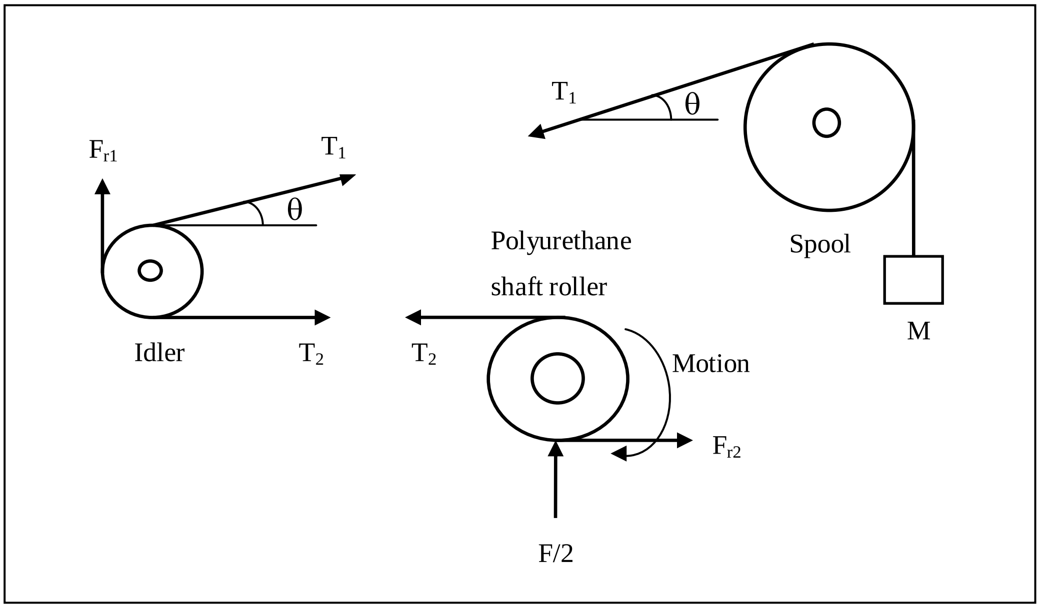


Figure 4. Free body diagram of a feeding mechanism for force analysis

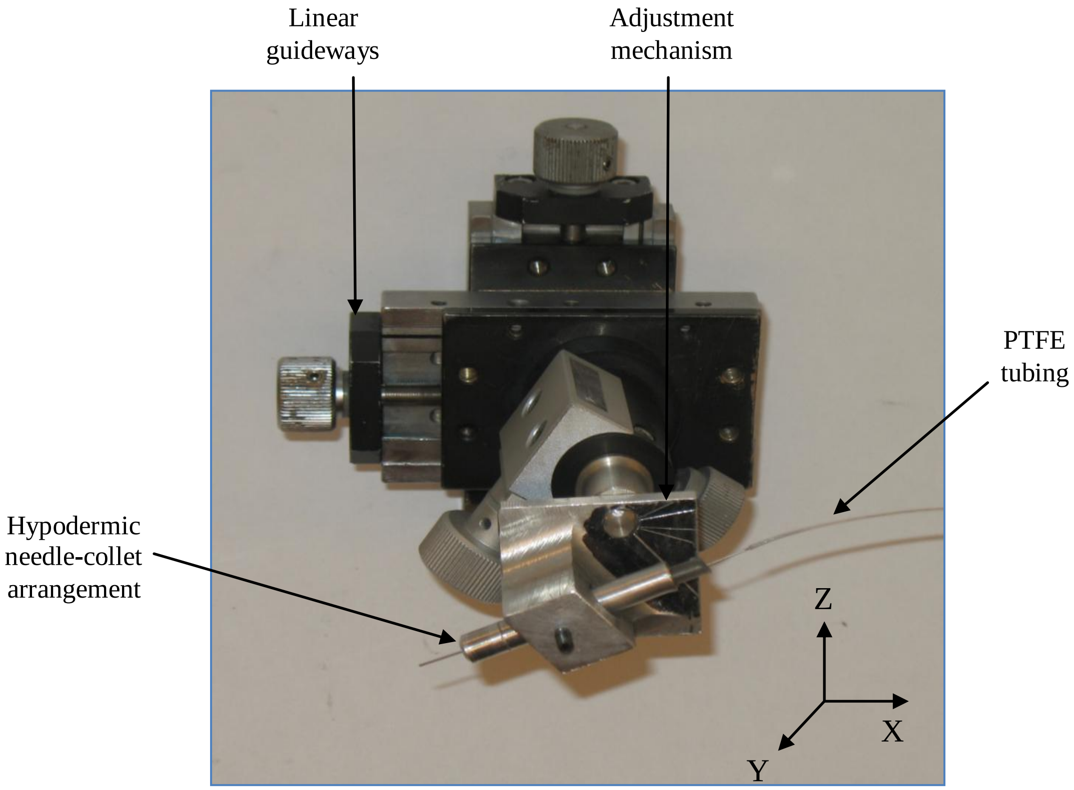


