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A REVIEW OF ASSISTED / AUGMENTED MANUFACTURING PROCESSES

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ABSTRACT

Manufacturing has a history almost as long as the humankind, but as materials get more and more complex due to material science technology, manufacturing them becomes increasingly difficult. Using processes in combination has been a common practice. Similarly, using a simple process to aid a more complex process has often been employed. However, more advanced technologies have been developed to manufacture difficult-to-manufacture materials, as well as advanced auxiliary techniques to aid the main manufacturing process. In most of these processes, the aim is to improve the manufacturability of the part. Initial considerations to improve manufacturability were focused on being able to produce the part in ways aligning with the design. For example, in hot forging, it was not possible to achieve the right product without the aid of the secondary process (heating). As the manufacturing field evolved, needs of the industry changed to improving part quality and lowering manufacturing costs. Modern methods of assisting main manufacturing processes focus on ensuring (1) an extended use of the tool quantified by lower tool wear and higher tool life, (2) improved machine capabilities quantified by lower maintenance times and higher automation, (3) improved final product quality quantified by dimensional accuracy and surface, subsurface, and bulk material quality, and (4) increased sustainability of the process quantified by lower resource use such as machine power and lubrication. In this study, an overview of the use of assistance in manufacturing processes is provided. The review is focused on more modern techniques such as laser, electrical, magnetic field, and ultrasonic assistance, more modern materials that are difficult-to-manufacture such as hardened steels and titanium and nickel-based alloys, and on machining processes that are more imminent for the critical industries such as automotive, aerospace, energy production, and biomedical industries.

Keywords: Assisted manufacturing, Ultrasonic-assisted manufacturing, Electrically-assisted manufacturing, Magnetic field-assisted manufacturing, Laser-assisted manufacturing.

INTRODUCTION

As the needs of people evolve, new materials that have better properties in some aspect beneficial to the furthering of technology are discovered and invented. These materials become commonly used in critical industries that spearhead the development of modern technologies. Researchers try to improve the manufacturability of such materials through various types of analyses including experimentation and empirical, numerical, and analytical modeling, there are always limitations to machine and equipment capability. These limitations suggest that with the current machines and equipment, the current processes can only be improved to a certain point. Therefore, using multiple processes at once can be an effective method of improving process capability without the need for better technology machinery and equipment.

For this purpose, since using two processes at once in a hybrid manner is rather difficult, researchers have been developing auxiliary techniques that aid the main manufacturing process, improving the capability of the same. This way, implementation of the auxiliary technique does not significantly affect the setup of the main process, which is favorable from the point of view of the industry. Since big changes are not required to the whole system, critical industries can pick up these developments relatively quickly and without much risk of return of investment.

In light of this reasoning, the authors will first introduce the relevant materials of interest for the subject matter, and their common industrial uses. This way, the reader can be more informed about the rationale for such assisted processes. Then, the most common assisted processes will be detailed and the most recent developments will be presented, including the

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modeling and analysis efforts on those processes. These processes are thermally-assisted manufacturing (TAM), which is mostly observed as laser-assisted manufacturing (LAM), as well as electrically-assisted manufacturing (EAM), magnetic field-assisted manufacturing (MFAM), and ultrasonically-assisted manufacturing (UAM). Finally, conclusions will be drawn from the studied content and future directions will be suggested for the audience interested in improving assisted manufacturing. Since the intended target industries of such processes and this work utilize modern manufacturing methods more frequently, the main focus of this work has been selected as assisted machining processes, though advancements in other manufacturing processes are also presented.

MATERIALS OF INTEREST

Virtually any material is manufacturable through a process or another; however, the focus of this review is materials for parts that are (1) commonly manufactured using assisted manufacturing processes, and (2) essential to the aforementioned critical industries. Thermally-assisted manufacturing (TAM) has been shown to improve the manufacturability of difficult-to-manufacture materials such as titanium alloys, nickel-based super alloys, ceramics, tool steels, and metal matrix composites [1]. Most research in TAM has been conducted studying titanium, nickel-based alloys, and ceramics because of their useful properties and difficulty to machine compared to other materials. Electrically-assisted manufacturing (EAM) is known to alter the lattice structure of the material in a fashion that manufacturing the material becomes easier. Research on EAM has covered many materials ranging from salts to nickel-based alloys, but mostly focused on aluminum and steel materials [2]. Magnetic field-assisted manufacturing (MFAM) is a relatively new and underexploited field, but it has been shown that the use of magnetic field can be used to alter mechanical properties of the workpiece [3]. However, since the ferromagnetism, magnetostrictive strain, and magnetic saturation levels are critical for use of magnetic fields, material selection is quite limited. Many researchers used MFAM in manufacturing ceramics [4-5], while few researchers worked with mild steels [6-9]. Ultrasonically-assisted manufacturing (UAM) is similarly an underexplored method of using assistance, where ultrasonic waves are superimposed on the manufacturing zone to ease the process [10-12]. Since there are not many restrictions for using this method, researchers have explored the use of UAM on even the most difficult-to-manufacture materials such as titanium alloys and nickel-based alloys.

