Steel Strips Made Directly from Bulk Material by Large Strain Extrusion Machining

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ABSTRACT

Large Strain Extrusion Machining (LSEM) is presented as a method for production of steel strips under reduced costs and energy inputs compared to conventional processing methods such as rolling and drawing. The shear deformation and hydrostatic pressure imposed on the strip material as it traverses the deformation zone during LSEM processing is modeled using the theory of slip line fields. Processing conditions that result in adequate deformation and pressure are elucidated. The microstructure and hardness of the resulting strip material are characterized.

ABSTRACTO

Se presenta el proceso de extrusión y maquinado simultáneos (LSEM por sus siglas en inglés) como método para la producción de filamentos de acero a bajo costo y requerimientos energéticos reducidos, en comparación a métodos convencionales como laminado y trefilado. Tanto la deformación plástica como la presión hidrostática impuestas sobre el material del filamento son calculadas usando teoría de líneas de cizalladura. Las condiciones de procesamiento que resultan en deformación y presión adecuadas son identificadas. Se reportan la microestructura y la dureza del filamento procesado.

Keywords: steel strips, deformation processing, machining, extrusion.

1. INTRODUCTION

Strips made from steel are desirable for the reinforcement of concrete, due to the material's high elastic modulus. For this application, usually steels that are inherently strong and ductile (i.e., in wrought form) are used [Cement and Concrete Institute, 2010]. The high elastic modulus of steel helps transfer tensile loads from the concrete to the steel strips embedded in it. Due to this load transfer, the strength and ductility of steel reinforced concrete approach those of steel, which are much greater than those of conventional concrete. Among currently available methods to create steel strips stand out strip rolling and drawing. However, these methods require complicated, multiple steps to produce strips from conventional stock (bulk forms) that involve intermediate annealing and result in high costs and energy consumption. A process called large strain extrusion machining (LSEM) has been studied as an alternative for the production of metal strips made of copper, aluminum and magnesium alloys in a single manufacturing step [Moscoso, 2008, Moscoso et al, 2007, Efe et al, 2012]. The process can introduce controlled deformation ranging from levels typical of processes such as rolling and drawing to extremely severe levels that result in substantial reduction of crystal size and change of orientation or texture [Moscoso, 2008, Sagapuram et al, 2013, Sagapuram et al, 2012, Sagapuram et al, 2011]. While it has been hypothesized that the method can also be applied to the production of low cost steel strips for concrete reinforcement made with minimal energy input, at present, there are no records of such use.

The application of LSEM (Fig. 1) as a method for the production of steel strips that may be used for concrete reinforcement (having properties similar to those of the standard steels) is the purpose of this paper. In LSEM, a continuous ribbon is peeled off the surface of a cylindrical workpiece, while its thickness is controlled at the point of its formation by the use of a constraining tool. It will be seen that using the method, shear strain and hydrostatic pressure can be independently controlled. For this purpose, an analysis drawn from the theory of plasticity is described. The results of such analysis are used as guidance for the selection of conditions that result in the production of integral steel strips (i.e., free of defects or cracks) and mechanical properties similar to those of standard steels. The demonstration of the applicability of LSEM to the production of steel strips is performed using grade AISI 1020.

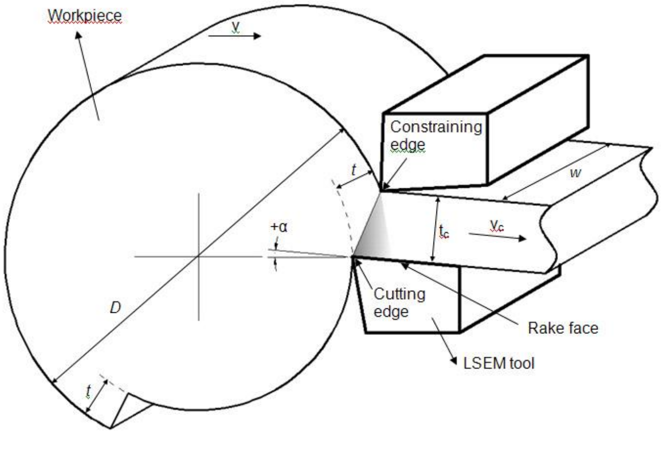


Figure 1. Schematic of the LSEM process.

