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(54) **SHEAR-ASSISTED EXTRUSION WITH VARIABLE EXTRUDATE PROPERTIES**

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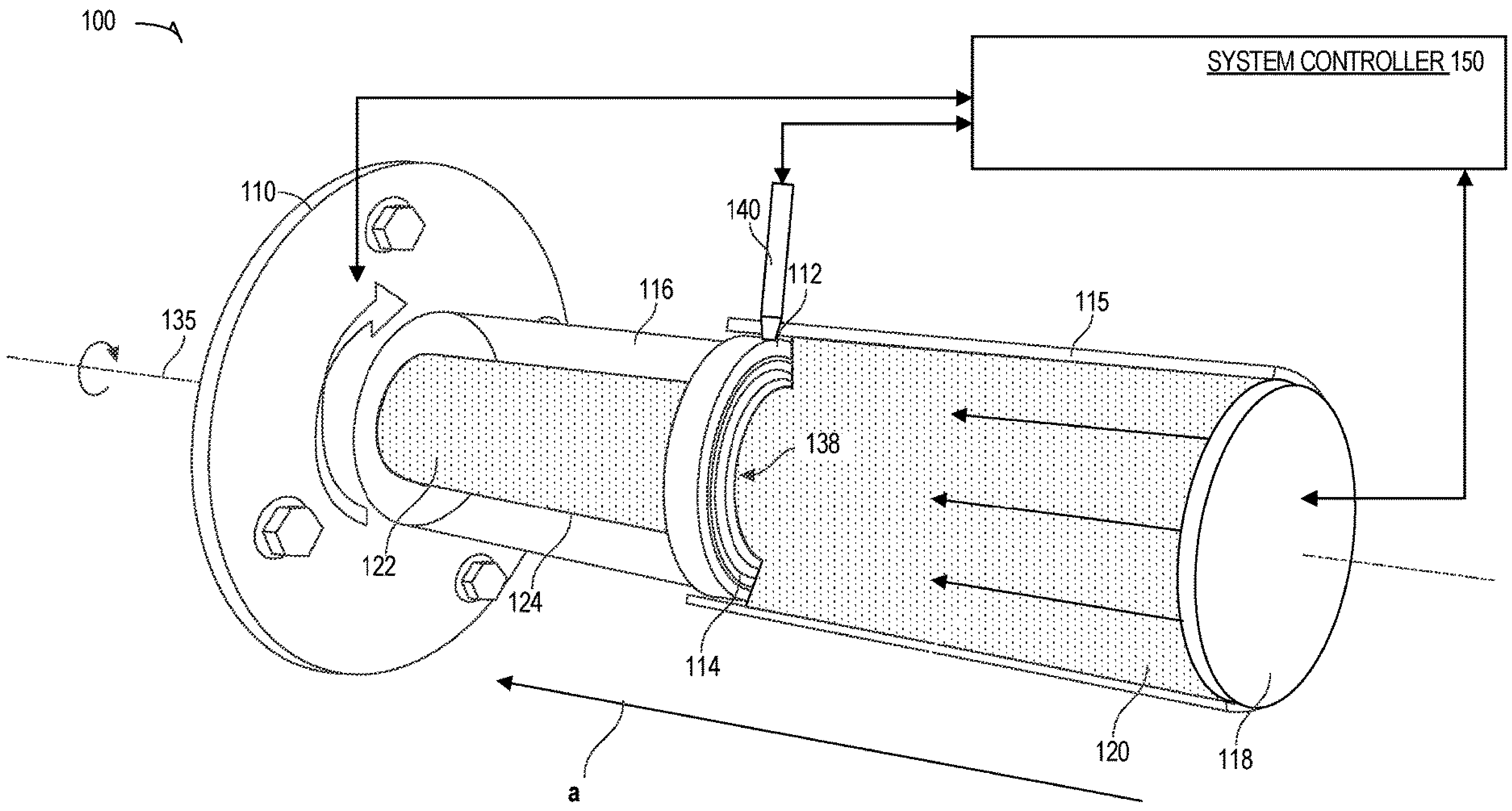
(57) **ABSTRACT**

A method for shear-assisted extrusion of a billet or feedstock can involve extruding a first portion of the feedstock through a die opening while rotating the die face relative to the feedstock at a first rotational rate and applying a first axial extrusion force. A second portion of the feedstock can be extruded through the opening while rotating the die face at a second rotational rate and applying a second axial extrusion force. This can establish different temperature ranges at the interface for each portion, resulting in a first extruded portion with different physical properties than the second extruded portion.