Figure 5. Precision wire guidance mechanism for microwire feeder

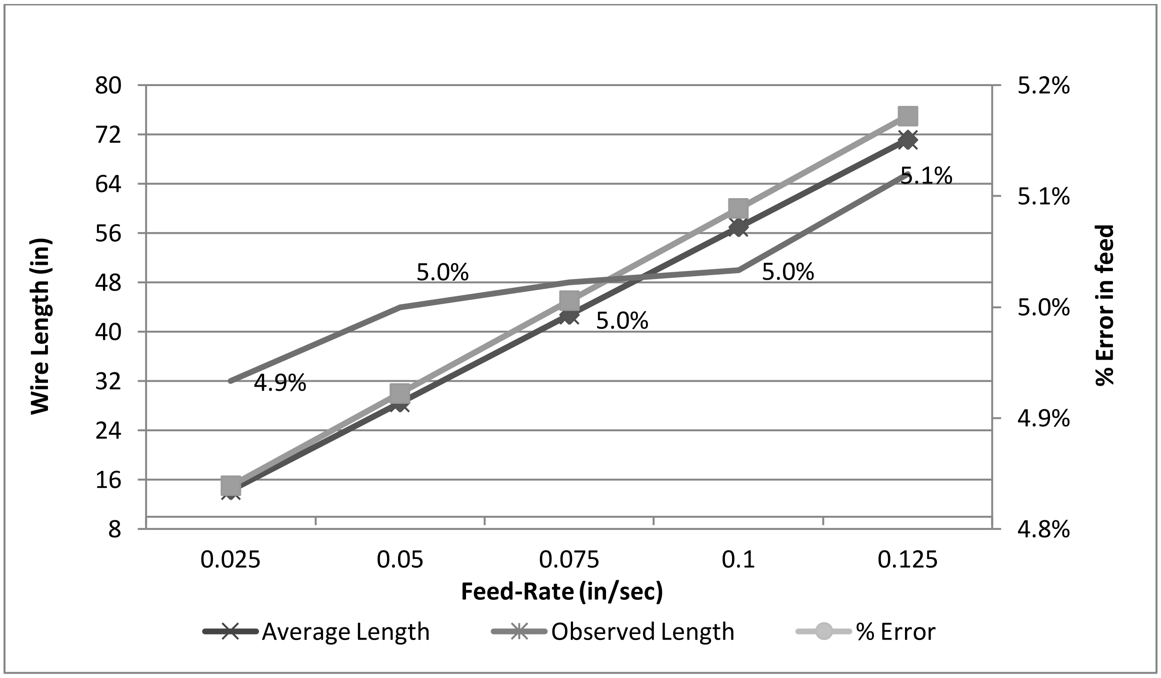