2.1 Brass, copper, ceramics, composites, and CFRP

Relatively simpler metals and metal alloys such as brass and copper were used by many researchers in understanding the electroplasticity effect before moving on to more advanced materials [14-19]. More advanced materials such as ceramics, composites, and carbon-fiber reinforced plastics (CFRP) were investigated with TAM [20-23], as well as MFAM [4-5] and UAM [24-27], mostly due to application-specific reasons. Particularly ceramics are known to be hard and brittle, which makes them very difficult to machine while incurring significant tool wear when machined conventionally [1, 20].

2.2 Aluminum and magnesium alloys

Aluminum and its alloys are relatively inexpensive and they still have a significant share in critical industries, so the use of EAM on Aluminum and its alloys was heavily studied [14-15,28-38], as well as with UAM [39-42]. Magnesium and its alloys are similarly inexpensive and lightweight, which is appealing for many of the critical industries, and EAM [43-44] and UAM [45] of a magnesium alloy AZ31B have been studied.

2.3 Steels and tool materials

Despite some of their advantages, many of these materials are either not heavily utilized in the critical industry, or they are not difficult to manufacture. However, when the level of material increases to steels, more imminent research is underway. Particularly with strengthened or hardened steels, assisted technologies can be extremely useful. For this reason, researchers have been heavily studying the assisted manufacturing of steels, with TAM [46-49], EAM [16,31,33,35,50-59], MFAM [6-9], and UAM [60-63]. Most common steel that was studied was tool steel, which indicates that efficient manufacture of tooling was targeted. Similarly, Ruszkiewicz and Mears studied the effect of EAM on tungsten carbide, a material commonly used to build cutting tools [64]. The amount and variety of work, as well as each method achieving notable improvements in manufacturing steel outlines why steel is an important material.

2.4 Titanium and nickel-based alloys

Although most of these materials heavily utilized in the critical industries, most of them have also been studied by researchers for a significant amount of time, and it is no longer considered difficult to machine most of these materials. Therefore, there is not much improvement that can be achieved using auxiliary techniques when manufacturing them. However, titanium and nickel-based alloys still pose a significant challenge to researchers in terms of the optimal ways to manufacture. Therefore, the main concentration and future direction suggestions of this work will be on titanium and nickel-based alloys.

Titanium alloys are used for components in aerospace and medical devices due to their excellent properties [65]. They have a high strength-to-weight ratio and they can keep their high strength and corrosion resistance properties at elevated temperatures, which make them excellent for high temperature applications. It is difficult to machine titanium alloys due to their low thermal conductivity and low modulus of elasticity. These properties result in high tool wear and poor surface finish that is caused by the high cutting temperatures and high vibration during machining [1]. Researchers have been conducting LAM experiments that resulted in increased tool life, increased material removal rate, and improved surface quality [66-70]. Similarly, titanium and its alloys have been somewhat popular in the EAM field as well. Researchers investigated tensile and compressive forming, incremental forming, micro-rolling, and machining of grade-2 and grade-5 titanium [36,71-74]. Spearheaded by a UK-based group, titanium and its alloys were also studied heavily using UAM [75-81].

Nickel-based superalloys such as Inconel 718 and Inconel 738 are used heavily particularly in the aerospace industry due to their high strength that does not drop significantly at elevated temperatures [65]. However, this superior property creates a problem when machining as it leads to high tool wear. However, researchers have found that using LAM to machine the nickel-based alloy Inconel 718 reduces cutting forces and tool wear while also improving surface quality and material removal rate [82-84]. The rare example of an investigation of EAM on nickel-based alloys is the electrically-assisted machining analysis conducted by Ulutan and colleagues [2], where the work using UAM is more pronounced and versatile [85-87], most likely due to the challenges of using electricity when machining nickel-based alloys.

ASSISTED / AUGMENTED PROCESSES

Using an external auxiliary process in assistance to the main manufacturing process of metals is not a new idea, but it is still a relatively under-explored territory. Mostly, what is targeted with any process is an increase in the general manufacturability of the metal, which can be in various forms including reduction in manufacturing difficulties (e.g. machining forces) or increasing the final product accuracy (e.g. reduced springback and increased dimensional accuracy). In the following sections, the processes, their use, advantages, disadvantages, benefits, and challenges will be discussed.

