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Design of a Desktop Wire-feed Prototyping Machine

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Abstract

Much additive manufacturing research focuses on systems suitable for industrial applications, especially research on metal processing. Our research aims to design a desktop-scale prototyping machine to process metal wire. Possible applications for this research include various wire structures, such as wire sculptures.

The wire joining technology is the most important subsystem of the envisioned layer-based process. In this research, three concepts are proposed and analyzed according to the power required to fully melt the wire. The selected approach uses a wire bender to create the desired geometry of the product, and a pulse TIG welder to join the metal wire to retain the shape. Experiments were conducted to evaluate the joining strength of pulse TIG welds to verify the joining efficiency of the method. The experimental results indicate that filler metal is required to produce acceptable welding strength. A conceptual CAD model of the complete system is presented.

Introduction

The appearance of desktop 3D printers has boosted the trend toward personal fabrication or "making" [1]. These desktop layer-based machines provide the ability for users to automatically create components with complex geometry. They not only benefit makers but also engineering education. However, most desktop machines are suitable for thermoplastics only, not for metals.

One limitation for the development of a desktop metal prototyping machine is due to available energy. It is common for additive manufacturing technology to use a heat source, such as a laser, to soften or join precursor material. A comparatively large amount of power is required to complete a metal joining process relative to polymer joining.

Recent research and new products [2-7] are focused on processing metal material with layer-based approaches. These fall into three primary categories. The first category usesmodified heating processes. Unlike traditional metal additive manufacturing processes that use a laser, such as Selective Laser Sintering (SLS), Anzalone et. al. develop a 3D printer with gas-metal arc welding (GMAW) to fuse and deposit carbon steel wire (ER 70S-6) [2]. Another example is the 888 printer (Ability 3D, Casselberry, FL, USA), which integrates a welder and a router. The 888 printer can process aluminum and steel [3]. The second category uses non-traditional precursor material, such as ColorFabb CopperFill metal filament [4] and Liquid Metal Jetting (LMJ), which uses liquid metal as the pre-cursor material [5]. The third category separates the geometry-forming process and the heating/joining process. The Mini Metal Maker uses metal clay, a material containing metal particles and binder, to create green components. The green component is then heated in a kiln to 600-900°C to remove the binder [6]. Selective Inhibition Sintering (SIS) extrudes an inhibitor to create the contour of the geometry. The material powder blank is sintered in a furnace, and the inhibitor is the removed by water or an organic solution [7].

The purpose of our research is to develop a different approach to manufacturing with metal wire. The research focuses on applications such as wire sculptures (See Figure 1). A common material for wire sculptures is copper, which is considered as one target material for our process.

Figure 1. Example of wire sculptors [8]

Functional Model of Additive Manufacturing

Additive manufacturing processes include five primary subsystems: signal control system, material delivery system, geometry forming process, material joining process, and support. Figure 2 shows a common functional model of additive manufacturing processes.

Williams et. al. [9] developed a functional framework for the conceptual design of additive manufacturing technologies based on physical principles. The sub-functions identified by them include store material, pattern material, pattern energy, create primitive, provide new material, and support previously deposited material. In our research, we assume metal wire is processed during the additive manufacturing process. Therefore, the framework from Figure 2 is recast as a function structure in Figure 3.