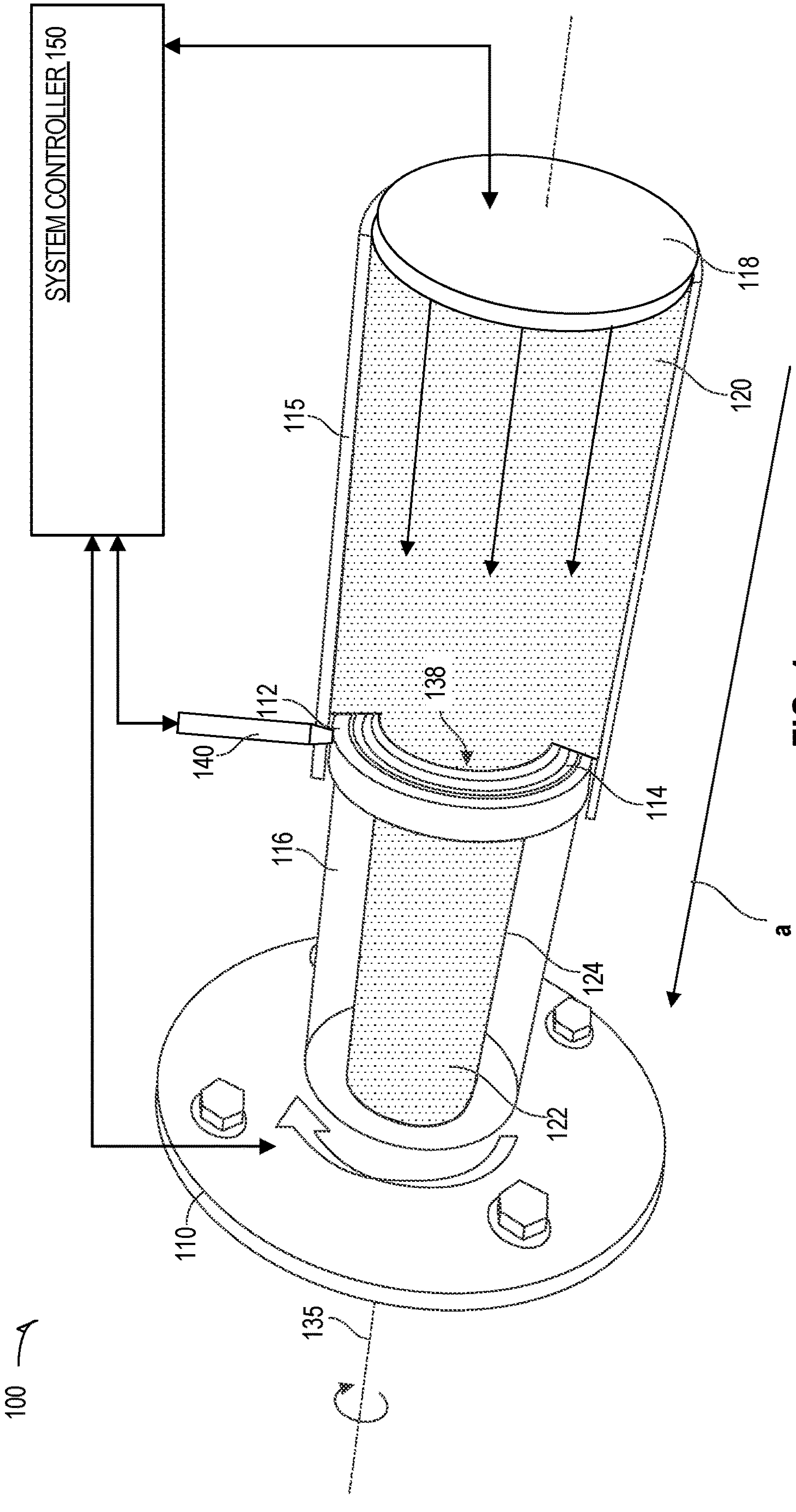

SYSTEM CONTROLLER 150
118
120
115
112
138
140
114
116
a
124
122
110
135
100

FIG. 1

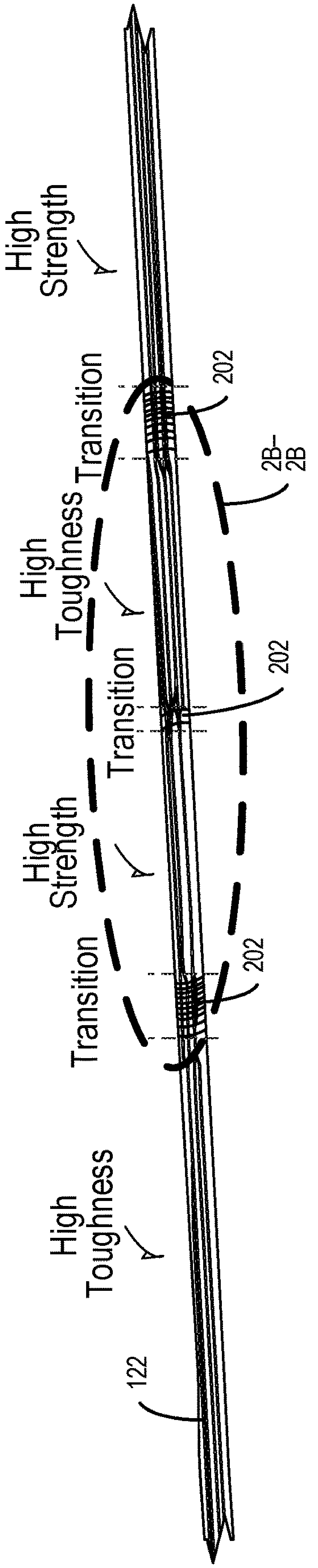

122
High Toughness
Transition
202
High Strength
Transition
202
High Toughness
2B–2B
Transition
202
High Strength

FIG. 2A

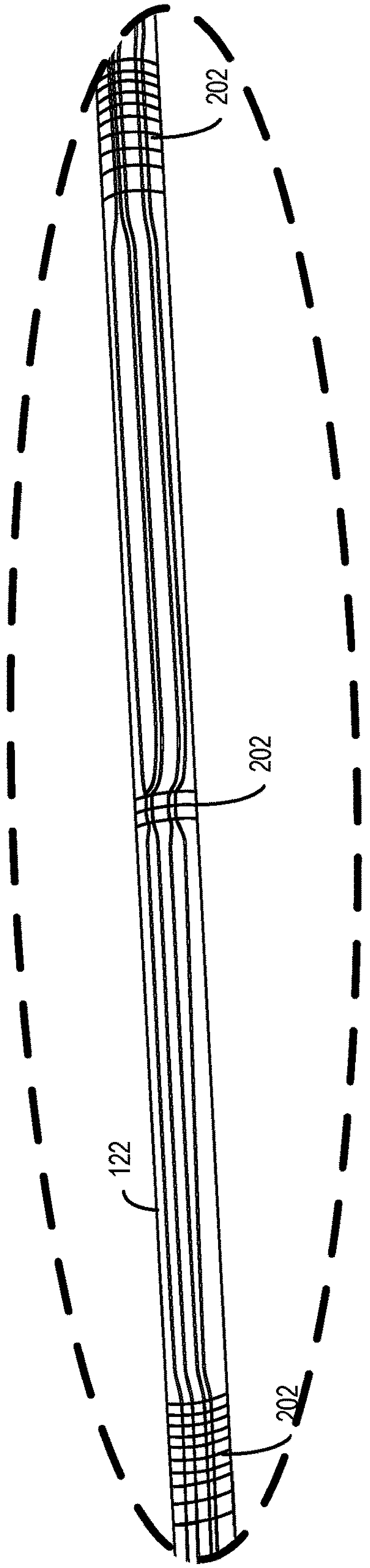

202
122
202
202

FIG. 2B

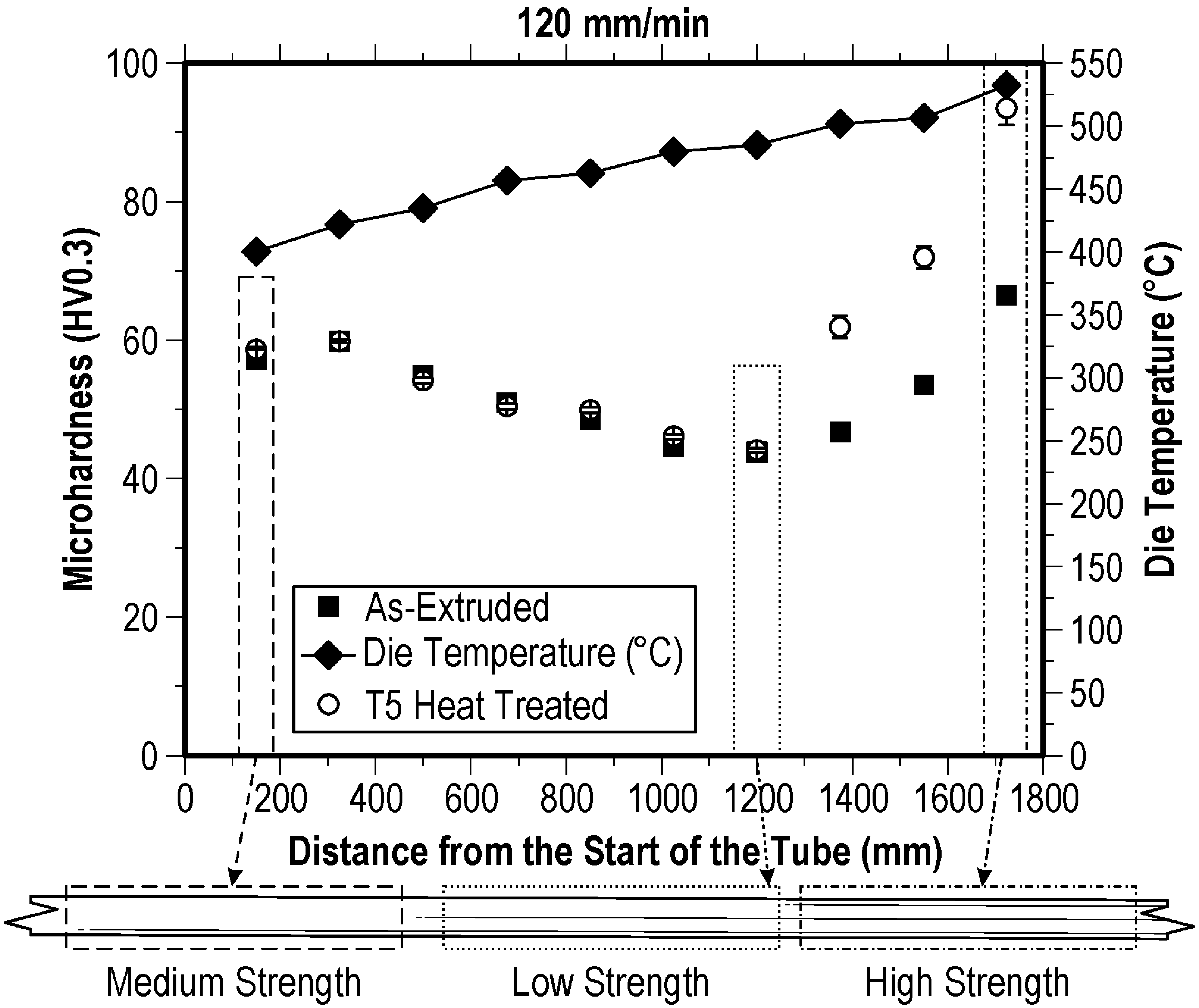

120 mm/min
Microhardness (HV0.3)
100
80
60
40
20
0
Die Temperature (°C)
550
500
450
400
350
300
250
200
150
100
50
0
0
200
400
600
800
1000
1200
1400
1600
1800
Distance from the Start of the Tube (mm)
■ As-Extruded
◆ Die Temperature (°C)
○ T5 Heat Treated
Medium Strength
Low Strength
High Strength

FIG. 2C

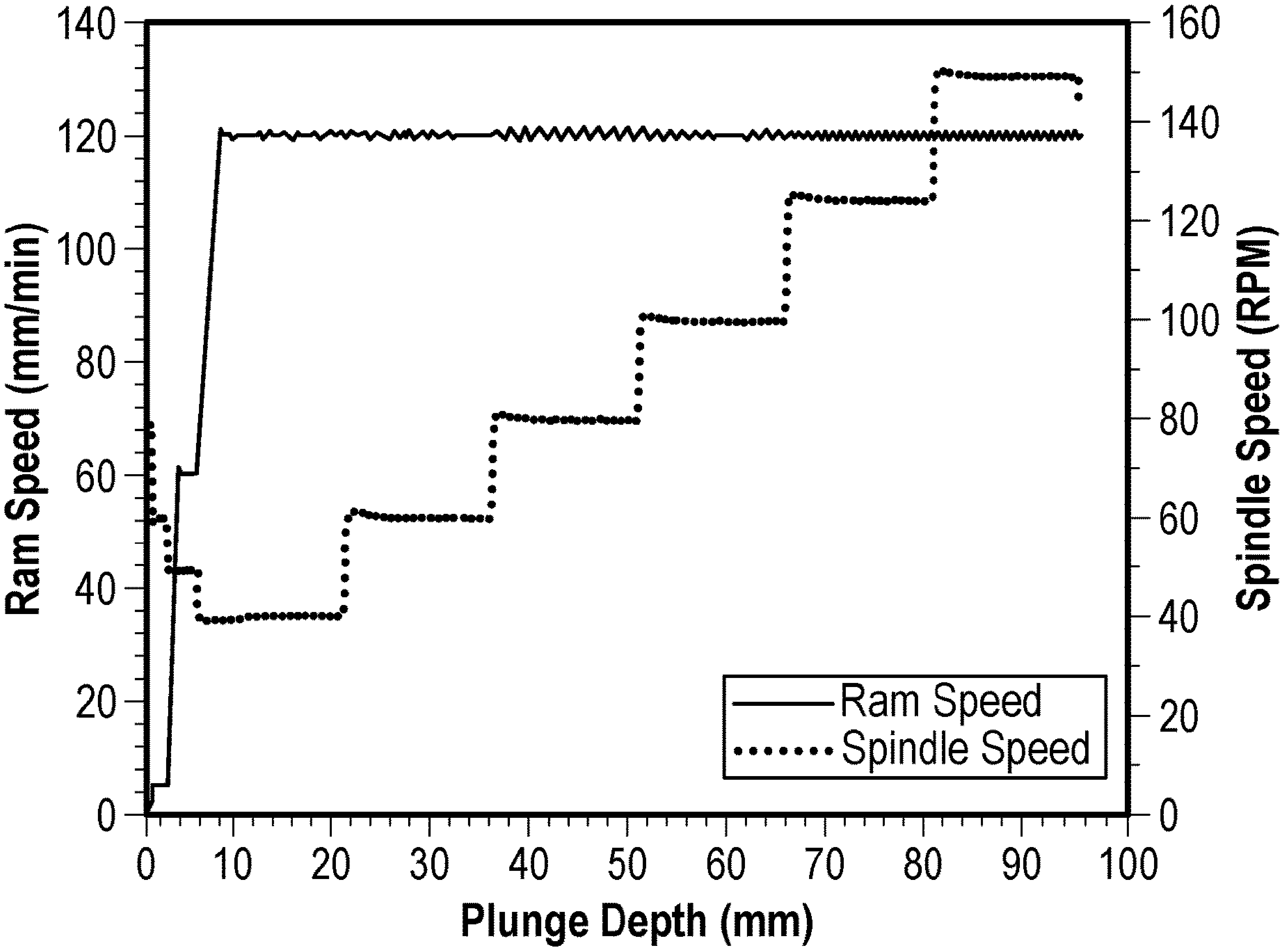

140
120
100
80
60
40
20
0
Ram Speed (mm/min)
160
140
120
100
80
60
40
20
0
Spindle Speed (RPM)
0
10
20
30
40
50
60
70
80
90
100
Plunge Depth (mm)
Ram Speed
Spindle Speed

FIG. 3

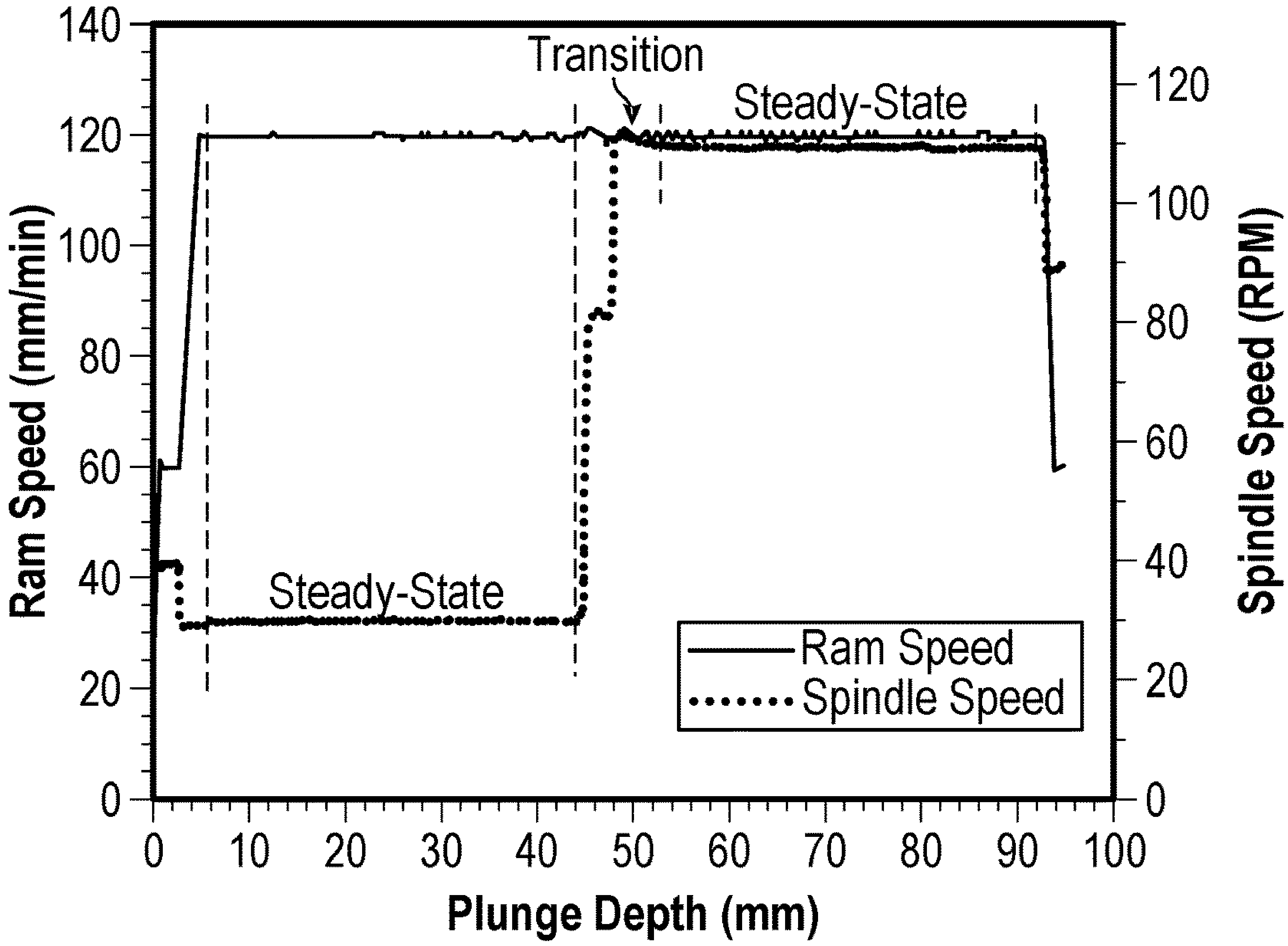

140
120
100
80
60
40
20
0
Ram Speed (mm/min)
120
100
80
60
40
20
0
Spindle Speed (RPM)
Transition
Steady-State
Steady-State
Ram Speed
Spindle Speed
0 10 20 30 40 50 60 70 80 90 100
Plunge Depth (mm)