In LSEM, material (chip or extrudate) of controlled thickness is produced in the form of strips using a combination of machining and extrusion imposed in a single step with a specially designed LSEM tool (Fig. 1). The LSEM tool moves radially into a disk-shaped workpiece rotating at a constant peripheral speed, V. The tool consists of two components – a wedge-shaped bottom section with a sharp cutting edge inclined at a rake angle (α) (Fig. 1); and a wedge-shaped top section that acts as a constraining edge. Both sections are made of a hard material. The machined material is simultaneously forced through an "extrusion" die formed by the bottom rake face and the top constraining edge, thereby, effecting dimensional control. Undeformed material is continuously fed into the machining zone by advancing the LSEM tool radially into the workpiece at a constant feed rate of t (mm/rev) (Fig. 1). This feed is the rate of radial advance of the tool per revolution of the workpiece and is the analog of the undeformed chip thickness in machining. Deformation takes place when the tool advances in the shaded region shown in Fig. 1. When plane strain conditions prevail, the velocity of the material at the exit of the LSEM tool is given by $V_c = Vt/t_c$, where t_c is the thickness of the deformed material. The strain and pressure levels are controlled by the chip compression ratio $\lambda = t_c/t$ and the tool rake angle (Eqns. 2.2 and 2.3, respectively).

2. DEFORMATION AND HYDROSTATIC PRESSURE

Figure 1 shows a schematic of the LSEM process. Constrained chip formation occurs by concentrated shear in a relatively narrow deformation zone on which lines of maximum shear (planes perpendicular to the plane of the schematic) can be determined using the theory of slip-line fields (SLFs) [Johnson et al, 1982]. One such SLF model is shown in Fig. 2a. This model assumes frictional contact between points along the tool rake face (line BCD) and rigid-perfectly plastic material. The model satisfies compatibility as evidenced by the hodograph in Fig 2b. The model was originally proposed by [Kudo, 1965] for the case of plane-strain machining and was first adopted in [Moscoso, 2008] for the purpose of calculation of the shear strain and the hydrostatic pressure imposed by the LSEM process on the work material. It can be shown that the fan angle (θ, Fig. 2a) can be calculated using the following two equations:

$$\left(\frac{1}{\lambda}-\frac{\sin(\alpha+\eta)}{\cos(\eta)}\right)\sin\left(\frac{\theta}{2}+\eta\right)=2\frac{\cos(\alpha)\sin\left(\frac{\theta}{2}\right)}{\cos(\eta)\sin(\theta+\eta)}\sin\left(\frac{\theta}{2}+\eta\right)\left(\sin\left(\frac{\theta}{2}\right)+\sin\left(\frac{\theta}{2}+\eta\right)\right) \tag{2.1a}$$

$$\eta=\frac{1}{2}\cos^{-1}\left(\frac{\tau}{k}\right) \tag{2.1b}$$

where α is the tool rake angle and λ is the chip compression ratio = t_c/t (Figs. 1 and 2), η is the friction angle, τ is the friction stress on the tool rake face (line BCD in Fig. 2) and k is the shear flow stress of the work material.

The tool rake angle may be positive as in the case depicted in Figs. 1 and 2, when the rake face is inclined away from the direction of the cutting velocity; or negative if the rake face is inclined towards the direction of the cutting velocity. The fan angle depends on both the tool geometry, i.e., the tool rake angle and chip compression ratio, and the frictional condition along the chip-tool contact; which is in turn characterized by the frictional stress on the tool rake face and the shear flow stress of the work material. For maximum friction ($\tau = k$) along the tool rake face (also known as sticking friction), the friction angle = 0°. This is the most likely condition in LSEM [Moscoso, 2008] and is used throughout the calculations presented herein.

The total shear strain imposed on a particle traversing the deformation field through fan OAC in Fig. 2a is:

$$\gamma=\frac{1}{\sin(\theta)}+\ln\left(\sec\left(\frac{\theta}{2}\right)+\tan\left(\frac{\theta}{2}\right)\right). \tag{2.2}$$

This shear strain is the maximum shear strain imposed on any material element traversing the deformation zone through the fan OAC.