Figure 6. Microwire feeder testing at varying speeds showing high precision

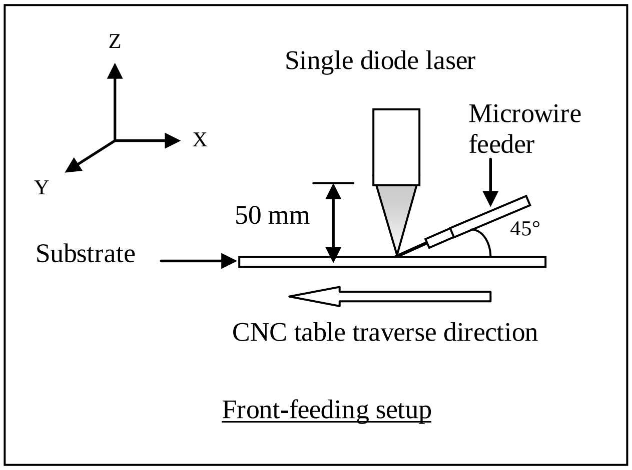
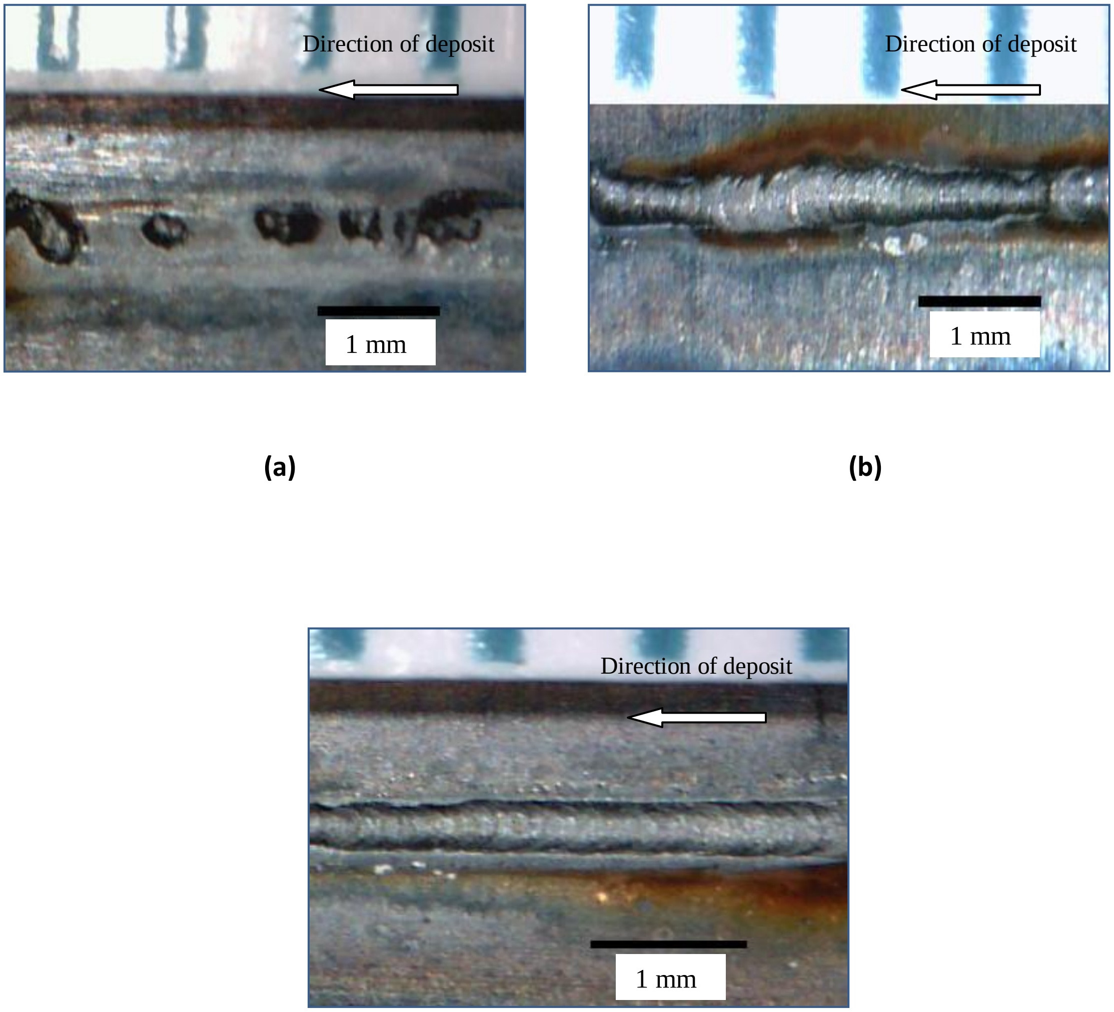