FIG. 4A

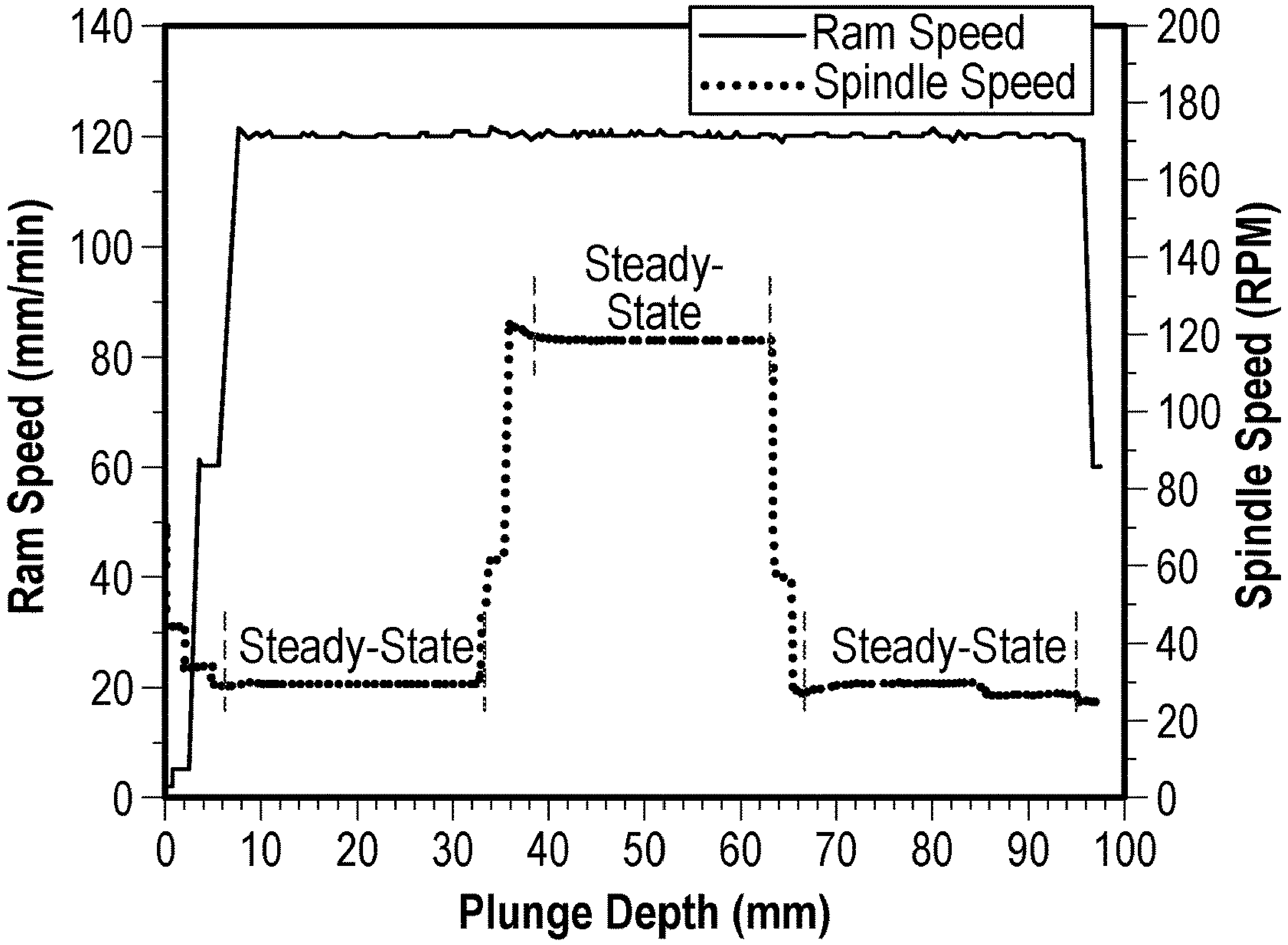

140
120
100
80
60
40
20
0
Ram Speed (mm/min)
200
180
160
140
120
100
80
60
40
20
0
Spindle Speed (RPM)
Ram Speed
Spindle Speed
Steady-
State
Steady-State
Steady-State
0 10 20 30 40 50 60 70 80 90 100
Plunge Depth (mm)

FIG. 4D

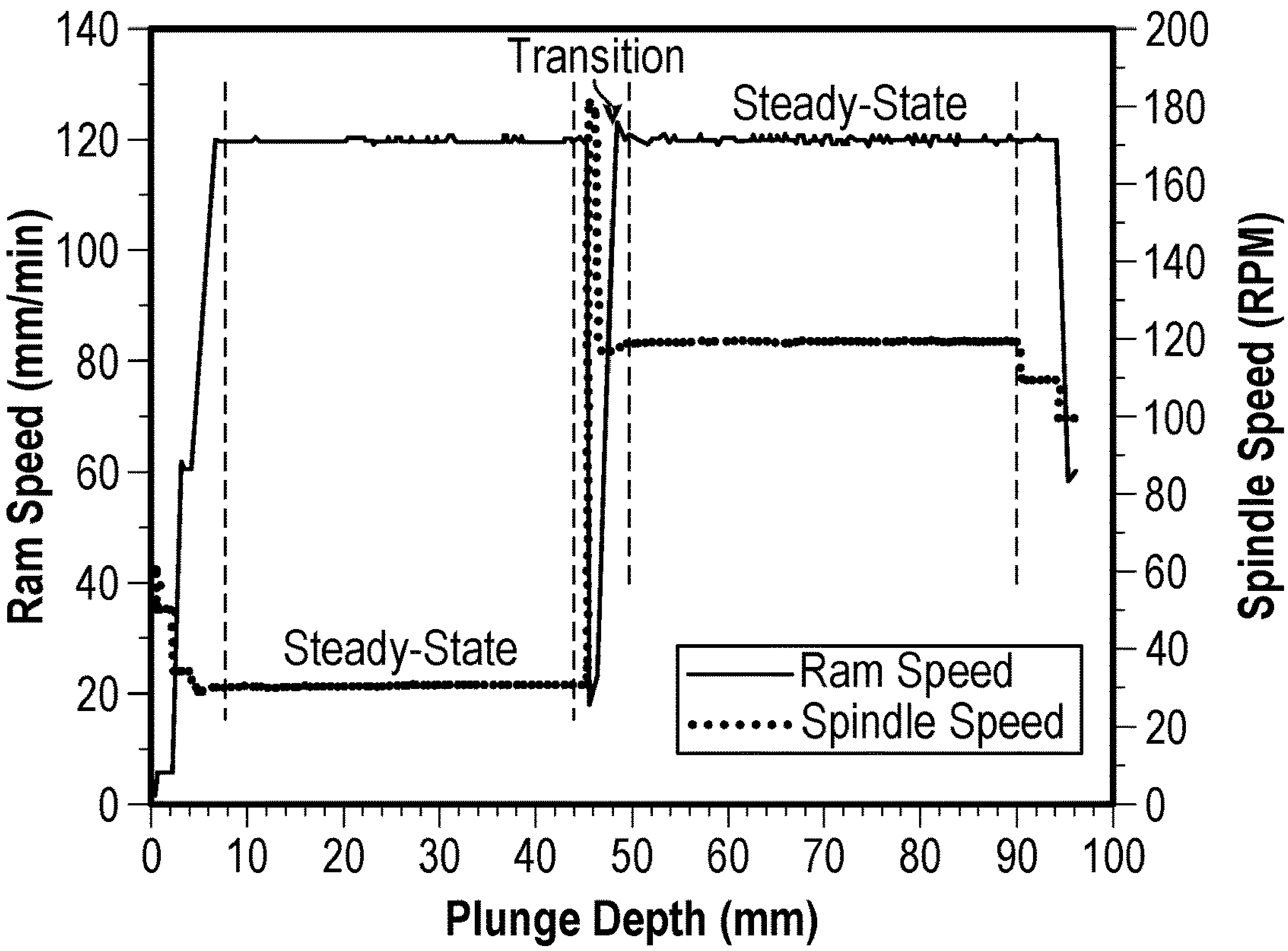

Transition
Steady-State
Steady-State
Ram Speed
Spindle Speed
Ram Speed (mm/min)
Spindle Speed (RPM)
Plunge Depth (mm)
0
20
40
60
80
100
120
140
0
20
40
60
80
100
120
140
160
180
200
0
10
20
30
40
50
60
70
80
90
100

FIG. 4B

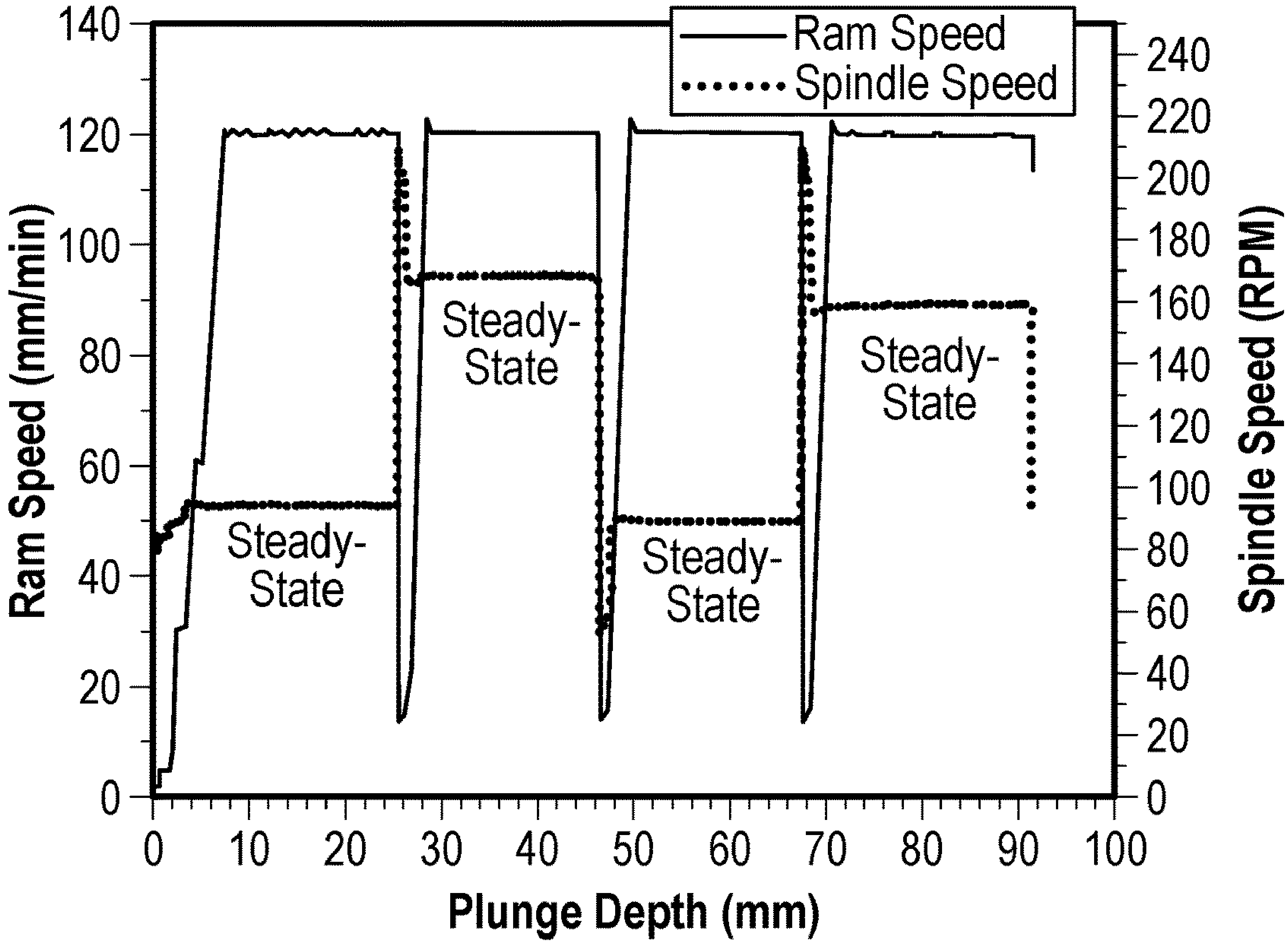

Ram Speed
Spindle Speed
Steady-State
Steady-State
Steady-State
Steady-State
Ram Speed (mm/min)
Spindle Speed (RPM)
Plunge Depth (mm)
0
20
40
60
80
100
120
140
0
20
40
60
80
100
120
140
160
180
200
220
240
0
10
20
30
40
50
60
70
80
90
100