The hydrostatic pressure along line OA in Fig. 2a, normalized with respect to the material shear yield strength, is:

$$p_{OA}/k=1+2\theta. \tag{2.3}$$

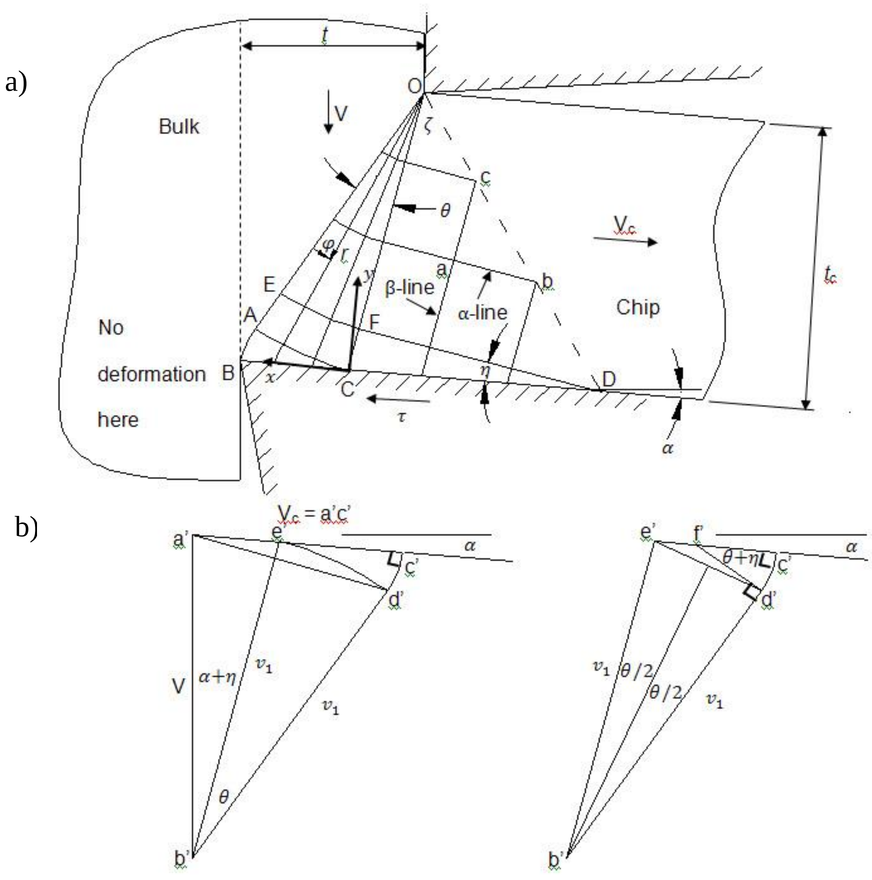


Figure 2. a) Slip line field for LSEM, b) hodograph.

The variation of shear strain and hydrostatic pressure with chip compression ratio, as calculated by Eqns 2.2 and 2.3, is shown in Fig. 3. Note that the shear strain shows a minimum for $\lambda = 1$ (chip or strip thickness = undeformed chip thickness), while the hydrostatic pressure decreases monotonically with increase in λ. The curves shown in Fig. 3 are for a zero tool rake angle. Both, the shear strain and the hydrostatic pressure increase with decrease in the tool rake angle. This suggests that LSEM can be used as a tool to produce high shear strain and high hydrostatic pressure, by selection of $\lambda < 1$ or high shear strain and low hydrostatic pressure by selection of $\lambda > 1$. Intermediate strain and high pressure results for $\lambda \sim 1$. Appropriate selection of the applied shear strain and hydrostatic pressure is critical for the introduction of microstructural changes that may affect the end product properties and the suppression of defects or cracks [Efe et al, 2012]. The fact that LSEM allows for the selection of values of shear strain independently from hydrostatic pressure implies flexibility in achieving desired material properties and physical integrity. This surprising effect is difficult to achieve in rolling or drawing where high strain is associated with high pressure and low strain is associated with low pressure. In fact, moderate strain and high pressure is generally needed in deformation processing that results in integral strips. This condition is possible in LSEM, but difficult in rolling and drawing. The SLF model, although for rigid-perfectly plastic materials, is consistent with simulations of the process by finite elements [Sevier et al, 2008] and direct measurements of shear strain from an analysis involving particle image velocimetry [Guo et al, 2012]. The predicted shear strain and pressure profiles should be applicable to elastic/strain hardening materials.