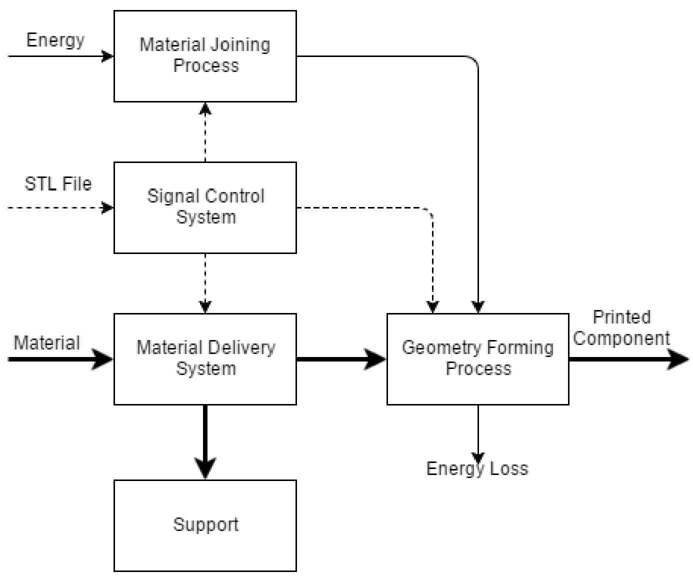

Figure 2. Framework of the additive manufacturing processes

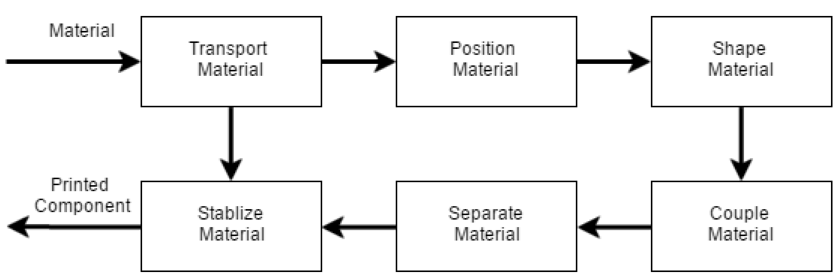

Figure 3. Function structure of additive manufacturing processes

The sub-functions used in our research are transport material, position material, shape material, couple material, and stabilize material. Note that "separate material" demonstrates the process of separating the pre-cursor material from printed material. Table 1 compares sub-functions identified in our research and and those proposed in [9].

From [9]	This Research
Store Material	Wire
Pattern Material	Transport Material
Pattern Energy	Couple Material
Create Primitive	Shape Material Separate Material
Provide New Material	Transport Material
Support	Stabilize Material

Table 1. Comparison of sub-functions between this research and [9]

Conceptual Designs

A morphological matrix [10] was developed based on the six sub-functions in Figure 3. Table 2 illustrates the morphological matrix with three conceptual designs: bending, laser, and welding.

Sub-function	Bending Concept	Laser Concept	Welding Concept
Transport Material	Roller	Roller	Roller
Position Material	Moving Platform	Moving Extrusion	Moving Platform
Shape Material	Wire Bender	Laser	Induction Welding
Couple Material	Pulse TIG Welding	Laser	Induction Welding
Separate Material	Pulse TIG Welding	n/a	n/a
Stabilize Material	Truss	Truss	Truss

Table 2 Concept variations based on the morphological matrix

- **Bending Configuration**
  In this concept, a wire bender is used to create the geometry of the component. Then, the shaped wire is joined by a welder. Since the geometry of the wire is created by the bender, it is possible to limit joining to specific spots (join discontinuously) instead of join continuously.
- **Laser Configuration**
  The laser configuration uses a desktop laser system to fully melt the metal wire continuously. Possible choices for the laser system include CO_2 laser and Nd:YAG lasers. Cost is an important consideration when selecting a commercial desktop laser system.

- **Welding Configuration**

  The welding concept uses a traditional welding process to melt the metal wire. Possible choices for the welding process include Gas Metal Arc Welding (GMAW), Tungsten Inert Gas (TIG) Welding, and induction welding. Since GMAW and TIG welding have been studied [2,3], this research focuses more on evaluating induction welding.

Concept Evaluation

Concept evaluation was conducted in order to investigate the feasibility and comparative performance of each concept. The evaluations of the laser and the induction welding configurations were based on simulations, and the bender concept was investigated by experiment.

Continuous Joining and Discontinuous Joining

It is important to evaluate whether the precursor material can be fully joined with a reasonable power input. Most additive manufacturing processes are continuous joining processes; that is, the pattern energy is delivered continuously to combine precursor material. Here, discontinuous joining is explored for the bending concept. Since the geometry is formed by a wire bender, it is only necessary to join selected points to create a stable part. Therefore, a pulsed joining method with comparatively low power requirement can be used in the discontinuous joining process. This significantly reduces the required power for the process, as shown below.

Laser Concept Evaluation

To evaluate the joining efficiency of the laser, it is important to investigate whether the metal wire can fully melted at selected reasonable speed. As stated earlier, this evaluation was conducted by simulation. The material properties for the simulation are provided in Table 4. Equation (4.1) is a heat transfer model developed to validate the laser continuous joining process.