FIG. 4E

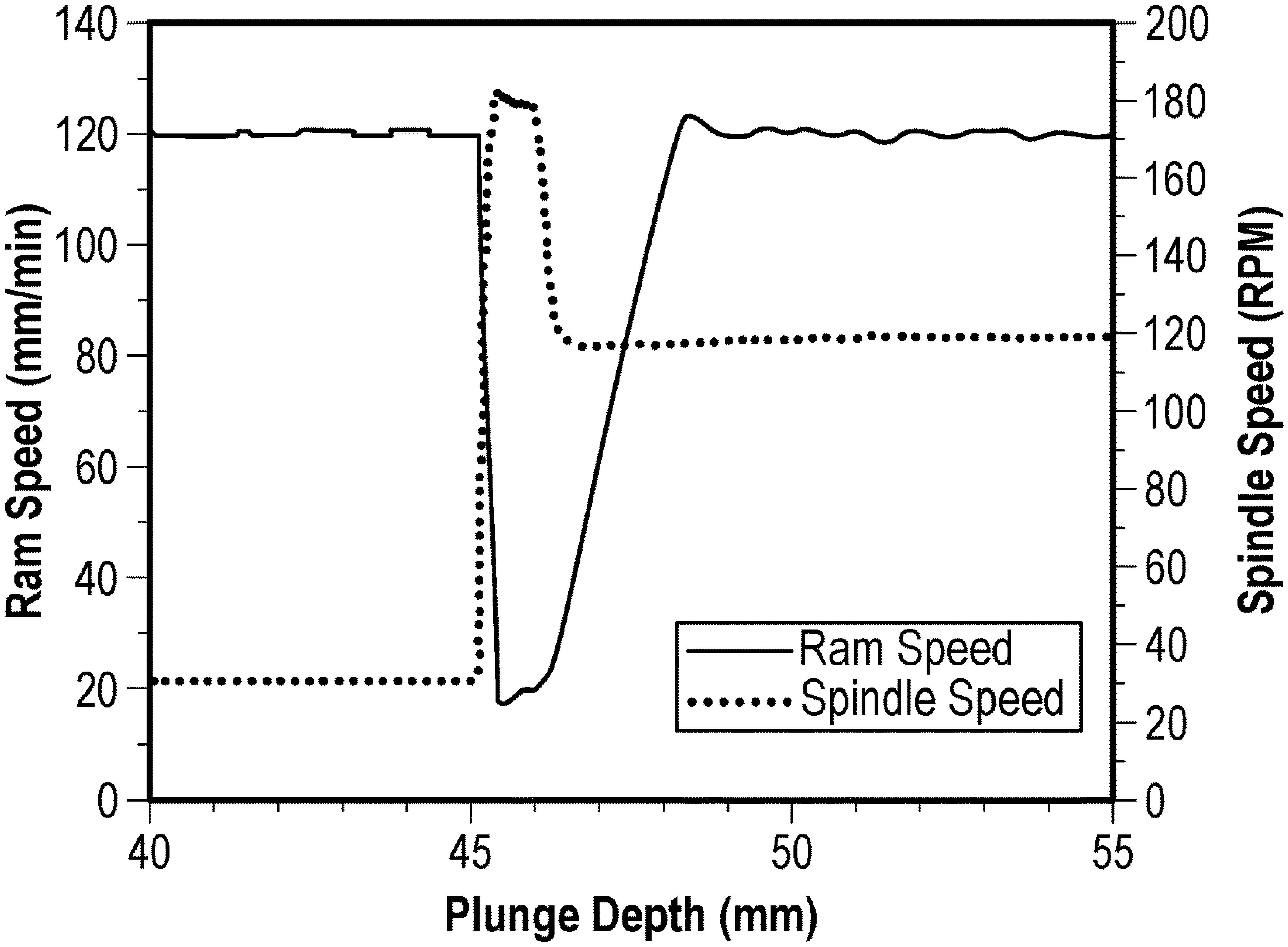

Ram Speed (mm/min)
140
120
100
80
60
40
20
0
Spindle Speed (RPM)
200
180
160
140
120
100
80
60
40
20
0
Plunge Depth (mm)
40
45
50
55
Ram Speed
Spindle Speed

FIG. 4C

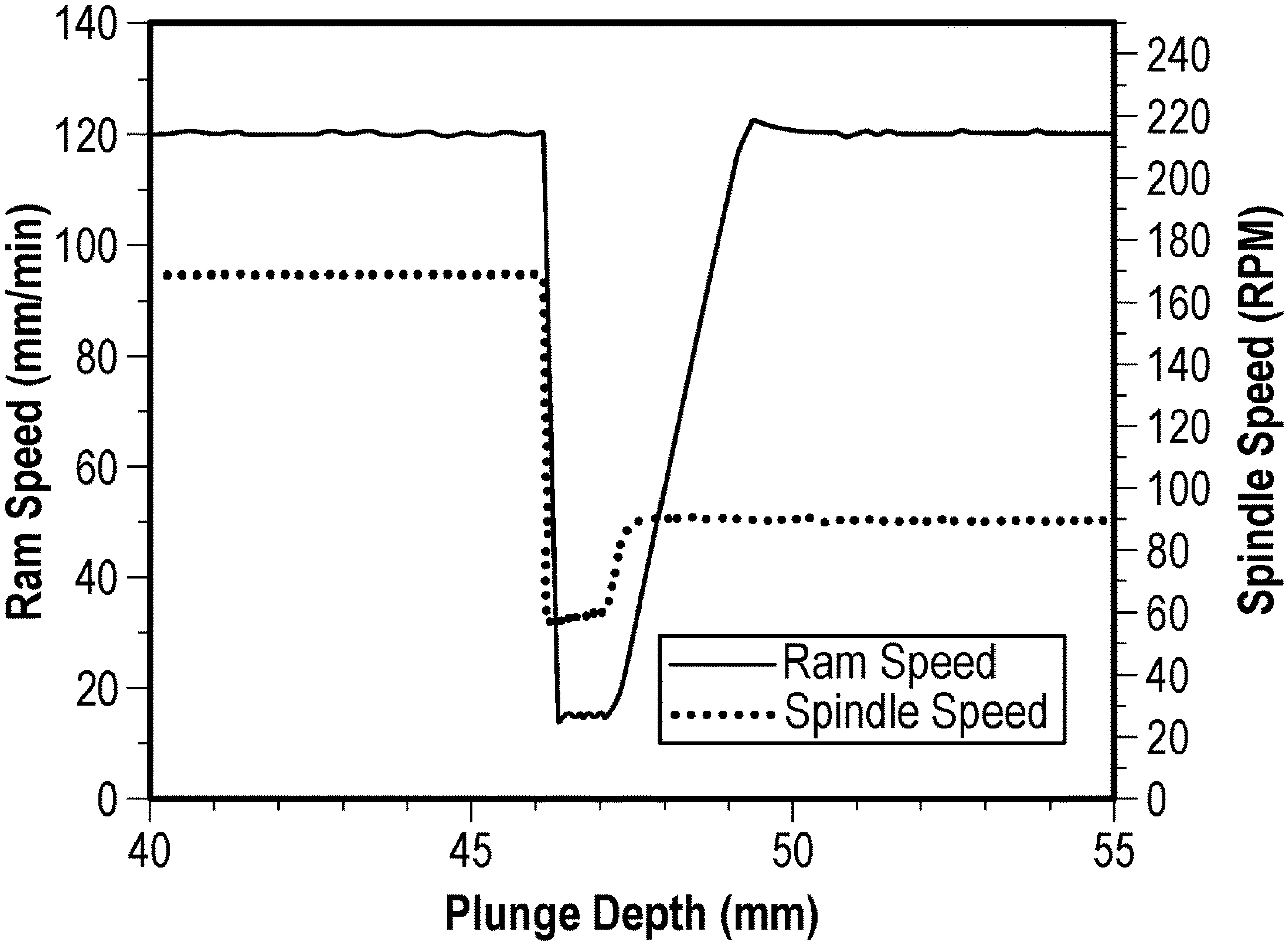

Ram Speed (mm/min)
140
120
100
80
60
40
20
0
Spindle Speed (RPM)
240
220
200
180
160
140
120
100
80
60
40
20
0
Plunge Depth (mm)
40
45
50
55
Ram Speed
Spindle Speed

FIG. 4F

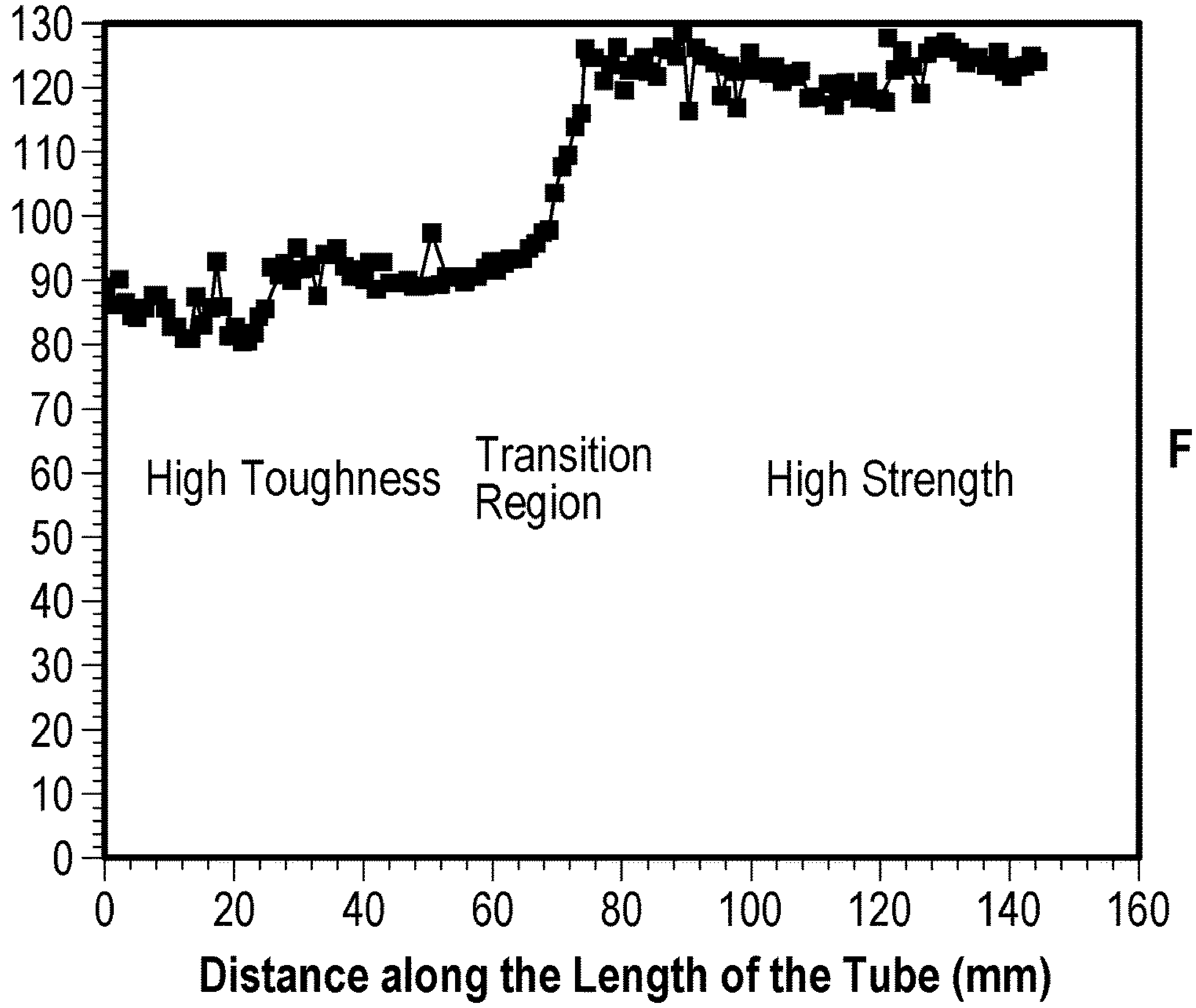

130
120
110
100
90
80
70
60
50
40
30
20
10
0
High Toughness
Transition Region
High Strength
0
20
40
60
80
100
120
140
160
Distance along the Length of the Tube (mm)