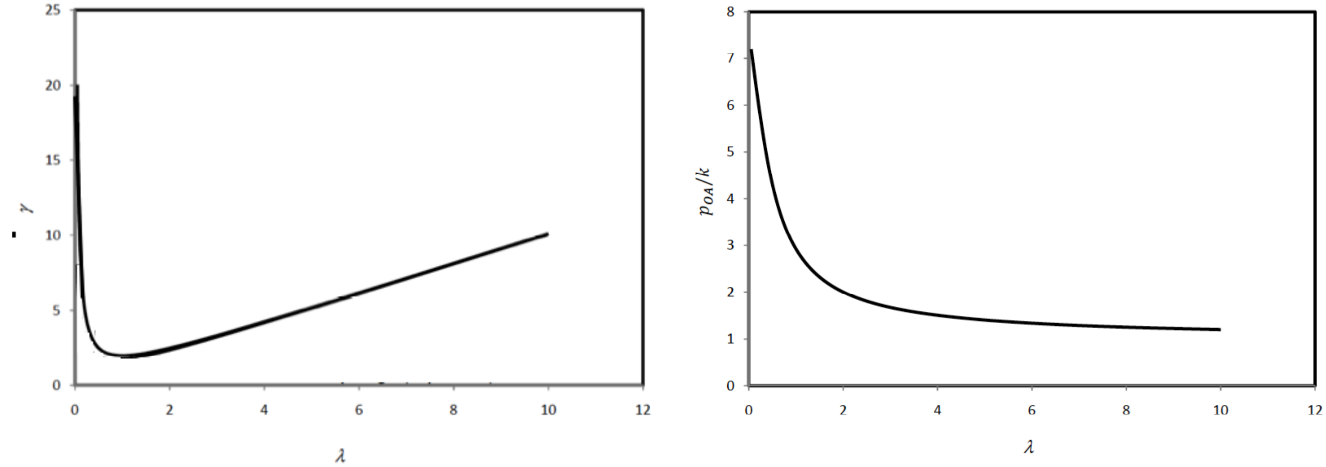


Figure 3. Variation of shear strain (*γ*) for a particle traversing fan OAC (Fig. 2) and hydrostatic pressure (p_{OA}/k) along line OA (Fig. 2) with chip compression ratio $\lambda = t_c/t$ for plane-strain LSEM.The calculations are based on Eqns. 2.2 and 2.3, with maximum friction along the tool rake face. $\alpha = 0°$.

3. EXPERIMENTAL DETAILS

The experiments presented in the next section involved the selection of a range of shear strains and hydrostatic pressures for the determination of conditions that produce integral AISI 1020 steel strips. This parametric study led to the determination of one condition that produced strips free from defects and cracks. The microstructure and hardness of this integral strip were then evaluated by optical microscopy and Vickers microindentation. The strip was evaluated for microstructure and hardness after processing by LSEM and after a subsequent heat treatment designed to bring the strip material back to pre-LSEM levels. This was performed to determine a condition that would result in strip properties similar to those of cold rolled steel AISI 1020. The "as-received" steel, cold rolled AISI 1020, had a Vickers hardness of ~126 Kg/mm^2 and a shear flow stress of ~175 MPa. This commercial alloy is typically in pearlitic form; showing ferritic grains intermixed with pearlitic regions composed of layers of ferrite and cementite. The alloy was selected because of its relatively high formability, when compared to other higher alloy steels.

Controlled shear strains ranging from ~1.5 (low) to ~3.5 (high) (Eqn. 2.2) and hydrostatic pressure ranging from ~250 MPa (low) to ~400 MPa (high) (Eqn. 2.3, with k = 175 MPa) were imposed using the schedule shown in Table 1. The physical appearance (integrity) of the resulting strip is also noted in the table. While all the LSEM experiments were performed at ambient temperature, the effect of temperature in the deformation zone with respect to strip physical appearance (integrity) was evaluated by changing the machining velocity (defined in Fig. 1) from 15 m/min to 60 m/min. The LSEM tool was made of high-speed steel and the machining was performed without any fluids.