3.1 Thermally-Assisted Processes

One of the earliest adaptation of assisted manufacturing, particularly for machining applications, was thermally-assisted manufacturing (TAM), where the temperature of the manufacturing zone is increased using a heat source of some sort. The most common method to accomplish that is a laser beam, which is why TAM is usually referred to as laser-assisted manufacturing (LAM). Pfefferkorn and colleagues are among the pioneers in this research field with their work on measurement of surface temperatures during laser-assisted machining processes, where they investigated the potential increase in process efficiency and surface quality [23]. Use of LAM increases the temperature of the workpiece and decreases the strength of the material, therefore reducing machining forces, while increasing the material removal rate and decreasing the surface roughness as well as tool wear [1,66,68,83]. This increase in productivity is important when machining titanium and nickel-based alloys, ceramics, and other difficult-to-machine materials. Conventionally machining of such materials incurs high costs due to increased machining time, high tool wear, and low surface finish. Softening of the material is done by applying heat specifically to the area being machined and avoiding the unmachined material as to not change the microstructure. With TAM, a laser or plasma is used to heat the workpiece locally. The heating can be introduced as an auxiliary process to a variety of machining processes such as milling, turning, drilling, grinding, and burnishing [1]. Application of heat is different for each machining process. Heat energy that is applied to the material must be high enough to reduce the yield strength of the material but not melt the piece or change the microstructure of the unmachined material. It must also not be too high to avoid raising the tool temperature, therefore increasing tool wear. Due to structural differences, each material is affected by heat differently, and parameters of heat application vary with the choice of machining process.

LAM has been applied to improve machinability of many difficult-to-machine materials. The most common methods of machining using LAM to improve machinability are turning and milling. Research has been conducted to find the proper machine and laser position using these machining methods [66,68,82-84]. Implementing LAM with turning is common because the heat source can be used in conjunction with the cutting tool. In addition, turning process is simple compared to other machining methods. Parameters that affect the efficiency of LAM are the laser power, laser spot size, position, and the incident angle [1]. In general, the distance between laser and tool rake face improves cutting conditions, as it is the aim to heat the workpiece with sufficient proximity [66]. While doing this, it should be made sure that the tool is not heated nor there are loose chips, so the laser needs to be positioned with sufficient distance from the machining zone [66].

Milling using TAM is more difficult to accomplish because of the rotating tool, compared to turning that has a fixed tool. Laser can be attached to the spindle or arranged separately but it must lead the path of the tool, which is the fundamental requirement of the process. However, milling produces vibration because of the impact forces during repeated contact between the tool and the workpiece. LAM aids in reducing the vibration and improving the surface furnish of the material [1,70]. Results from research using milling are very limited due to the complicated setup required to implement laser assistance to the milling process.

Researchers also worked on modeling the TAM process to optimize machining and heat parameters for machining difficult-to-machine materials. After conducting experiments and a numerical analysis, researchers found that reducing the cutting forces by 40% is possible if cutting and laser parameters are selected at the optimal level [66]. Others investigated the effects of pulse duration, frequency, laser power, and laser beam diameter, and found that it is possible to simultaneously reduce cutting forces, tool wear, and surface roughness [82]. To better understand the behavior of TAM, researchers relied heavily on numerical analyses after verifying their models with experiments [1,66-67,69-70,88]. Yang and colleagues built a model to investigate the depth and width of the heat affected zone (HAZ) [67], choosing laser power, spot size, and travel speed as their parameters to investigate. They conducted a thermal-numerical simulation to find the shape, size, and temperature of the HAZ. They found that the HAZ decreases when the laser spot size and travel speed increases, but it is inversely related to laser power.

They also found that depth of the HAZ is smaller than its width, which must be taken into account when selecting cutting parameters.

3.2 Electrically-Assisted Processes

In electrically-assisted manufacturing (EAM), electricity is applied to the main manufacturing process to benefit from the electroplastic effect [89]. This effect is known to increase the deformation that the part can go through prior to failure, thus increasing the formability of the part [14]. Another benefit of the electroplastic effect is that it reduces the flow stress during plastic deformation, which means the load on the equipment and hence the power consumption during the process will both decrease [90]. This is particularly useful when the process is challenging to the equipment being used. Finally, electroplastic effect also reduces the springback effect in parts being deformed, essentially increasing the dimensional accuracy of the final product [28]. However, despite the many advantages to aiding the deformation of the part during manufacturing, this process is not heavily picked up by the industry due to its serious disadvantages. First and foremost, similar to any other application with electricity, the non-negligible risk of electrocution is a big issue [89]. Since most of the machinery is metallic as well as most of the parts, they conduct electricity quite well, which is difficult to deal with in terms of safety, though being beneficial in terms of the process [91]. Moreover, the basics of the process affects the applicability of electricity. When the workpiece is stationary (forging, turning), applying the electricity is relatively simpler. However, when the workpiece is moving (welding, milling), since the applicator of electricity needs to stay in constant contact with the workpiece to be able to close the electric circuit, potential crossing paths of the workpiece and the applicator must be considered and plugged into the design of the system. Finally, because most insulating materials such as nylons and rubbers are soft and brittle, choice of material becomes an issue as well [91].