Material	$\boldsymbol{k}\left(\frac{\mathbf{W}}{\mathbf{mK}}\right)$	$\boldsymbol{C_p}\left(\frac{\mathbf{J}}{\mathbf{kgK}}\right)$	$\boldsymbol{\rho}\left(\frac{\mathbf{kg}}{\mathbf{m^3}}\right)$	$\boldsymbol{\alpha}\left(\frac{\mathbf{m^2}}{\mathbf{s}}\right)$	$\boldsymbol{T_m}(\mathbf{K})$
Aluminum	237	903	2702	97.1×10^{-6}	933
Copper	401	385	8933	117×10^{-6}	1358
Iron	80.2	447	7870	23.1×10^{-6}	1810

Table 4 Material properties for the simulation

$$\nabla^2 T + \frac{1}{k} q\delta(x - vt)\delta(y - 0)\delta(z - 0) = \frac{1}{\alpha}\frac{\partial T}{\partial t} \tag{4.1}$$

where T = transient temperature (K),

k = conduction coefficient $\left(\mathrm{W}/_{\mathrm{mK}}\right)$,

q = rate of energy production by a specific heat source (W),

v = constant velocity of heat source $\left(\mathrm{m}/_{\mathrm{s}}\right)$,

α = diffusion coefficient $\left(\mathrm{m}/_{\mathrm{s}^2}\right)$,

$\delta(x)$ = Dirac delta function, and

x, y, z = Distance from the heat source in x, y, and z directions.

The three-dimensional model can be converted into a one-dimensional model since the primary concern is heat conduction within the copper wire. Additionally, the model is assumed to be quasi-steady state. By substituting $\varepsilon = x - vt$. Equation (4.1) can be rewritten as

$$\frac{\partial^2 T}{\partial \varepsilon^2} + \frac{1}{k} q'' \delta(\varepsilon) = -\frac{v}{\alpha}\frac{\partial T}{\partial \varepsilon} \tag{4.2}$$

The final solution is

$$T = T_0 + \frac{q''}{v\rho C_p}, \qquad x < 0$$

$$T = T_0 + \frac{q''}{v\rho C_p} e^{-\frac{v}{\alpha}x}, \qquad x \geq 0 \tag{4.3}$$

The goal of the simulation is to fully melt 0.64 mm metal wire, which is a common wire gauge for handcrafts [17]. The input heat flux of the laser can be defined by equation (4.4). The spot diameter is assumed to be 0.4 mm in the simulation [16]. Table 5 shows the reflectivity of materials under CO_2 laser and Nd:YAG laser irradiation. The relationship between speed (10 mm/s to 20 mm/s) and laser power is demonstrated in Figure 3 (CO_2 laser) and Figure 4 (Nd:YAG laser).

$$I = (1 - R)\frac{P}{A} \tag{4.4}$$

where I = power intensity $\left(\mathrm{W}/_{\mathrm{m}^2}\right)$,

R = reflectivity,

P = laser power (W), and
A = area of spot size (m^2).

	CO_2 laser	Nd:YAG laser
Aluminum	0.94	0.8
Copper	0.97	0.96
Iron	0.88	0.68

Table 5. Reflectivity of various materials under CO_2 laser and Nd:YAG laser [11]

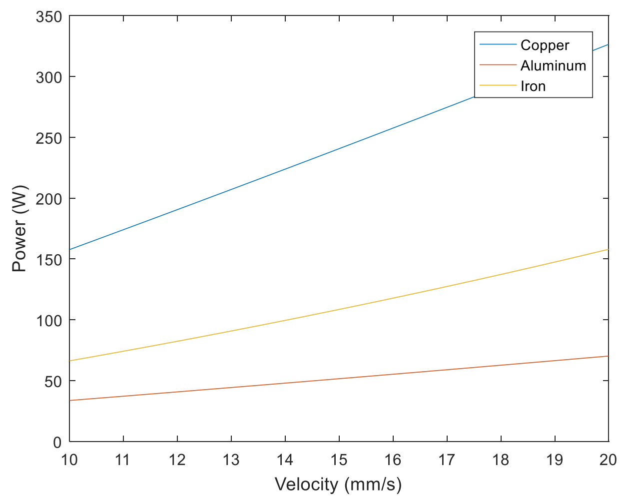

Figure 3. Power requirement for aluminum, copper, and iron for various scanning speeds under CO_2 laser