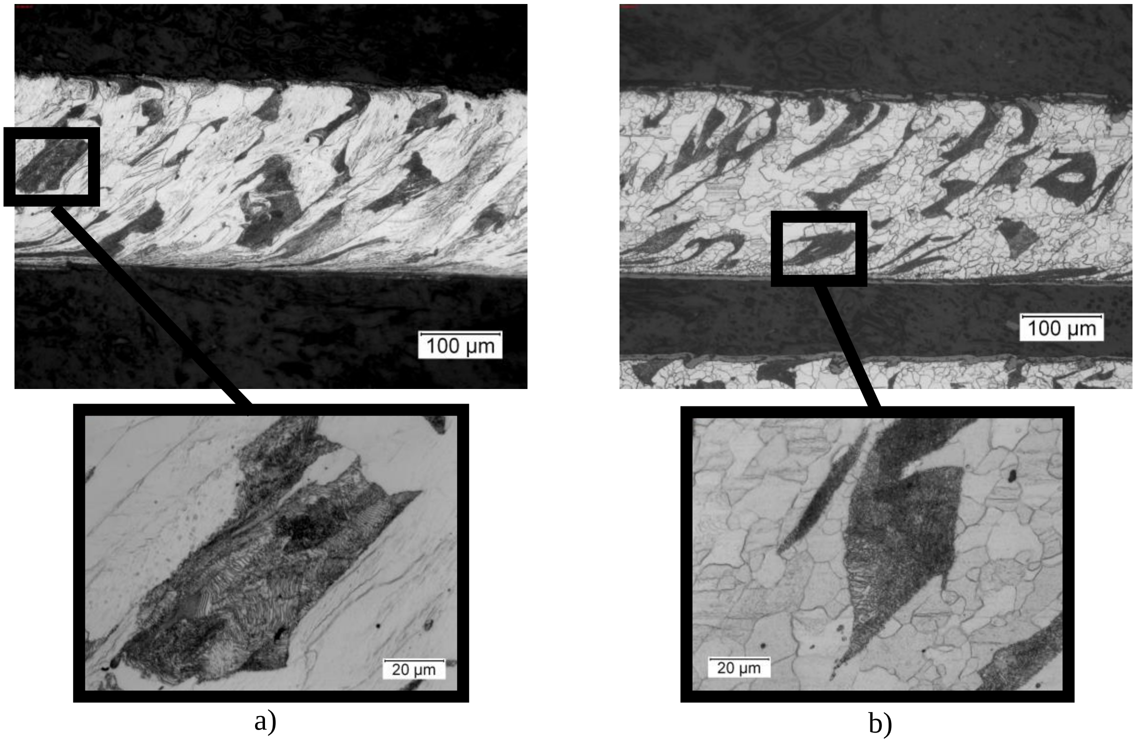
Table 1. Selected experimental conditions for the processing of AISI steel 1020 by LSEM.

Rake angle	Chip compression ratio	Undeformed chip thickness (mm)	Shear strain	Hydrostatic pressure	Machining velocity (m/min)	Strip appearance
20	4	0.03	High	Low	15	Serrated
	3	0.05	High	Low	15	Serrated
	4	0.08	High	Low	15	Serrated
	3.2	0.10	High	Low	15	Serrated
	4.5	0.25	High	Low	15	Heavily serrated
20	4	0.03	High	Low	60	Serrated
	3.5	0.05	High	Low	60	Serrated
	3.7	0.08	High	Low	60	Serrated
	2.6	0.10	High	Low	60	Serrated
	3.5	0.25	High	Low	60	Heavily serrated
5	1.5	0.10	Intermediate	High	15	Serrated
5	1.5	0.10	Intermediate	High	60	Continuous (crack free)

4. RESULTS

As can be observed from Table 1, the conditions that result in high shear strain but low hydrostatic pressure (chip compression ratios above 2, Fig. 3) also result in chip segmentation and lead to strips that show surface defects and cracks. It was not possible to try the same level of shear strain at higher hydrostatic pressure (by choosing chip compression ratios smaller than 1, Fig. 3) due to excessive tool wear. The use of harder tool materials to create conditions of high shear strain and high hydrostatic pressure will be part of future explorations. Conditions that were possible using the HSS tools, which resulted in strips free of defects or cracks, correspond to intermediate strain and high pressure (γ = 2 and p_{OA}/k = 2.3), at the higher machining velocity V = 60 m/min. The fact that a higher machining velocity (strip temperature) was required to produce integral strips should be viewed as positive, since higher machining velocity means higher strip production rate. The integral strip, before any post-processing is shown in Fig. 4. Note, also from Table 1, that as the undeformed chip thickness is reduced, there is a tendency towards integrity. Unlike rolling and drawing, LSEM makes the production of thin strips easier. This is because in LSEM, the required machining force and energy reduce with reductions in undeformed chip thickness and when the undeformed chip thickness is reduced, strip defects or cracks tend to disappear. In rolling and drawing, forces/energy and strip defects increase with decrease in strip thickness, since more processing steps are needed.