Although not in manufacturing terms, effects of electricity on different materials have been studied for many decades. Studies initially started with understanding its effects on salts [92]. Work on its effects on metals was initiated almost a decade later when researchers worked on zinc, tin, lead, and indium [93]. They found that using electricity, particularly pulsed electricity, they can lower the flow stress of the metals, which helps with their manufacturability. Continuous charge of electricity, on the other hand, was found to increase recrystallization of some metals, during which the size of the grains also increased [94]. Initial thought was that Joule heating effect of electricity increased the temperature of metal, thus leading to its ease of manufacture. However, researchers showed later that there is much more to the effects of electricity than Joule heating [95]. Electric flow through a metal was found to be a reason for creation of some intermetallic bonds. It was also found that use of electricity, particularly when at a high-amplitude low-frequency manner (high current - short duration), increases the plasticity of the metal and forces some phase transformations where they should not occur [14-15].

Work on electrically-assisted manufacturing has sped up in recent years. Researchers were able to increase the formability of an aluminum workpiece by reducing the energy needed to uniaxially deform it and found that there was not much temperature rise on the material during this process [96]. This finding supports the hypothesis that Joule heating was not the source of improved manufacturability. Other researchers did similar tests either during uniaxial tension or compression [18,29.30,37-38,43-44,53,55,58,64,71,73-74], and found mostly supporting evidence that the force required to deform the material decreased, but tests were conflicting to show the increase and decrease in the total amount of deformation during the process, potentially due to the type of the process they used.

Accurately describing, modeling, and predicting the electroplastic effect on metals has not been successfully done yet. However, electroplastic effect is commonly said to have three results, where all of them contribute to the manufacturability of the metals [89]: (1) Due to the electrons running into the metal, and randomly scattering and moving around to increase the resistivity of the material, added electrons cause increased temperature that is different than the bulk temperature increase in the material. Therefore, materials that conduct electricity less (more resistive) undergo bigger changes in their structure due to more localized heating, so their formability increase more than those materials with less resistivity. (2) Some electrons fill in the voids in the lattice of the metal and are added to the metal's microstructure. These electrons decrease the bonding of the metal atoms by stealing electrons to form their own bonds, which makes the actual process easier to break the remaining metallic bonds. (3) While electrons are moving in one direction, they move the existing dislocation lines and create new lines that increases plastic deformation. This way, the workability of the metal can be enhanced. Due to the nature of this phenomenon, its effect is limited when the electric current is applied orthogonal to the dislocation lines, but it can be significant when the current is applied parallel to the dislocation lines. Therefore, if there is a process where dislocation happens, simultaneous addition of electric current in the same direction can help immensely in improving the manufacturability of the metal [89].

In addition to the theory of electroplasticity and electrically-assisted forming, researchers have also studied electrically-assisted machining processes. While some preferred turning and orthogonal machining due to the relative ease of setting up the system [51,97], others conducted studies on more complex machining processes that are more applicable to the industry such as drilling and friction stir welding [35,52,56], as well as milling [2]. The common denominator of these studies was that machining forces reduced when electric current was applied, making the machining operation easier. However, it was also observed that tool wear increased when electricity was turned on. Also, it was observed that when the current density increased more than a threshold level, machining forces increased to a level even higher than the tests where no electric current was used. Therefore, it was concluded that there is no simple answer to the decision of adding electricity to the machining process and further research needs to be conducted to be able to fully answer the unanswered questions.

There are not too many viable modeling efforts regarding EAM, most likely due to the fact that the process is not known sufficiently to construct mathematical models. However, researchers studied the effect of current density on machining forces and found that electric current has minimal effect if at all, before a certain threshold is reached [2,51]. However, after that threshold is exceeded, a stable reduction in machining forces was observed [97]. If a higher second threshold was reached, the benefits of EAM started to vanish, meaning the current density needs to be within a lower and a higher limit for the auxiliary process to be able to have a positive effect [2]. Also, further investigation of tool wear was suggested, since machining forces do not directly and solely imply manufacturability. However, it is possible that the second threshold in the tests were where the tool started to wear off, hence tool wear issue may be resolved together with the inflating machining forces.

3.3 Magnetic Field-Assisted Processes

In order to advance towards modern industrial applications, new processes with high efficiency, high quality of surface finishing, and reliability should be developed. Electrical discharge machining (EDM) is a widely used manufacturing method, where the ability to remove chips is limited [8]. Researchers were able to realize this suboptimality and they developed a technique to drive the machining debris away from the machining zone. They attached a magnetic force device which facilitated such a motion by magnetic abrasion, improving the stability of the EDM process by preventing debris accumulation on the machining zone. This is a good example of a magnetic field-assisted process, where the magnetic force itself is not contributing to the material removal but aids the main process by increasing its efficiency.