Figure 7. Mini-laser deposition experimental arrangement



(a) **(b)**

(c)

Figure 8. Deposition of 0.125 mm 316 stainless steel wire on 0.2 mm mild steel substrate (a) Discontinuous track (b) Continuous non-uniform track (c) Continuous uniform track

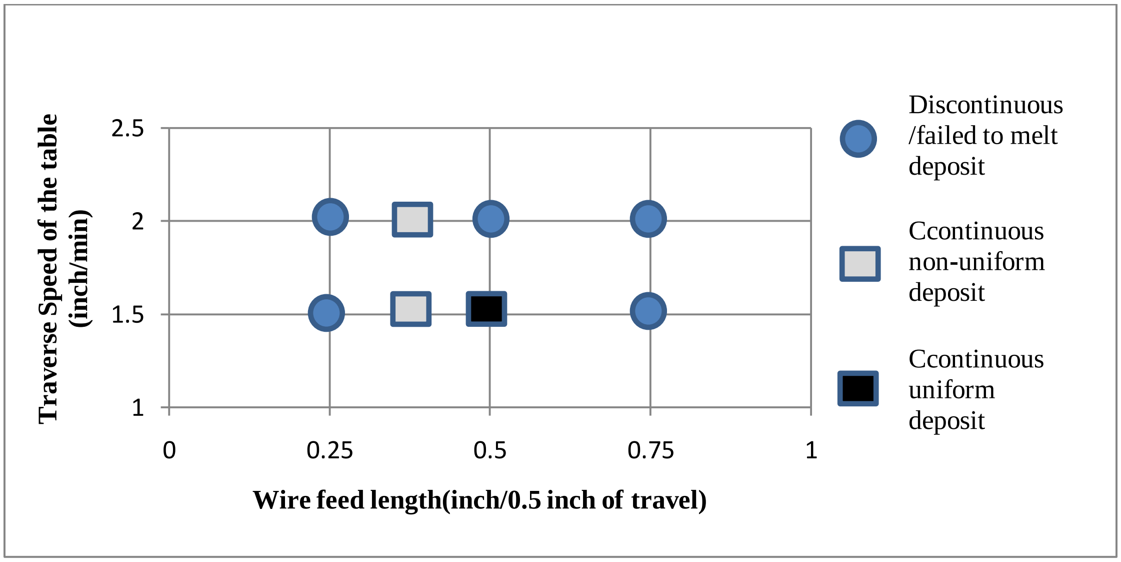


Figure 9. Boundaries defined for deposition of 0.125 mm 316 stainless steel wire on 0.2 mm mild steel substrate