FIG. 5A

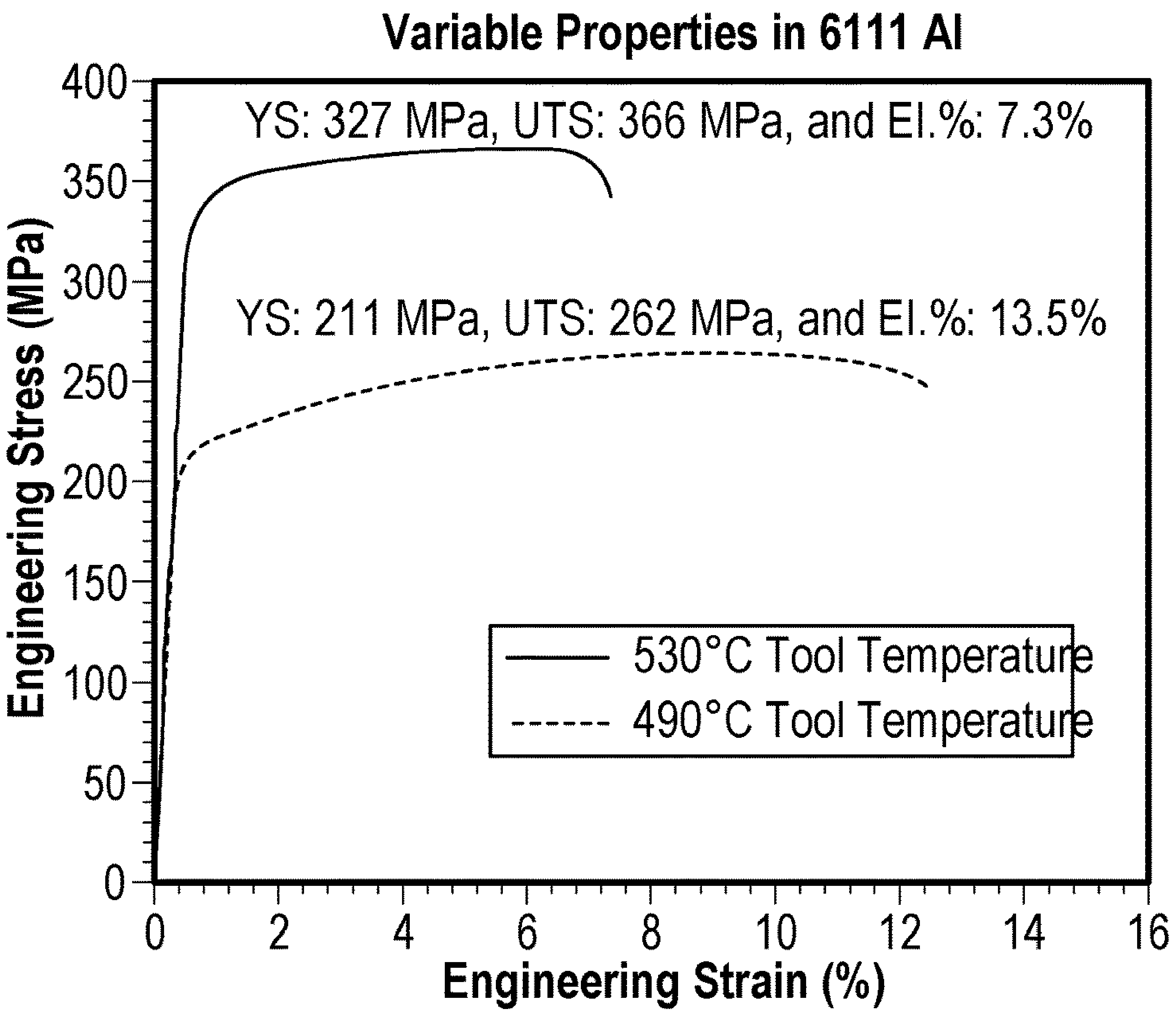

Variable Properties in 6111 Al
Engineering Stress (MPa)
400
350
300
250
200
150
100
50
0
YS: 327 MPa, UTS: 366 MPa, and El.%: 7.3%
YS: 211 MPa, UTS: 262 MPa, and El.%: 13.5%
530°C Tool Temperature
490°C Tool Temperature
0
2
4
6
8
10
12
14
16
Engineering Strain (%)

FIG. 5B

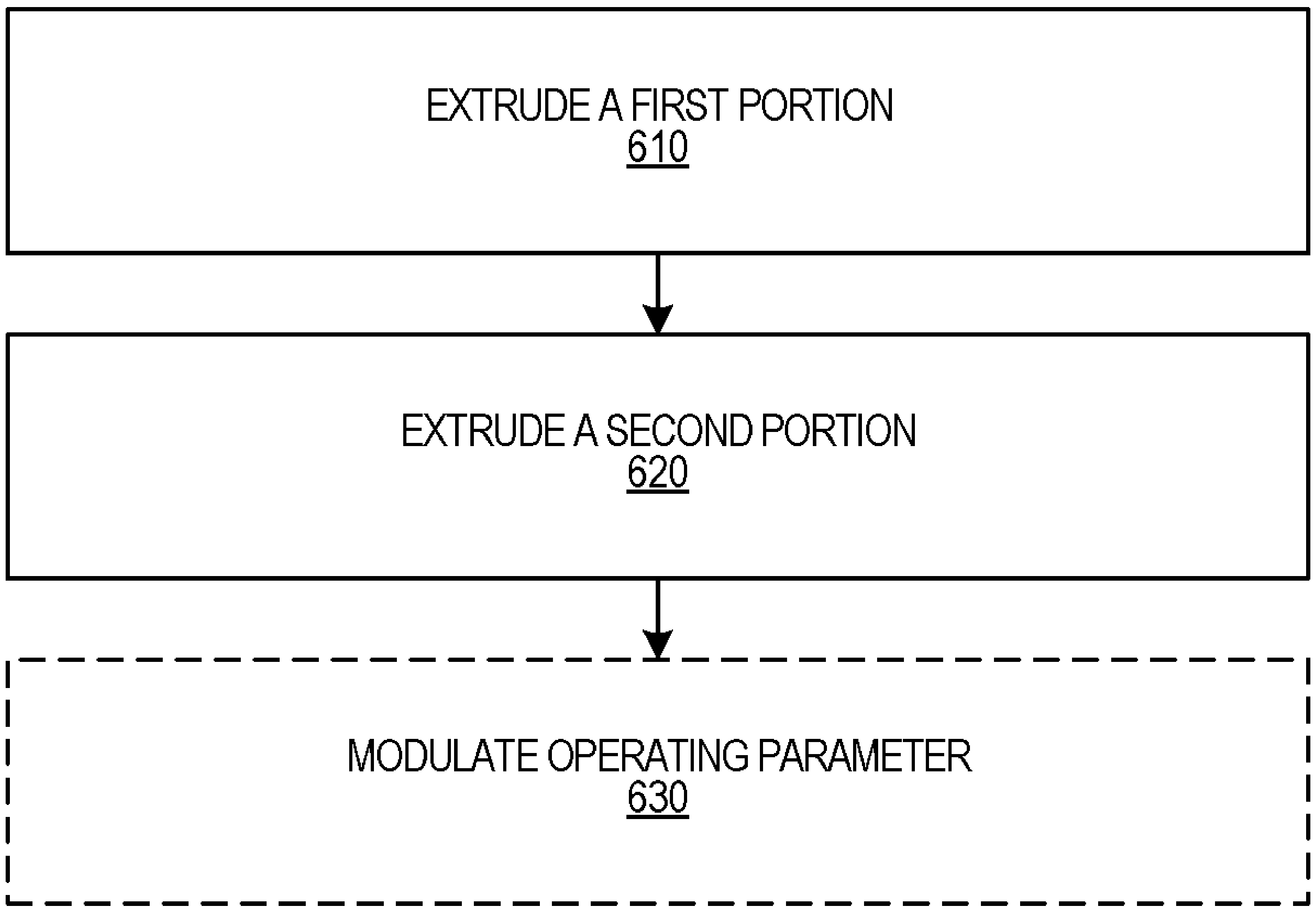

EXTRUDE A FIRST PORTION
610
EXTRUDE A SECOND PORTION
620
MODULATE OPERATING PARAMETER
630

FIG. 6

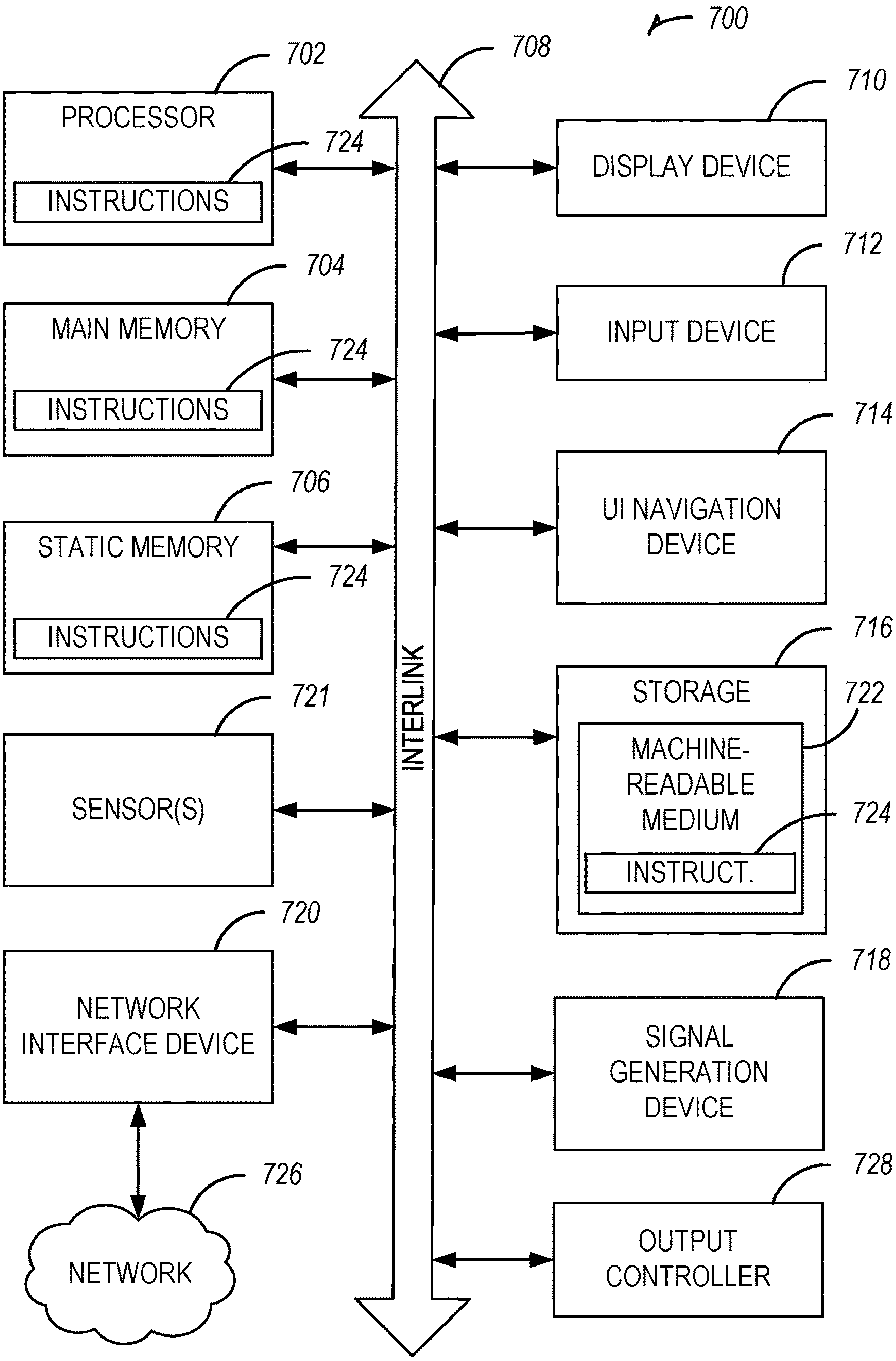

700
702
PROCESSOR
724
INSTRUCTIONS
708
710
DISPLAY DEVICE
704
MAIN MEMORY
724
INSTRUCTIONS
712
INPUT DEVICE
706
STATIC MEMORY
724
INSTRUCTIONS
714
UI NAVIGATION DEVICE
INTERLINK
721
SENSOR(S)
716
STORAGE
722
MACHINE-READABLE MEDIUM
724
INSTRUCT.
720
NETWORK INTERFACE DEVICE
718
SIGNAL GENERATION DEVICE
726
NETWORK
728
OUTPUT CONTROLLER

FIG. 7

SHEAR-ASSISTED EXTRUSION WITH VARIABLE EXTRUDATE PROPERTIES

CLAIM OF PRIORITY

[0001] This application claims priority to and the benefit of U.S. Provisional Application Ser. No. 63/426,498 filed on Nov. 18, 2022, which is incorporated by reference herein in its entirety, and the benefit of priority of which is claimed herein.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

[0002] This invention was made with Government support under Contract DE-AC0576RL01830 awarded by the U.S. Department of Energy. The Government has certain rights in the invention.

BACKGROUND

[0003] Metal extrusion is a manufacturing process involving pressing a feedstock against an extrusion die opening, e.g., using a hydraulic ram. The feedstock can deform plastically as it flows through the die opening, resulting in an extruded product with refined microstructure. Aluminum can be used as a feedstock in extrusion due to its light weight, high strength-to-weight ratio, and corrosion resistance. Aluminum extrusion can be used, for example, in manufacturing parts for aircraft and automobiles.