In order to establish a magnetic field in machining gap, researchers built a magnetic disk that rotates with planetary movement of the tool [9]. Four parallel ultrasonic transducers were employed to generate vibrations at 28 kHz frequency and up to 12 μm amplitude. The transducers were attached on a table where four magnets were attached to the tool holder. With this setup, they were able to achieve higher MRR that provided a smoother surface while using EDM on cold work steel under magnetic field assistance [9]. Lin and colleagues did a similar study and found that the electrode wear rate (EWR) during magnetic field- assisted EDM is reduced [8]. There is a scarcity of investigations on magnetic field-assisted manufacturing methods, which may be due to the limiting material selection constraints intrinsic to the process.

3.4 Ultrasonically-Assisted Processes

Ultrasonically-assisted manufacturing (UAM) is the addition of an ultrasonic shaker to the system where low-amplitude (5-20 μm) high-frequency (>20 kHz) vibrations are superimposed on the main process. Though ultrasonic assistance can be used for other processes, machining processes benefit significantly from an introduced ultrasonic assistance. During machining processes, particularly intermittent cutting, vibrations that are caused due to the impact forces are a concern. These vibrations cause instability of the system, and it may lead to issues such as chatter, or at the very least, part quality issues such as a rough surface or an inaccurate part dimension [80].

When ultrasonic assistance is introduced, cutting stability is significantly improved, cutting forces are reduced, and therefore tool life is improved [80]. The amplitude of ultrasonic waves is very small compared to feed and depth of cut. However, even a small reduction of chip load due to added vibrations helps the tool to cool down sufficiently. As a result, surface issues such as high surface roughness and tensile residual stresses are eliminated, in addition to reduced cutting temperatures. It was also found that, even with materials that are difficult-to-machine such as titanium and nickel-based alloys, UAM can reduce the surface defects such as deformation zone thickness, by way of reduced friction and thus reduced machining temperatures [10]. Moreover, UAM was found to aid reducing the surface roughness through improved chip formation. With UAM, it was found that built-up edge formation was minimized, improving the overall surface quality [10,61].

Ultrasonic assistance has virtually no limit in usage, which is why it has been applied to turning, drilling, and micro-milling [10,13,40,41,75-80,85-87]. Most UAM studies are based on assisted turning and drilling due to the amount of information that can be gathered and the ease of setting up compared to milling. However, it was observed within the investigated studies that all UAM methods employed resulted in improved process results with difficult-to-machine materials such as titanium and nickel-based alloys [61]. Particularly when machining such difficult-to-manufacture materials, UAM was found to reduce milling forces [62]. It was further found that as cutting speed increases, the benefits of UAM decrease, due to the reduction in the frequency of separation of tool and chip [80]. Since UAM allows the tool cutting edge to cool down for some duration during turning, higher maximum cutting temperatures can be achieved compared to conventional turning [81]. Researchers found that further increasing the cutting speed can be possible due to this decrease in maximum cutting temperature by utilizing UAM [80]. Other researchers found that in addition to the reduced effective stresses with increased cutting speed, using UAM further decreases those stresses, making the workpiece easier to manufacture [12]. UAM was also found to add aerodynamic lubrication when the tool is partially separated from the chip, which reduces friction and generation of built-up-edge [80]. Researchers also found that during UAM, the cutting form of the workpiece and the tool has changed making the overall surface look symmetrical and smooth, and the appearance looks to have more convex and concave grid compared to the conventional method where its appearance is irregular [43]. Some more details regarding ultrasonically-assisted processes and materials that have been investigated in the literature are provided in Table 1 and Table 2 for the convenience of the audience.

TABLE 1: SUMMARY OF ULTRASONICALLY-ASSISTED MANUFACTURING RESEARCH – MATERIALS

Material	Alloys	Reference
Aluminum	7075	39
	6061	40, 41,42
Magnesium	AZ31	45
Steel	420	60
	1045	61
	4340	62
	304	63
Titanium	Grade 2	13
	Ti-64	13,42,78,80,81
	Ti-15V-3Al-3Cr-3Sn	75,77,79
	Ti-6246, Ti-676-0.9La	76
Carbide	Tungsten Carbide	64
Nickel	Inconel 738-LC	85-86
	Inconel 718	87
CFRP	CFRP	24, 26, 27
Glass	BK7/K9 glass	25

TABLE 2: SUMMARY OF ULTRASONICALLY-ASSISTED MANUFACTURING RESEARCH - METHODS

Material	Method	Reference
Aluminum	Turning	39,40
	Micro-milling	41,42
Magnesium	Spray Deposition	45
Steel	Drilling	60
	Turning	61,62,63
Titanium	Drilling	13,78
	Turning	75-77,79,80,81
	Micro-milling	42
Nickel	Drilling	85, 86
	Turning	87
CFRP	Drilling	24, 26
	End milling	27
Glass	Rotary UM	25

CONCLUSIONS AND FUTURE DIRECTIONS

In light of the information gathered from literature, following conclusions were drawn:

- Assisted manufacturing techniques are still underexploited.
- Studies in laser-assisted manufacturing are the most advanced, but even with laser assistance, the dynamics of the process is not fully understood.
- Magnetic field-assisted processes are extremely limited due to the nature of the process.
- Electrically-assisted processes are promising in terms of their results. However, the risk that an industrial company needs to take in terms of safety of the workers and equipment as well as return of investment may not be favorable. Still, significantly more experiments and analyses need to be conducted to reach to final conclusions.
- Ultrasonically-assisted manufacturing has many benefits over all of the other processes, where the risk that needs to be taken is minimal, the process is inherently safe, setting up the system does not require a complete overhaul, and benefits are easily observable. Therefore, there is an imminent need in researchers working on understanding, analyzing, modeling, and improving ultrasonically-assisted manufacturing processes.