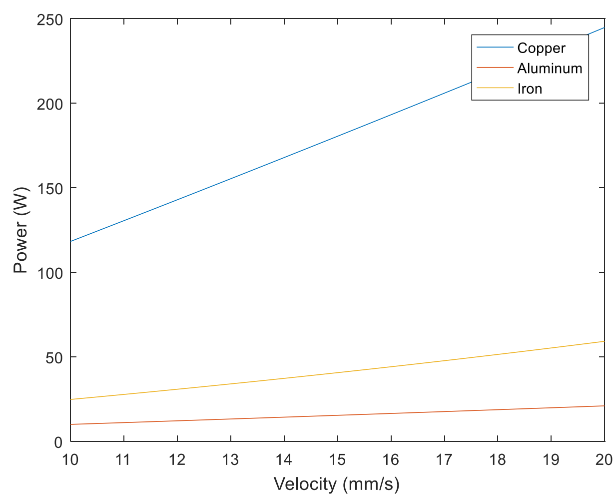

Figure 4. Power requirement for aluminum, copper, and iron for various scanning speeds under Nd:YAG laser

Figure 3 and Figure 4 show the power requirement to melt copper is much higher than for aluminum and iron. The laser concept is potentially feasible for both iron and aluminum, especially for a Nd:YAG laser.

Induction Welding Concept Evaluation

The minimum required power for the induction welding concept can be evaluated by equation (4.3). Figure 5 shows the relationship between power and velocity (10 mm/s to 25 mm/s). The price of a 5000 W induction welder, such as the UltraFlex UPT S5/2000 (Ronkonkoma, NY, USA), is approximately 10,000 USD, which is in a similar price range as a 45 W laser system with a cooling system [12].

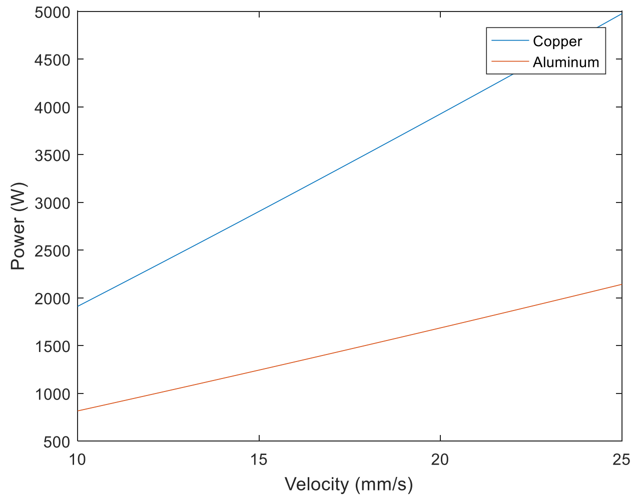

Figure 5. Minimum induction welding power for various velocities

Bending Concept Evaluation

The bending concept includes a discontinuous joining process. A TIG pulse welder was evaluated as a feasible joining technology. For this research, we evaluated the DingXing DX-YQ0505 TIG pulse welder with 120 V power input using a 2 % lanthanated electrode with 1/16” diameter and 38° tip angle. The peak output current is approximately 2828A over 5 ms, and the output arc voltage is 161V.

An Instron Model 2519-107 tensile test machine was used to determine the breaking force of the weld in order to evaluate the joining performance. The specimen material was annealed copper (ASTM 3B, 22 AWG). The gauge length was 30 mm. The specimens were straightened and cleaned with acetone before butt welding. The speed of the tensile test was 1mm/min at room temperature. The details of the tensile test are outlined in ASTM E8 [13].

Figure 5 shows the results of the tensile tests of the spot welds. The stress-strain curve of annealed copper wire is given as a reference (See Figure 6). The breaking point of the welding specimens (20-40 N) is much less than the breaking force (56N) of the annealed copper wire. Additionally, the strain of the welded specimens is smaller. The primary reason is due to the misalignment of the welder and anisotropy of the welded joint. These two factors cause the breaking force for the pulse welded joint to be far less than that of the copper wire. Figure 6 also compares the copper wire with a filler metal, EURO TOOL SS75 (a typical chemical composition hard silver solder is 75% Ag, 22% Cu, and 3% Zn). The result shows that the wire breaks in other locations and not at the joints. This demonstrates that the use of a filler metal can improve the joint strength.