BRIEF DESCRIPTION OF THE DRAWINGS

[0004] In the drawings, which are not necessarily drawn to scale, like numerals may describe similar components in different views. Like numerals having different letter suffixes may represent different instances of similar components. Various embodiments are illustrated by way of example in the figures of the accompanying drawings. Such embodiments are demonstrative and not intended to be exhaustive or exclusive embodiments of the present subject matter.

[0005] FIG. **1** depicts an example of portions of a system for performing Shear Assisted Processing and Extrusion (ShAPE).

[0006] FIG. **2**A depicts an example of a ShAPE-processed extrudate including varying physical properties along a length of the extrudate.

[0007] FIG. **2**B is a detail view of the depiction in FIG. **2**A.

[0008] FIG. **2**C is a chart showing die temperature and hardness along the tube length along with a visual representation of an extrudate tube.

[0009] FIG. **3** is a chart showing extruding using a constant ram speed and progressively increasing rotation of a die face relative to a billet.

[0010] FIG. **4**A is a chart showing a transition in material properties of an extrudate based on various operating parameters during extrusion.

[0011] FIG. **4**B is a chart showing a transition in material properties of an extrudate based on various operating parameters during extrusion.

[0012] FIG. **4**C is a chart showing a transition in material properties of an extrudate based on various operating parameters during extrusion.

[0013] FIG. **4**D is a chart showing a transition in material properties of an extrudate based on various operating parameters during extrusion.

[0014] FIG. **4**E is a chart showing a transition in material properties of an extrudate based on various operating parameters during extrusion.

[0015] FIG. **4**F is a chart showing a transition in material properties of an extrudate based on various operating parameters during extrusion.

[0016] FIG. **5**A is a chart showing a hardness along the tube length across a transition portion.

[0017] FIG. **5**B is a chart illustrating varying properties in 6111 Aluminum for two different extrusion die temperatures.

[0018] FIG. **6** is a flowchart outlining the steps of an exemplary technique for shear-assisted extrusion.

[0019] FIG. **7** illustrates generally an example of a block diagram of a machine.

DETAILED DESCRIPTION

[0020] A metal extrusion manufacturing process can be useful in fabricating metal components including a controlled microstructure and having one or more specified mechanical properties. For example, the mechanical properties of an extrudate can depend at least in part on extrusion temperature, ram speed, die geometry, and alloy composition. Generally, extrusion temperature, opening size in the extrusion die, and ram speed can each affect the resulting strength and ductility. Accordingly, one or more of the mechanical properties of the extrudate can be established by controlling these variables. Following extrusion, one or more of the physical properties of the extrudate can be further manipulated via downstream processing conditions, such as cooling sections, quenching, and tempering. In general, the physical properties of the extrudate can be tailored to meet specific design requirements of downstream applications in areas such as automotive, aerospace, and shipbuilding.

[0021] Certain approaches to extrusion involve preheating of the feedstock (e.g., a billet, powder, flake, or other similar material) or preheating of the extrusion die prior to commencing extrusion. For example, preheating the billet can help control temperature distribution of the billet, limiting extrusion defects due to thermal non-uniformity. In other approaches, rather than the billet or the die being preheated, the billet can be rapidly heated during the pressing and extrusion, with the heating uniformity and rate being important to the quality and properties of the extrudate. Whether preheating or rapidly heating the billet during extrusion, such approaches generally involve techniques in attempt to achieve a static, target set of operating parameters and to produce an extrudate having uniform properties.

[0022] It can be desirable to produce fabricated metal components having differing mechanical properties, such as varying along a length of an individual component. For instance, it can be desirable to fabricate automotive B-pillars such that a middle portion thereof has a relatively high strength to perform against impact while lateral portions each have a relatively high ductility (or “toughness”) at the ends to promote energy absorption. It can be challenging to fabricate such a component having differing mechanical properties using certain extrusion techniques in which establishing each individual target set of operating parameters involves stopping and starting the extrusion (e.g., to preheat the billet while extrusion is stopped or paused). One approach to fabricating a part having varied or differing mechanical properties using extruded materials involves tailored welded blanks. Here, a plurality of blanks can be extruded to each form respective portions of the part and can each exhibit different mechanical properties. The portions can be welded together and subjected to downstream processing conditions such as heat treating and quenching, thus forming the single fabricated component. Welding can involve expensive manufacturing steps and can complicate a geometry of the fabricated component. Another approach to fabricating a component having varied mechanical properties involves variable cooling of an extrudate, e.g., to induce martensite or bainite microstructures and thus localize one or both of strength and ductility along an extrudate. However, variable cooling temperature and cooling rate can make reproducibility difficult, thereby limiting application of such an approach. The present inventors have recognized a need for an improved manner of fabricating components having one or more differing mechanical properties along a length thereof using metal extrusion techniques.

[0023] This document describes systems and methods for fabricating a metal component via extrusion, including features for producing a component having one or more different mechanical properties along a length thereof. Such extrusion can include a Shear Assisted Processing and Extrusion (ShAPE) technique, which can involve rotation of at least one of the die extrusion or the billet relative to the other during pressing of the feedstock against the face of the extrusion die. Such rotating and pressing can facilitate highly controlled plastic deformation of the microstructure. An extrusion method can be performed for producing aluminum feedstock with controlled variations in one or more properties, geometry, or both, along the length of the extruded product. Such a method can involve rotating the die face relative to the feedstock while applying axial force to push the feedstock material through the die opening. By using different specified parameters for the rotation speed and axial force when extruding sequential portions of the feedstock, the resulting extruded portions can exhibit tailored differences in one or more properties, such as at least a 15% difference in tensile strength. The operating parameters can also be coordinated to control the transition length between portions. Overall, this shear-assisted extrusion technique can help enable fabrication of single aluminum profiles with graded properties and shapes and without requiring secondary processing steps.

[0024] FIG. **1** depicts an example of portions of a system for performing Shear Assisted Processing and Extrusion (ShAPE). The system **100** can include an extrusion die **110**, a container or other plasticization channel **115**, a driver **118**, at least one thermocouple **140** and a system controller **150**. As depicted in FIG. **1**, the die face **112** can define a die face orifice **138**, and a longitudinal axis (or "central longitudinal axis") **135** can be defined to extend through a center of the die face orifice **138**. The extrusion die **110** can include an outer diameter (OD), such as within a range of about 25 mm and about 35 mm, for example, an OD of about 31.7 mm. The extrusion die can include an inner diameter (ID) (e.g., defined by the die face orifice **138**) within a range of about 5 mm and about 28 mm, or an ID of about 12 mm. The extrusion die **110** can include a die face **112** that can be thrust against and into a billet material **120** (or other feedstock, e.g., powder or flake). For example, the billet material **120** can be fed into the plasticization channel **115** and pressed against the die face **112**, such as by being compressed or moved via a driver **118**. In an example, the driver **118** can include a piston, a hydraulic ram, a screw mechanism, or another mechanism for applying compressive or extrusion forces to the billet or feedstock. The driver **118** can provide a specified amount of force at a target speed, to push or thrust the billet material **120** in an axial extrusion direction a and through an die orifice **138** or a porthole or other opening of the die face **112**. Alternatively or additionally, driver **118** can move or press the extrusion die **110** toward the billet material **120** to supply thrust of the die face **112** against the billet material **120**, and to push the billet material **120** in the axial extrusion direction a and through the die orifice **138**. The driver **118** can be arranged to regulate a rate at which the billet material **120** and the die face are pressed against each other.

[0025] Concurrent with the thrust of the billet material **120** in the extrusion direction a and through the die orifice **138**, the system **100** can include a motor that can be arranged to rotate at least one of the die face **112** or the billet material **120** relative to the other. The motor can be disposed as or within a rotating unit, e.g., a rotating collet, a rotating material handling device, a rotating arm, a spindle, a rotating platform, a chuck or other gripping component, a bearing, another suitable rotating device, or one or more combinations thereof. A thermocouple **140** can be embedded or otherwise positioned proximal to a contact region between the die face **112** and the billet material **120** such as to measure an indication a temperature at an extrusion die-billet interface (e.g., at the die face **112**) during extrusion. A thermocouple **140** can be embedded at or near one or more of the channel **115**, the die **110**, the driver **118**, etc., to measure an indication of a temperature or a temperature gradient during extrusion. For example, the thermocouple **140** can include a k-type thermocouple that can be spot-welded onto the die face **112** at a location that is <20 mm radially from the center of the die face **112**, such as at a location that is about 10 mm radially from the center.

[0026] The system controller **150** can receive information provided by the driver **118**, the motor, the thermocouple **140**, or other control or sensing systems or devices. The controller **150** can receive temperature information from the thermocouple **140** and accordingly issue control instructions (e.g., "commands") to regulate an output of the driver **118** (e.g., to establish a thrust rate relative to the billet material **120**) and/or to regulate an output of the motor (e.g., to adjust a rotation speed of the extrusion die **110** or the billet material **120**). This control can be coordinated in accordance with specified shear assisted extrusion parameters. For example, a system controller **150** can establish or adjust rotation (e.g., via the motor) of the die face **112** relative to the billet material **120** according to first and second specified operating parameters. Also the system controller **150** can, contemporaneously with the establishing or adjusting the rotation, establish or adjust an axial extrusion force (e.g., via the driver **118**) to drive the billet material **120** and the die face **112** together according to first and second specified operating parameters. Here, at least one of the second specified operating parameters can be different than at least one of the first specified operating parameters, such as to establish different specified temperature ranges at an interface between the die face **112** the billet material **120**. Alternatively or additionally, the first and second operating parameters can include, e.g., spindle speed, spindle power, temperature, ram speed, ram force, extrudate speed, or a cooling/quench rate applied to the extrudate.

[0027] A first portion of a resulting extruded product **122** (also referred to as an "extrusion product" or an "extrudate"), along a first axial region extruded from the first portion of the billet material **120** can include one or more different physical properties than a second portion of the resulting extrudate **122** along a second axial region extruded from the second portion of the billet material **120**. Herein, "physical properties" can otherwise refer to one or more mechanical properties including, e.g., tensile strength, ductility, toughness, formability, yield strength, tensile elongation, fracture toughness, hardness, and fatigue resistance. In an example, the first portion of the resulting extrudate **122** can differ in one or more physical properties from the second portion of the resulting extrudate **122**. For example, respective values of ductility can differ by a percentage within a range of about 5% to about 25%, within a range of about 10% to about 20% or differ by about 15%. Similarly, the first portion of the resulting extrudate **122** can differ in one or more physical properties from the second portion of the resulting extrudate **122**. For example, respective values of tensile strength can differ by a percentage within a range of about 5% to about 50%, within a range of about 15% to about 35%, or can differ by about 25%.

[0028] The system controller **150** can facilitate, via establishing and/or adjusting relative i) an amount of axial force of the billet material **120** toward the die face **112** and ii) a rate of rotation of the die face **112** to apply shear force between the die face **112** and the billet material **120**, such as to provide extrusion of varying material properties along the extrusion length. Here, contact between the rotating die face **112** and the billet material **120** can generate heat at the die-billet interface, e.g., caused by friction and heat from within the billet material **120** caused by plastic deformation of the billet material **120**. The extent of heat generation can be controlled by regulating rotational speed, ram speed, or both. Such a configuration for heating the billet material **120** can be facilitated without requiring that the billet material is pre-heated. Effectively, the system controller **150** can facilitate real-time control and manipulation of the temperature during (e.g., without requiring stopping) mid-extrusion that is not possible using certain other extrusion methods.

[0029] The die face **112** can include one or more scrolls **114** (e.g., spiral structures protruding outward that direct plasticized material inward as the die face **112** rotates relative to the billet material **120**). The die face **112** can include other surface morphology features, or alternatively can be planar. Rotational shear force (via the die face **112**) and the longitudinal axial compressive force of the die face **112** and the die shank **116** can each contribute toward plasticizing the billet material **120** at the interface between the die face **112** and the billet material **120**.

[0030] Following plastic deformation of the billet material **120** through the orifice **138** of the die face **112**, a die bearing surface **124** can facilitate reconstitution of the plasticized material into an arrangement that exhibits a more refined grain size and texture control at the microscopic level as compared with the raw billet material **120** before extrusion. As such, the extrusion die **110** can facilitate forming the extrudate **122**, such as can include one or more desired characteristics.