REFERENCES

[1] Sun, S., Brandt, M., Dargusch, M.S., 2010, “Thermally enhanced machining of hard-to-machine materials - a review,” International Journal of Machine Tools & Manufacture, pp. 663-680.

[2] Ulutan, D., Pleta, A., Mears, L., 2015, “Electrically-assisted machining of titanium alloy Ti-6Al-4V and nickel-based alloy IN-738: an investigation,” Proceedings of the ASME 2015 International Manufacturing Science and Engineering Conference (MSEC 2015), Vol.1: Processing, paper number MSEC2015-9465, pp. V001T02A013+5.

[3] El Mansori, M., Klamecki, B.E., 2006, “Magnetic field effects in machining processes and on manufactured part mechanical characteristics,” Journal of Manufacturing Science and Engineering, Transactions of the ASME, Vol. 128(1), pp. 136-145.

[4] Chang, C.P., Wu, K.L., Mai, C.C., Hsu, Y.S., Yan, B.H., 2010, “Magnetic field-assisted electrochemical discharge machining,” Journal of Micromechanics and Microengineering, Vol. 20, pp. 075019+07.

[5] Yamaguchi, H., Shinmura, T., 2004, “Internal finishing process for alumina ceramic components by a magnetic field assisted finishing process,” Precision Engineering, Vol. 28, pp. 135-142.

[6] Zou, Y., Shinmura, T., 2004, “A study on the magnetic field assisted machining process for internal finishing using a magnetic machining jig,” Key Engineering Materials, Vols. 257-258, pp. 505-510.

[7] El Mansori, M., Mkaddem, A., 2007, “Surface plastic deformation in dry cutting at magnetically assisted machining,” Surface & Coatings Technology, Vol. 202, pp. 1118-1122.

[8] Lin, Y.C., Chen, Y.F., Wang, D.A., Lee, H.S., 2009, “Optimization of machining parameters in magnetic force assisted EDM based on Taguchi method,” Journal of Materials Processing Technology, Vol. 209, pp. 3374-3383.

[9] Teimouri, R., Baseri, H., 2013, “Experimental study of rotary magnetic field-assisted dry EDM with ultrasonic vibration of workpiece,” International Journal of Advanced Manufacturing Technology, Vol. 67, pp. 1371-1384.

[10] Kuşhan, M.C., Orak, S., Uzunonat, Y., 2017, “Ultrasonic assisted machining methods: a review,” International

Journal of Advanced Engineering Research and Applications, Vol. 3(5), pp. 294-302.

[11] Brehl, D.E., Dow, T.A., 2008, "Review of vibration-assisted machining," Precision Engineering, Vol. 32, pp. 153-172.

[12] Naresh Kumar, M., Kanmani Subbu, S., Vamsi Krishna, P., Venugopal, A., 2014, "Vibration assisted conventional and advanced machining: a review," Procedia Engineering, Vol. 97, pp. 1577-1586.

[13] Singh R., Khamba, J.S., 2006, "Ultrasonic machining of titanium and its alloys: a review," Journal of Materials Processing Technology, Vol. 173, pp. 125-135.

[14] Conrad, H., 2000, "Electroplasticity in metals and ceramics," Materials Science and Engineering A, Vol. 287 (2), pp. 276-287.

[15] Conrad, H., 2000, "Effects of electric current on solid state phase transformations in metals," Materials Science and Engineering A, Vol. 287, pp. 227-237.

[16] Conrad, H., 1989, "A study into the mechanism(s) for the electroplastic effect in metals and its application to metalworking, processing and fatigue," Final Report to US Army Research Office, ARO Proposal Number 23090-MS.

[17] Dzialo, C.M., Siopis, M.S., Kinsey, B.L., Weinmann, K.J., 2010, "Effect of current density and zinc content during electrical-assisted forming of copper alloys," CIRP Annals – Manufacturing Technology, Vol. 59, pp. 299-302.

[18] Fan, R., Magargee, J., Hu, P., Cao, J., 2013, "Influence of grain size and grain boundaries on the thermal and mechanical behavior of 70/30 brass under electrically-assisted deformation," Materials Science and Engineering A, Vol. 574, pp. 218-225.

[19] Jordan, A., Kinsey, B., 2015, "Investigation of thermal and mechanical effects during electrically-assisted microbending," Journal of Materials Processing Technology, Vol. 221, pp. 1-12.