Figure 4. Steel 1020 strip produced by LSEM for γ = 2, p_{OA}/k = 2.5 and V= 60 m/min (before heat treatment). Thickness = 0.15 mm, width = 3 mm.



a) b)

Figure 5. Typical microstructure of AISI 1020 steel produced by LSEM. a) γ = 2, p_{OA}/k = 2.5 and b) γ = 2, p_{OA}/k = 2.5, followed by heat treatment @ 550 °C for 2 hours.

The microstructure of the strip made at the intermediate strain and high pressure (γ = 2 and p_{OA}/k = 2.3), before and after heat treatment @ 550°C for 2 hours, is shown in Fig. 5 (V = 60 m/min). Notice that microscale ferritic grains are observable using the optical microscope for both before and after the heat treatment. This implies that the deformation level imposed by the LSEM was not sufficient to refine the material crystals substantially. This result makes contrast with LSEM processing of copper and aluminum alloys, whose grains can be refined to the nano-scale level at this same shear strain level [Moscoso, 2008]. For this steel, the pearlite regions (Fig. 5) resemble those observable in the "as received" material. The ferritic grains before heat treatment appear elongated (with mean width ~10 µm), which is consistent with a structure having a relatively high concentration of dislocations. The ferritic grains after heat treatment appear re-crystalized (with mean diameter ~8 µm). These microstructures are consistent with the hardness data in Table 2, which show that the hardness of the strip material before heat treatment is ~1.7 times that after heat treatment. While the high hardness of the material right after processing by LSEM is associated with high strength, the ductility of the material is low, as evidenced by the fact that this strip will not bend past a few degrees before cracking. The low hardness of the material after the heat treatment is associated with low strength, but high ductility, also as evident after bending. The hardness of the LSEM strip material is almost twice that of cold rolled AISI 1020, but the hardness of the LSEM+heat treatment strip material is similar to that of cold rolled AISI 1020. Due to similarity with colled rolled steel, the LSEM+heat treatment strips may be suitable for concrete re-inforcement. It should be possible to produce the microstructure and properties of this heat-treated strip directly by LSEM, without any external heating, by increasing the machining velocity. This would require machine tool power higher than available at present and will be part of future explorations.

Table 2. Typical Vickers hardness and ferrite grain size of AISI steel 1020 processed by LSEM with and without post-process annealing.

Condition	Shear strain (γ) and hydrostatic pressure (p_{OA}/k)	Vickers hardness (Kg/mm^2)	% increase in hardness	Ferritic grain width (μm)
“As received” material		126		-
LSEM	2.0/2.3	240+/-5	68	10
LSEM + heat treatment @ 550 °C for 2 hours	2.0/2.3	141+/-5	0	8*

*Equiaxed.

5. CONCLUSIONS

It has been shown that LSEM is a process that can be used to produce, in one manufacturing step, integral steel strips having thicknesses smaller than 0.25 mm, which are essentially free of defects and cracks. The simplicity of the process may lead to substantial cost and energy reductions in the manufacturing of strips that are suitable for concrete reinforcement. The shear strain and hydrostatic pressure introduced by the process on the work material is controllable, and unlike in other methods such as rolling and drawing, can be set independently from each other in a single stage. The independent control of deformation and pressure in LSEM gives it flexibility to induce moderate strains and high pressures simultaneously, which are desirable for the processing of alloys that show limited formability, such as the steel tested. The applicable shear strain and hydrostatic pressure during the present work was limited by the hardness of the LSEM tools available. These limitations can be overcome by suitable choice of tool material, including carbides and diamond, and will be addressed in future work. AISI 1020 steel strips can be easily made at relatively high production rates of ~50 m/min by LSEM at ambient temperature. It was also shown that the end product can have mechanical properties similar to standard AISI 1020 after an appropriate heat treatment. It may be possible to obtain this result directly by LSEM, without any external heating, by processing at higher machining velocities. This will also be addressed in future work.

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