[0031] In an example, the system **100** can include or use a mandrel located proximate to the die face **112**. The mandrel can extend through the orifice **138** and can define an inner dimension, around which the extrudate **122** is formed, such as for forming a hollow or tubular extrudate **122**. A similar system is described in U.S. patent application Ser. No. 18/244,614, which is incorporated by reference herein in its entirety, including for its teaching of a moveable mandrel for forming an annular extrusion aperture.

[0032] In an example, the billet material **120** can be aluminum. Alternatively or additionally, the billet material **120** can include one or more other metals such as copper, steel, or titanium. In an example, the billet material **120** can be selected such that it includes a precipitate-strengthened aluminum alloy, e.g., as 2-series (2xxx), 6-series (6xxx), or 7-series (7xxx) aluminum alloy, before commencing extrusion via system **100**. Examples of such suitable alloys include Al 6061, Al 6111, or Al 6082 aluminum alloys, represented below in table 1 by weight percentage (wt. %).

TABLE 1

Nominal composition of 6061, 6082, and 6111 Al are presented (in wt. %)

	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Others Total	Al
6061	0.40-0.8	0.7	0.15-0.40	0.15	0.8-1.2	0.04-0.35	0.25	0.15	0.15	Bal.
6082	0.70-1.30	0.50	0.10	0.40-1.00	0.60-1.20	0.25	0.20	0.10	0.15	Bal.
6111	0.6-1.1	0.40	0.5-0.9	0.10-0.45	0.50-1.0	0.10	0.15	0.10	0.15	Bal.

[0033] Alternatively or additionally, other aluminum alloys such as Al 2024, Al 6063, and Al 7075 can be included in the billet material **120**.

[0034] FIG. **2**A, FIG. **2**B, and FIG. **2**C each illustrate examples of a ShAPE-processed extrudate including varying physical properties along a length of the extrudate. As depicted in FIG. **2**A, the system **100** (as depicted in FIG. **1**) can produce an extrudate **122** having at least one high "toughness" (or high ductility) portion and at least one high tensile strength portion, e.g., based on different specified temperature ranges applied at the die face **112** (as depicted in FIG. **1**) via that first and second specified operating parameters, respectively. For example, the at least one high toughness portion can include multiple axial regions where the toughness or ductility is higher (e.g., at least 15% higher) than the at least one high tensile strength region. Similarly, the at least one high tensile strength portion can include multiple axial regions where the tensile strength is higher (e.g., at least 25% higher) than the at least one high toughness portion. In an example, the extrudate **122** can include high tensile strength portions alternating with high toughness portions, e.g., extruded according to the different specified temperature ranges and without requiring stopping of the rotation of the die face relative to the billet material or without requiring stopping of the axial extrusion force to drive the billet and the die face together. In an example, the extrudate **122** can include one or more transition portions **202** located between each high tensile strength portion and each high toughness portion. Herein, the term "transition portion" can refer to an intermediate portion exhibiting a change in one or more physical properties moving from a first portion and toward a second portion. As shown by the detail view of FIG. **2**B, an individual transition portion **202** can manifest on the extrudate **122** as a visual artefact, such as spiraled lines or sharp ridges, but the visual artefact need not define an axial length of the region. Instead, herein, an axial length of an individual transition portion can be defined by its physical properties. As explained below with respect to FIG. **5**A, visual artefacts manifested by an individual transition portion can span an axial region wider than the transition portion itself. In an example, the one or more transition portions **202** can each define a region extending no longer than about 100 millimeters (mm) in the axial direction, no longer than about 50 mm in an axial direction, or no longer than about 30 mm in the axial direction. In an example, a transition region length can be controlled based on selection of the first specified set of operating parameters and the second specified set of operating parameters. For example, during a given temperature increase (e.g., from about 375° C. to about 490° C.), altering only a rotation (e.g., without altering a corresponding the axial extrusion force or ram speed of the driver) of the die face relative to the billet material can result in a relatively longer transition (e.g., about 15 mm in the axial direction). However, for the same given temperature increase, altering both i) a rotation of the die face relative to the billet material and ii) the axial extrusion force can result in a relatively shorter transition (e.g., about 3 mm in the axial direction).

[0035] FIG. **2**C is a chart showing an example of die temperature and hardness along the tube length along with a visual representation of an extrudate tube. In an example, an extrusion can involve establishing first specified operating parameters such that a temperature at a die face is within a range of about 350° C. and about 450° C., or about 400° C. In an example, such a temperature can further increase, e.g., due to the increase in spindle speed, toward second specified operating parameters including a maximum temperature within a range of about 500° C. and about 575° C., or a maximum temperature of about 535° C. Such a progressive change in temperature can correspond with a progressive change in hardness in the as-extruded extrudate **122** and similarly when the extrudate **122** is subject to a T5 temper. In an example, the first specified operating parameters can result in a hardness of the as-extruded extrudate **122** within a range of about 45 Vickers hardness value (HV0.3) and about 75 HV0.3, or about 59 HV0.3. In an example, as the die temperature is increased, the hardness of the as-extruded extrudate **122** can first decrease (e.g., to a value within a range of about 20 HV0.3 and about 60 HV0.3 or about 44 HV0.3) until a critical die temperature (e.g., about 485° C.) is reached. Once the critical die temperature is reached, the hardness of the as-extruded extrudate **122** can then increase to (or return toward) a value within a range of about 45 HV0.3 and about 75 HV0.3, or about 66 HV0.3 toward an end of the extrudate **122**. As shown in FIG. **2**C, a response of the extrudate **122** to a T5 temper heat treatment (about 180° C. for about 18 hours for 6061 Al or about 200° C. for about 4 hours for 6111 Al) can include a "delayed" response the die temperature approaches the critical die temperature, and the hardness response can exhibit a continuous increase corresponding with further increases in die temperature. In an example, an extrudate **122** subject to a T5 temper can exhibit <90 HV0.3 as the die temperature approaches the maximum temperature.

[0036] FIG. **3** is a chart showing an example of extruding using a constant ram speed and progressively increasing rotation of a die face relative to a billet. In an example, the system can perform extrusion including a uniform axial extrusion force (e.g., a constant ram speed via the driver), such as at about 120 mm/min. Here, a rotation of the die face relative to the billet material can be progressively increased, e.g., about every 15 mm of plunge depth from about 40 to about 60 to about 80 to about 100 to about 125 to about 150 RPM.

[0037] FIG. **4**A, FIG. **4**B, FIG. **4**C, FIG. **4**D, FIG. **4**E, and FIG. **4**F are charts, each showing a transition in material properties of an extrudate based on various operating parameters during extrusion.

[0038] FIG. **4**A and FIG. **4**B depict a length of a transition portion during the extruding described with respect to FIG. **3**. Here, a change the rotational RPM while at a constant ram speed of 120 mm/min, is represented for both single and double transitions. A single transition can involve an increase in a spindle speed, such as to obtain two steady-state processing temperatures in the tube. In a double transition, the spindle speed can be increased followed with a reduction in spindle speed, such as to obtain three steady-state processing temperatures.

[0039] As depicted in FIG. **4**C and FIG. **4**D, a ram speed can be reduced to about 20 mm/min from 120 mm/min during the spindle speed change. In an example, to change the processing temperature as quickly as possible, during the transition the spindle speed can be briefly changed beyond the steady state rotational speed for maintaining the new temperature steady state. An example of such a technique of briefly changing a spindle speed beyond a steady state rotational speed is further represented in the magnified views of FIG. **4**E an FIG. **4**F.

[0040] FIG. **5**A is a chart showing an example of hardness along the tube length across a transition portion. As shown in FIG. **5**A, a length of a transition portion (as defined herein based on its physical properties) can be shorter than a visual artefact manifested by the same transition portion. For instance, a length of a transition portion based on hardness may only span an axial region of about 19 mm, while the visual artefact manifested by the same transition portion may span an axial region of about 31 mm.

[0041] FIG. **5**B is a chart illustrating varying properties in 6111 Aluminum for two different extrusion die temperatures. In an example, the system can extrude first and second portions, respectively, via first specified operating parameters controlling a temperature at a die face of about 490° C. via second specified operating parameters controlling a temperature at a die face of about 530° C. As depicted in FIG. **5**B, a first extrudate portion extruded at a lower die temperature can be capable of withstanding greater strain than that of a second extrudate portion extruded at a higher die temperature. Also, the second extrudate portion extruded at the higher die temperature can be capable of withstanding greater stress than that of the first extrudate portion extruded at the lower die temperature.

[0042] FIG. **6** is a flowchart outlining the steps of an exemplary technique **600** for shear-assisted extrusion. The technique **600** can be implemented using one or more devices or systems described herein, such as the system controller of FIG. **1**, the processor of FIG. **7**, etc.

[0043] At **610**, a first portion of the aluminum feedstock can be extruded through the opening defined by the die tool. During this extrusion of the first portion, the die tool face can be rotated relative to the feedstock material at a first specified rotational speed. Contemporaneously with the rotating, an axial extrusion force can be applied in step to drive the feedstock and die tool face together according to first specified operating parameters. For example, the first rotational speed can be one of the operating parameters that can be varied between extruding the first and second portions. Also, the first operating parameters can include a ram rate, or a ram force used for applying the axial extrusion force.

[0044] At **620**, a second portion of the aluminum feedstock can be extruded through the same die tool opening. While extruding the second portion, the die tool face can be rotated relative to the feedstock material at a second, different specified rotational speed than during extruding of the first portion. The rotational speed can be accelerated or decelerated between the first and second rotational speeds, e.g., without fully stopping the rotation. Contemporaneously, the axial extrusion force can be applied such as to drive the feedstock and die tool face together according to second specified operating parameters that are different from the first operating parameters. The second operating parameters can also include a different ram rate or ram force compared to the first operating parameters. Additionally, the ram rate can be reduced, such as without requiring an interruption, during the transition between the first and second portions.

[0045] Optionally, at **630**, at least one operating parameter such as at least one of a rotational rate for the rotation, a ram rate, or ram force used for applying the axial extrusion force, a spindle power, a die temperature, an extrudate speed, a cooling or quenching parameter, or a ramping or other change in one or any combination thereof can be modulated. Such modulation can be introduced via different rotational speeds or operating parameters when extruding the first and second portions, and different temperature ranges can be established at the interface between the die tool face and the feedstock material. Monitoring the interface temperature with a thermocouple can further help provide sensor feedback to establish or adjust the rotational speed, ram rate, and other parameters. As a result, the first extruded portion can exhibit different physical properties as compared to the second extruded portion. For example, the difference in ductility between portions can be at least 15%, and the difference in tensile strength between portions can be at least 25%. Furthermore, extrusion of the first and second portions can require no longer than a relatively short (e.g., <30 mm long) transition portion can be extruded between the first and second portions. Such a transition portion can include a tensile strength greater than at least one of the first and second portions, such that the transition portion does not define a weak or susceptible point disposed between the first and second portions.

[0046] FIG. **7** illustrates generally an example of a block diagram of a machine **700** upon which any one or more of the techniques (e.g., methodologies) discussed herein may perform in accordance with some examples. In alternative embodiments, the machine **700** may operate as a standalone device or may be connected (e.g., networked) to other machines. In a networked deployment, the machine **700** may operate in the capacity of a server machine, a client machine, or both in server-client network environments. In an example, the machine **700** may act as a peer machine in peer-to-peer (P2P) (or other distributed) network environment. The machine **700** may be a personal computer (PC), a tablet PC, a set-top box (STB), a personal digital assistant (PDA), a mobile telephone, a web appliance, a network router, switch or bridge, or any machine capable of executing instructions (sequential or otherwise) that specify actions to be taken by that machine. Further, while only a single machine is illustrated, the term "machine" shall also be taken to include any collection of machines that individually or jointly execute a set (or multiple sets) of instructions to perform any one or more of the methodologies discussed herein, such as cloud computing, software as a service (SaaS), other computer cluster configurations.

[0047] Examples, as described herein, may include, or may operate on, logic or a number of components, modules, or mechanisms. Modules are tangible entities (e.g., hardware) capable of performing specified operations when operating. A module includes hardware. In an example, the hardware may be specifically configured to carry out a specific operation (e.g., hardwired). In an example, the hardware may include configurable execution units (e.g., transistors, circuits, etc.) and a computer readable medium containing instructions, where the instructions configure the execution units to carry out a specific operation when in operation. The configuring may occur under the direction of the execution units or a loading mechanism. Accordingly, the execution units are communicatively coupled to the computer readable medium when the device is operating. In this example, the execution units may be a member of more than one module. For example, under operation, the execution units may be configured by a first set of instructions to implement a first module at one point in time and reconfigured by a second set of instructions to implement a second module.