[20] Samant, A.N., Dahotre, N.B., 2009, "Laser machining of structural ceramics - a review," Journal of the European Ceramic Society, Vol. 29, pp. 969-993.

[21] Shanmugam, N., Yu, X., Alkotami, H., Devin, G., Lei, S., 2016, "Machining of transparent brittle material assisted by laser-induced seed cracks," Proceedings of the ASME 2016 International Manufacturing Science and Engineering Conference (MSEC 2016), Vol. 1: Processing, paper number MSEC2016-8734, pp. V001T02A019+7.

[22] Park, S.S., Wei, Y., Jin, X.L., 2018, "Direct laser assisted machining with a sapphire tool for bulk metallic glass," CIRP Annals – Manufacturing Technology, Vol. 67, pp. 193-196.

[23] Pfefferkorn, F.E., Rozzi, J.C., Incropera, F.P., Shin, Y.C., 1997, "Surface temperature measurement in laser-assisted machining processes," Experimental Heat Transfer, Vol. 10, pp. 291-313.

[24] Fernando, P.K.S.C., Pei, Z., Zhang, M., Song, X., 2016, "Rotary ultrasonic drilling of CFRP: effect of process parameters on delamination," Proceedings of the ASME 2016 International Manufacturing Science and Engineering Conference (MSEC 2016), Vol. 1: Processing, paper number MSEC2016-8611, pp. V001T02A017+6.

[25] Hu, Y., Wang, H., Ning, F., Cong, W., Li., Y., 2017, "Surface grinding of optical BK7/K9 glass using rotary ultrasonic machining: an experimental study," Proceedings of the ASME 2017 International Manufacturing Science and Engineering Conference (MSEC 2017), Vol. 1: Processing, paper number MSEC2017-2780, pp. V001T02A014+7.

[26] Fernando, P.K.S.C., Zhang, M., Pei, Z., Cong, W., 2017, "Rotary ultrasonic machining: effects of tool end angle on delamination of CFRP drilling," Proceedings of the ASME 2017 International Manufacturing Science and Engineering Conference (MSEC 2017), Vol. 1: Processing, paper number MSEC2017-2863, pp. V001T02A015+6.

[27] Nor Farah Huda, A.H., Ascroft, H., Barnes, S., 2016, "Machinability study of ultrasonic assisted machining (UAM) of carbon fibre reinforced plastic (CFRP) with multifaceted tool," Procedia CIRP, Vol. 46, pp. 488-491.

[28] Adams, D.W., 2013, "Improvements on single point incremental forming through electrically assisted forming, contact area prediction and tool development," PhD thesis, Queens University, Kingston, ON, Canada.

[29] Bunget, C., Salandro, W.A., Mears, L., Roth, J.T., 2010, "Energy-based modeling of an electrically-assisted forging process," Transactions of the North American Manufacturing Research Institute of SME (NAMRC), Vol. 38, pp. 647-654.

[30] Bunget, C., Salandro, W.A., Mears, L., 2010, "Tribological aspects in electrically-assisted forming," Proceedings of the ASME 2010 International Manufacturing Science and Engineering Conference (MSEC 2010), Vol. 1, paper number MSEC2010-34249, pp. 723-730.

[31] Sanchez Egea, A.J., González Rojas, H.A., Celentano, D.J., Travieso-Rodríguez, J.A., Llumà i Fuentes, J., 2014, "Electroplasticity- assisted bottom bending process," Journal of Materials Processing Technology, Vol. 214, pp. 2261-2267.

[32] Green, C.R., McNeal, T.A., Roth, J.T., 2009, "Springback elimination for Al-6111 alloys using electrically-assisted manufacturing (EAM)," Transactions of the North American Manufacturing Research Institute of SME (NAMRC), Vol. 37, pp. 403-410.

[33] Hameed, S., González Rojas, H.A., Sánchez Egea, A.J., Napoles Alberro, A., 2016, "Electroplastic cutting influence on power consumption during drilling process," International Journal of Advanced Manufacturing Technology, Vol. 87, pp. 1835-1841.

[34] Kim, M.J., Lee, M.G., Hariharan, K., Hong, S.T., Choi, I.S., Kim, D., Oh, K.H., Han, H.N., 2017, "Electric current-assisted deformation behavior of Al-Mg-Si alloy under uniaxial tension," International Journal of Plasticity, Vol. 94, pp. 148-170.

[35] Liu, X., Lan, S., Ni, J., 2015, "Electrically assisted friction stir welding for joining Al 6061 to TRIP 780 steel," Journal of Materials Processing Technology, Vol. 219, 112-123.

[36] Ng, M.K., Fan, Z., Cao, R.X., Smith III, E.F., Cao, J., 2014, "Characterization of electrically-assisted micro-rolling for surface texturing using embedded sensor," CIRP Annals – Manufacturing Technology, Vol. 63, pp. 269-272.