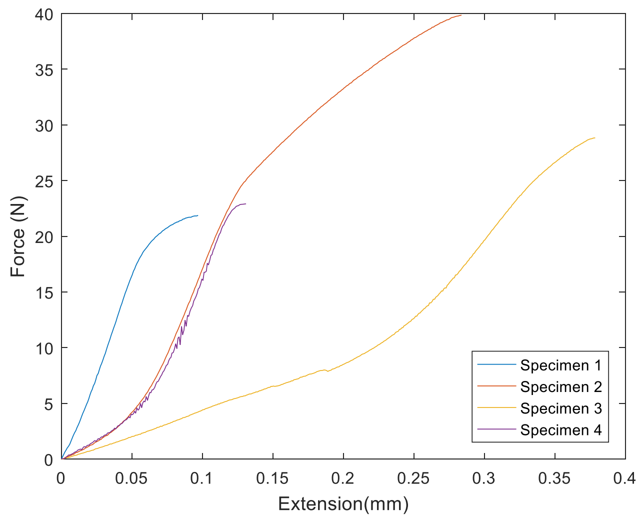

Figure 5 Tensile test for welding copper wire

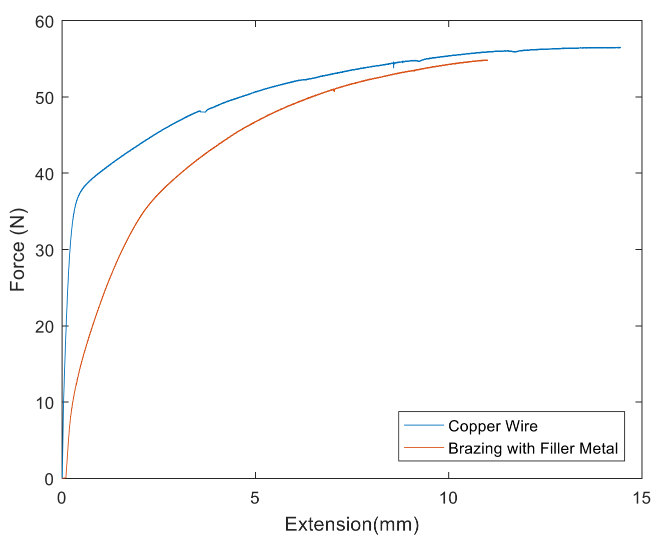

Figure 6. Tensile test result for the copper wire and brazing with filler metal

Discussion

The laser and bending concepts show potential to produce additively manufactured components. A low reflectivity material is suitable for the laser concept. However, the main issue for the laser is cost. A cooling system is required for the laser concept, and the cost for the laser concept is at least $6000 [12]. On the other hand, the bending concept shows potential to deal with high reflectivity metal. The primary issue in this research is that the breaking force of the welding specimen is less than 56 N, which is easy to damage. Filler material is required to improve the strength of the welding joint.

The bending concept is selected for further development because high reflectivity material is common for jewelry or wire sculptures (copper).

Design of the Wire-Feed Prototyping Machine

The bending concept includes a pulse TIG welding system and a wire bender. A compression bender is selected because it is suitable for the desktop design. The detailed components and sub-functions of the bender are shown in Figure 7 and Table 6.

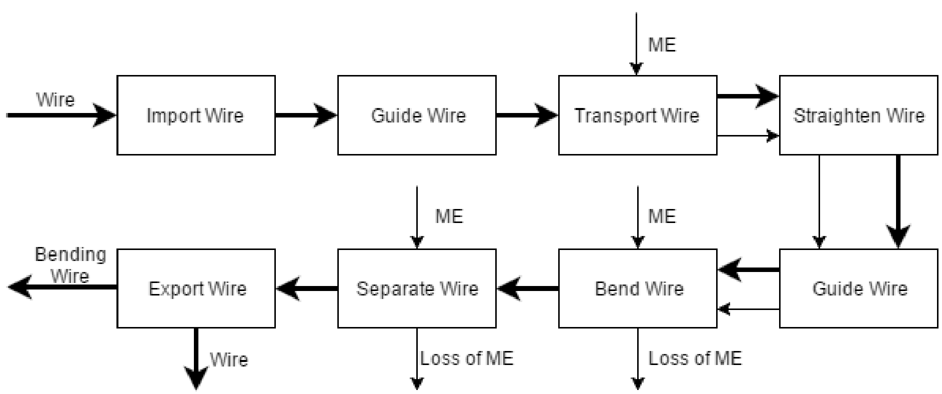

Figure 7. Function structure for a wire bender [14]