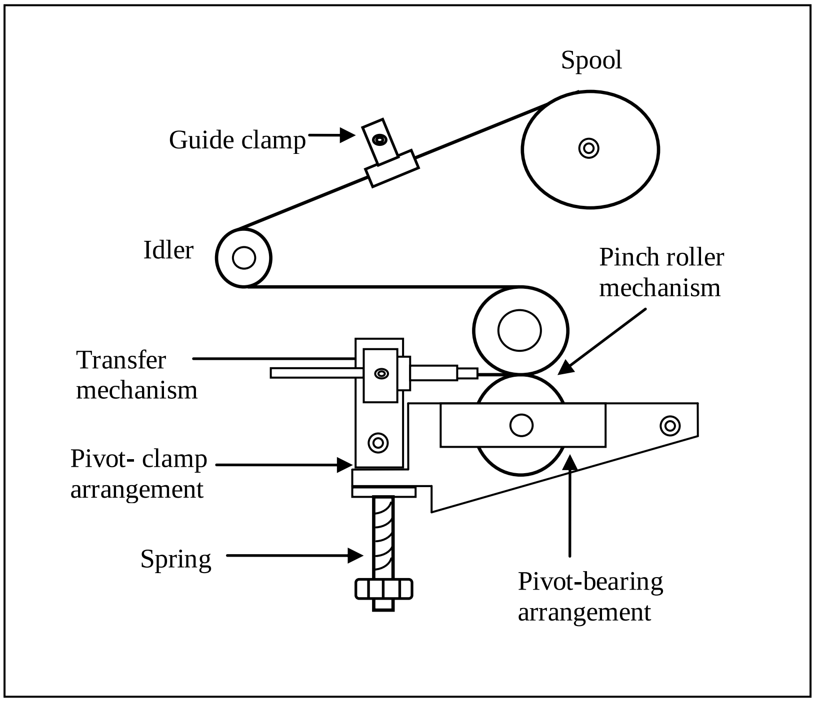


Figure 10. Second generation microwire feeder for ease of setup

SECTION

2. CONCLUSION

The design and development of microwire feeders, capable of handling microdiameter wires is often considered to be difficult due to its low buckling strength and high precision required for laser application usage. There are wire feeders which can feed wires as low as 0.25 mm diameter. Thus the need for systematically developing a wire feeder capable of handling wires as low as 0.05 mm was initiated. This work developed a microwire handling device capable of accommodating wires as low as 0.05 mm in diameter. This was done by integrating four different sub-mechanisms: feeding mechanism, transfer mechanism, precision guidance mechanism and adjustment mechanism. These mechanisms facilitated the compactness, flexibility and high precision requirements for varying laser applications. The microwire handling device was tested for precision and was found to be 95% precise. The reliability of the system was verified by normal distribution and the system was found to be 97% reliable. A case study on mini-laser deposition was presented to verify the effectiveness of the microwire feeder, where a 0.125 mm wire was fed into a melt pool of 0.2 mm. The effect on deposition quality with varying wire feed rate and table traverse speed were studied to obtain a continuous uniform deposit. The results show standard deviation of deposition width between a uniform and non-uniform continuous deposit. Thus the validity and effectiveness of the microwire feeder in terms of its accuracy and precision of delivering micro-diameter wires to very small melt pool sizes in laser applications is experimentally verified.

VITA

Amogh Shenoy, son of Jeevan Shenoy and Gayatri Shenoy, was born on June 27, 1986, in Mumbai, India. He received his Bachelor of Engineering in Mechanical Engineering in 2007, from University of Mumbai, India. He worked as a Lecturer in University of Mumbai until December 2007; where he was assigned to teach Engineering Mechanics. In January, 2008, he joined Missouri University of Science and Technology to pursue his Master's in Manufacturing Engineering. Amogh worked as a Graduate Research Assistant in Laser Aided Manufactuing Process Laboratory at Missouri S & T. His research was focussed on developing a microwire feeder for effective deposition for the mini-laser system. Amogh got his Master's in Manufacturing Engineering in July, 2010.

During his masters; he interned with Cohen Architechtural Woodworking, a customized furniture company located in St. James, and worked as a Lean Project Engineer in Fall 2008. He was employed with Harley-Davidson Motor Company, Kansas City, as a Manufacturing Engineer – Co-op during the spring and summer of 2009.