[0048] Machine (e.g., computer system) **700** may include a hardware processor **702** (e.g., a central processing unit (CPU), a graphics processing unit (GPU), a hardware processor core, or any combination thereof), a main memory **704** and a static memory **706**, some or all of which may communicate with each other via an interlink (e.g., bus) **708**. The machine **700** may further include a display unit **710**, an alphanumeric input device **712** (e.g., a keyboard), and a user interface (UI) navigation device **714** (e.g., a mouse). In an example, the display unit **710**, alphanumeric input device **712** and UI navigation device **714** may be a touch screen display. The machine **700** may additionally include a storage device (e.g., drive unit) **716**, a signal generation device **718** (e.g., a speaker), a network interface device **720**, and one or more sensors **721**, such as a global positioning system (GPS) sensor, compass, accelerometer, or another sensor. The machine **700** may include an output controller **728**, such as a serial (e.g., universal serial bus (USB), parallel, or other wired or wireless (e.g., infrared (IR), near field communication (NFC), etc.) connection to communicate or control one or more peripheral devices (e.g., a printer, card reader, etc.).

[0049] The storage device **716** may include a machine readable medium **722** that is non-transitory on which is stored one or more sets of data structures or instructions **724** (e.g., software) embodying or utilized by any one or more of the techniques or functions described herein. The instructions **724** may also reside, completely or at least partially, within the main memory **704**, within static memory **706**, or within the hardware processor **702** during execution thereof by the machine **700**. In an example, one or any combination of the hardware processor **702**, the main memory **704**, the static memory **706**, or the storage device **716** may constitute machine readable media.

[0050] While the machine readable medium **722** is illustrated as a single medium, the term "machine readable medium" may include a single medium or multiple media (e.g., a centralized or distributed database, or associated caches and servers) configured to store the one or more instructions **724**.

[0051] The term "machine readable medium" may include any medium that is capable of storing, encoding, or carrying instructions for execution by the machine **700** and that cause the machine **700** to perform any one or more of the techniques of the present disclosure, or that is capable of storing, encoding or carrying data structures used by or associated with such instructions. Non-limiting machine-readable medium examples may include solid-state memories, and optical and magnetic media. Specific examples of machine-readable media may include: non-volatile memory, such as semiconductor memory devices (e.g., Electrically Programmable Read-Only Memory (EPROM), Electrically Erasable Programmable Read-Only Memory (EEPROM)) and flash memory devices; magnetic disks, such as internal hard disks and removable disks; magneto-optical disks; and CD-ROM and DVD-ROM disks.

[0052] The instructions **724** may further be transmitted or received over a communications network **726** using a transmission medium via the network interface device **720** utilizing any one of a number of transfer protocols (e.g., frame relay, internet protocol (IP), transmission control protocol (TCP), user datagram protocol (UDP), hypertext transfer protocol (HTTP), etc.). Example communication networks may include a local area network (LAN), a wide area network (WAN), a packet data network (e.g., the Internet), mobile telephone networks (e.g., cellular networks), Plain Old Telephone (POTS) networks, and wireless data networks (e.g., Institute of Electrical and Electronics Engineers (IEEE) 602.11 family of standards known as Wi-Fi®, IEEE 602.16 family of standards known as WiMax®), IEEE 602.15.4 family of standards, peer-to-peer (P2P) networks, among others. In an example, the network interface device **720** may include one or more physical jacks (e.g., Ethernet, coaxial, or phone jacks) or one or more antennas to connect to the communications network **726**. In an example, the network interface device **720** may include a plurality of antennas to wirelessly communicate using at least one of single-input multiple-output (SIMO), multiple-input multiple-output (MIMO), or multiple-input single-output (MISO) techniques. The term "transmission medium" shall be taken to include any intangible medium that is capable of storing, encoding or carrying instructions for execution by the machine **700**, and includes digital or analog communications signals or other intangible medium to facilitate communication of such software.

[0053] The above detailed description includes references to the accompanying drawings, which form a part of the detailed description. The drawings show, by way of illustration, specific embodiments in which the invention can be practiced. These embodiments are also referred to generally as "examples." Such examples can include elements in addition to those shown or described. However, the present inventors also contemplate examples in which only those elements shown or described are provided. Moreover, the present inventors also contemplate examples using any combination or permutation of those elements shown or described (or one or more aspects thereof), either with respect to a particular example (or one or more aspects thereof), or with respect to other examples (or one or more aspects thereof) shown or described herein.

[0054] In the event of inconsistent usages between this document and any documents so incorporated by reference, the usage in this document controls.

[0055] In this document, the terms "a" or "an" are used, as is common in patent documents, to include one or more than one, independent of any other instances or usages of "at least one" or "one or more." In this document, the term "or" is used to refer to a nonexclusive or, such that "A or B" includes "A but not B," "B but not A," and "A and B," unless otherwise indicated. In this document, the terms "including" and "in which" are used as the plain-English equivalents of the respective terms "comprising" and "wherein." Also, in the following claims, the terms "including" and "comprising" are open-ended, that is, a system, device, article, composition, formulation, or process that includes elements in addition to those listed after such a term in a claim are still deemed to fall within the scope of that claim. Moreover, in the following claims, the terms "first," "second," and "third," etc., are used merely as labels, and are not intended to impose numerical requirements on their objects.

[0056] Method examples described herein can be machine or computer-implemented at least in part. Some examples can include a computer-readable medium or machine-readable medium encoded with instructions operable to configure an electronic device to perform methods as described in the above examples. An implementation of such methods can include code, such as microcode, assembly language code, a higher-level language code, or the like. Such code can include computer readable instructions for performing various methods. The code may form portions of computer program products. Such instructions can be read and executed by one or more processors to enable performance of operations comprising a method, for example. The instructions are in any suitable form, such as but not limited to source code, compiled code, interpreted code, executable code, static code, dynamic code, and the like.

[0057] Further, in an example, the code can be tangibly stored on one or more volatile, non-transitory, or non-volatile tangible computer-readable media, such as during execution or at other times. Examples of these tangible computer-readable media can include, but are not limited to, hard disks, removable magnetic disks, removable optical disks (e.g., compact disks and digital video disks), magnetic cassettes, memory cards or sticks, random access memories (RAMs), read only memories (ROMs), and the like.

[0058] The above description is intended to be illustrative, and not restrictive. For example, the above-described examples (or one or more aspects thereof) may be used in combination with each other. Other embodiments can be used, such as by one of ordinary skill in the art upon reviewing the above description. The Abstract is provided to allow the reader to quickly ascertain the nature of the technical disclosure. It is submitted with the understanding that it will not be used to interpret or limit the scope or meaning of the claims. Also, in the above Detailed Description, various features may be grouped together to streamline the disclosure. This should not be interpreted as intending that an unclaimed disclosed feature is essential to any claim. Rather, inventive subject matter may lie in less than all features of a particular disclosed embodiment. Thus, the following claims are hereby incorporated into the Detailed Description as examples or embodiments, with each claim standing on its own as a separate embodiment, and it is contemplated that such embodiments can be combined with each other in various combinations or permutations. The scope of the invention should be determined with reference to the appended claims, along with the full scope of equivalents to which such claims are entitled.

[0059] The above detailed description is intended to be illustrative, and not restrictive. The scope of the disclosure should, therefore, be determined with references to the appended claims, along with the full scope of equivalents to which such claims are entitled.

What is claimed is:

1. A method for shear-assisted extrusion of a billet or other feedstock, the method comprising:

extruding a first portion of the feedstock through an opening defined by a die tool, the extruding comprising establishing rotation of a die tool face relative to a feedstock material according to first specified operating parameters and, contemporaneously, applying an axial extrusion force to drive the feedstock and the die tool face together according to the first specified operating parameters; and

extruding a second portion of the feedstock through the opening defined by the die tool, the extruding comprising establishing rotation of the die tool face relative to the feedstock material according to second specified operating parameters and contemporaneously, applying the axial extrusion force to drive the feedstock and the die tool face together according to the second specified operating parameters, wherein at least one of the second specified operating parameters is different than at least one of the first specified operating parameters to establish different specified temperature ranges at an interface between the die tool face the feedstock such that a first portion of a resulting extrudate along a first axial region extruded from the first portion of the feedstock comprises one or more different physical properties than a second portion of the resulting extrudate along a second axial region extruded from the second portion of the feedstock.

2. The method of claim **1**, wherein the first specified operating parameters define a first rotational rate for the rotation during extrusion and the different second specified operating parameters define a different second rotational rate for the rotation during extrusion.

3. The method of claim **1**, wherein the first specified operating parameters define a first ram rate used for applying the axial extrusion force and the different second specified operating parameters define a different second ram rate use for applying the axial extrusion force.

4. The method of claim **1**, comprising modulating at least one of a rotational rate for the rotation, a ram rate, or ram force used for applying the axial extrusion force, a spindle power, a die temperature, an extrudate speed, a cooling or quenching parameter, or a ramping or other change in one or any combination thereof.

5. The method of claim **1**, wherein the feedstock comprises an aluminum alloy.

6. The method of claim **1**, wherein the feedstock comprises a 2-series, 6-series, or 7-series aluminum alloy.

7. The method of claim **1**, comprising accelerating or decelerating the rotation, without stopping the rotation, to transition from a first rotational rate associated with the first specified operating parameters to a second rotational rate associated with the different second specified operating parameters.

8. The method of claim **7**, comprising reducing, without interrupting, a ram rate associated with applying the axial extrusion force contemporaneously with the accelerating or the decelerating the rotation.

9. The method of claim **8**, wherein a first steady-state ram rate associated with applying the axial extrusion force corresponding to the first specified operating parameters and a second steady-state ram rate associated with applying the axial extrusion force corresponding to the different second specified operating parameters are the same.

10. The method of claim **1**, comprising:

extruding a transition portion located between the first portion and the second portion; wherein the transition portion of a resulting extrudate along a transition axial region extruded from the transition portion of the feedstock is located between the first axial region and the second axial region.

11. The method of claim **10**, wherein the transition axial region defines a region extending no longer than 30 millimeters (mm) in an axial direction.

12. The method of claim **1**, wherein a tensile strength of the extruded transition portion along the transition axial region is greater than at least one of the tensile strength of the extruded first portion or the tensile strength of the extruded second portion.

13. The method of claim **1**, wherein the one or more different physical properties of the first axial region and the second axial region include respective values of ductility differing by at least 15%.

14. The method of claim **1**, wherein the one or more different physical properties of the first axial region and the second axial region include respective values of tensile strength differing by at least 25%.

15. A shear-assisted extrusion product, comprising:

a first portion of extrudate along a first axial region extruded from a first portion of a feedstock;

a second portion of extrudate along a second axial region extruded from a second portion of a same feedstock; and

a transition region between the first axial region and the second axial region;

wherein the first portion of the extrudate comprises one or more different physical properties than the second axial portion.

16. A system for shear-assisted extrusion of a billet or other feedstock, the system comprising:

a die tool, comprising a die tool face and defining an opening for extruding a first portion of the feedstock therethrough, the die tool configured to have relative rotational motion relative to a feedstock material according to first specified operating parameters;

a driver configured to apply an axial extrusion force to drive the feedstock and the die tool face together, during the relative rotational motion and according to the first specified operating parameters; and

a system controller configured to establish or adjust rotation of the die tool face relative to the feedstock material according to second specified operating parameters and contemporaneously, establish or adjust the axial extrusion force to drive the feedstock and the die tool face together according to the second specified operating parameters;

wherein at least one of the second specified operating parameters is different than at least one of the first specified operating parameters to establish different specified temperature ranges at an interface between the die tool face the feedstock such that a first portion of a resulting extrudate along a first axial region extruded from the first portion of the feedstock comprises one or more different physical properties than a second portion of the resulting extrudate along a second axial region extruded from the second portion of the feedstock.

17. The system of claim **16**, wherein the first specified operating parameters define a first rotational rate for the rotation during extrusion and the different second specified operating parameters define a different second rotational rate for the rotation during extrusion.

18. The system of claim **16**, wherein the first specified operating parameters define a first ram rate used for applying the axial extrusion force and the different second specified operating parameters define a different second ram rate use for applying the axial extrusion force.

19. The system of claim **16**, comprising a thermocouple arranged to provide an indication of an temperature at an interface between the feedstock and the die face, wherein the system controller is configured to modulating at least one of a rotational rate for the rotation, a ram rate, or a ram force used for applying the axial extrusion force based on the indication of the temperature at the interface.

20. The system of claim **16**, wherein the system controller is configured to accelerate or decelerate the rotation, without stopping the rotation, to transition from a first rotational rate associated with the first specified operating parameters to a second rotational rate associated with the different second specified operating parameters.

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