The proposed CAD model for the desktop metal wire-feed prototyping machine is shown in Figure 8. The wire bender is designed to operated\ in the vertical direction to easily position the shaped wire. The welder torch can rotate to cut the wire or weld the wire. For annealed copper wire, the recommended average energy set up to cut 0.64 mm diameter wireis at least 8000 J based on experiments [14].

Sub-function	**Component**
Import Wire	Motor-driven wire feeder
Transport Wire	Roller sets
Straighten Wire	Roller sets
Guide Wire	Plastic pipe
Bender Wire	Bend die, sliding piece
Separate Wire	Pulse TIG welder
Export Wire	Moving platform

Table 6. Sub-functions and components of the wire bender for the metal prototyping machine

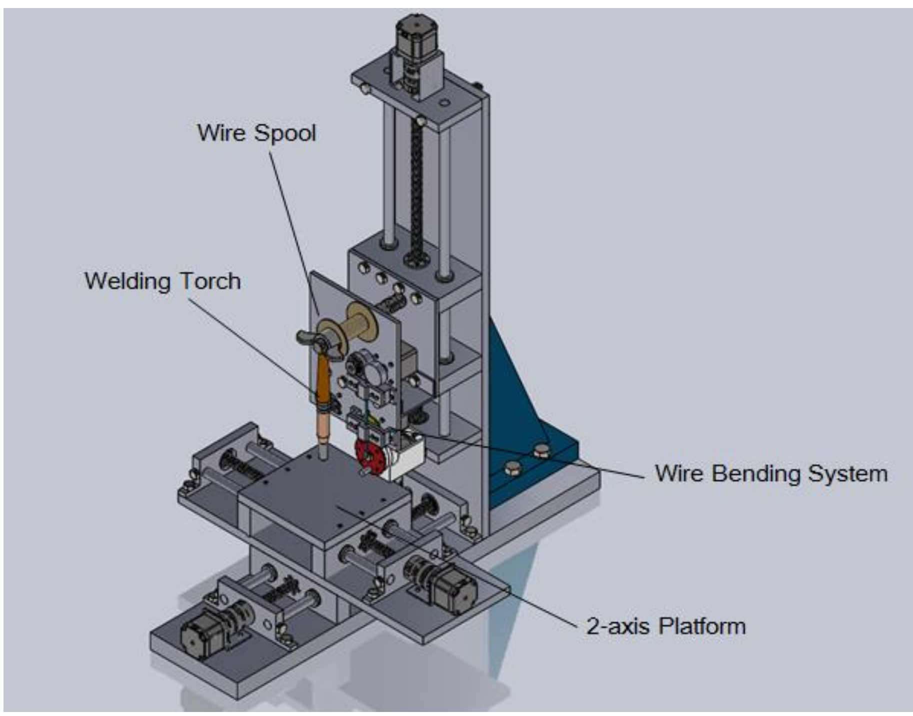

Figure 8. Proposed structure for the metal wire-feed prototyping machine [14]

<u>Conclusion and Future Work</u>

This research proposes a novel design for a desktop metal wire-feed additive manufacturing machine. Topics for further development include:

- **Improve the welding strength**

  Based on Figure 5, the welding strength is not high and is non-repeatable. It is necessary to investigate the strength of the joint when filler material is used in the process.

- **Develop the three-dimensional joining process**

  In this research, the design focuses on two-dimensional structures. Three-dimensional structures such as lattice structures [15] require further studies. Additionally, another control channel may be required in order to accurately position the shaped wire for three-dimensional structures. Integration of the system is necessary to investigate these questions.

- **Modify the control program**

  Software development is required. Since the proposed design does not melt the precursor material directly, it is necessary to develop software specific to the process.

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