[37] Roh, J.H., Seo, J.J., Hong, S.T., Kim, M.J., Han, H.N., Roth, J.T., 2014, "The mechanical behavior of 5052-H32 aluminum alloys under a pulsed electric current," International Journal of Plasticity, Vol. 58, pp. 84-99.

[38] Salandro, W.A., Roth, J.T., 2009, "Formation of 5052 aluminum channels using electrically-assisted manufacturing (EAM)," Proceedings of the ASME 2009 International Manufacturing Science and Engineering Conference (MSEC 2009), Vol. 1, paper number MSEC2009-84117, pp. 599-608.

[39] Sajjady, S.A., Hossein Abadi, H.N., Amini, S., Nosouhi, R., 2016, "Analytical and experimental study of topography of surface texture in ultrasonic vibration assisted turning," Materials and Design, Vol. 93, pp. 311-323.

[40] Jamshidi, H., Nategh, M.J., 2013. Theoretical and experimental investigation of the frictional behavior of the tool-chip interface in ultrasonic-vibration assisted turning," International Journal of Machine Tools & Manufacture, Vol. 65, pp. 1-7.

[41] Lian, H., Guo, Z., Huang, Z., Tang, Y., Song, J., 2013, Experimental research of Al6061 on ultrasonic vibration assisted micro-milling," Procedia CIRP, Vol. 6, pp. 561-564.

[42] Xu, L-h., Na, H-b., Han, G-c., 2018, "Machinability improvement with ultrasonic vibration-assisted micro-milling," Advances in Vibration Control of Structures and Machinery, Vol. 10(12), pp. 1-12.

[43] Jones, J.J., Mears, L., Roth, J.T., 2010, "Empirical modeling of the stress-strain relationship for an upsetting process under direct electrical current," Transactions of the North American Manufacturing Research Institute of SME (NAMRC), Vol. 38.

[44] McNeal, T.A., Beers, J.A., Roth, J.T., 2009, "The Microstructural effects on magnesium alloy AZ31B-O while undergoing an electrically-assisted manufacturing process," Proceedings of the ASME 2009 International Manufacturing Science and Engineering Conference (MSEC 2009), Vol. 1, paper number MSEC2009-84377, pp. 641-650.

[45] Bastwros, M., Kim, G.Y., 2016, "Fabrication of custom pattern reinforced AZ31 multilayer composite using ultrasonic spray deposition," Proceedings of the ASME 2016 International Manufacturing Science and Engineering Conference (MSEC 2016), Vol. 1: Processing, paper number MSEC2016-8605, pp. V001T02A016+10.

[46] Germain, G., Dal Santo, P., Lebrun, J.L., 2011, "Comprehension of chip formation in laser assisted machining,' International Journal of Machine Tools and Manufacture, Vol. 51, pp. 230-238.

[47] Melkote, S., Kumar, M., Hashimoto, F., Lahoti, G., 2009, "Laser assisted micro-milling of hard-to-machine materials," CIRP Annals – Manufacturing Technology, Vol. 58, pp. 45-48.

[48] Tagliaferri, F., Leopardi, G., Semmler, U., Kuhl, M., Palumbo, B., 2013, "Study of the influences of laser parameters on laser assisted machining processes," Procedia CIRP, Vol. 8, pp. 170-175.

[49] Karmakar, D.P., Gopinath, M., Nath, A.K., 2017, "Effect of tempering temperature on hardness and microstructure of laser surface remelt ed AISI H13 tool steel," Proceedings of the ASME 2017 International Manufacturing Science and Engineering Conference (MSEC 2017), Vol. 1: Processing, paper number MSEC2017-3014, pp. V001T02A019+5.

[50] Jones, J.J., Mears, L., 2010, "A process comparison of simple stretch-forming using both conventional and electrically-assisted forming techniques," Proceedings of the ASME 2010 International Manufacturing Science and Engineering Conference (MSEC 2010), Vol. 1, paper number MSEC2010-34144, pp. 623-631.

[51] Jones, E., Jones, J.J., Mears, L., 2013, "Empirical modeling of direct electric current effect on machining cutting force," Proceedings of the ASME 2013 International Manufacturing Science and Engineering Conference (MSEC 2013), Vol. 1, paper number MSEC2013-1229, pp. V001T01A059+7.

[52] Karumatt, N.G., Ruszkiewicz, B.J., Mears, L., 2017, "Electrically assisted drilling of USIBOR 1500 boron steel and its implications for electrically assisted machining," Proceedings of the ASME 2017 International Manufacturing Science and Engineering Conference (MSEC 2017), Vol. 1, paper number MSEC2017-3046, pp. V001T02A020+7.

[53] Kim, Yeom, K.H., Thien, N.T., Hong, S.T., Min, B.K., Oh, S.I., Kim, M.J., Han, H.N., Lee, H.W., 2014, "Electrically assisted blanking using the electroplasticity of ultra-high strength metal alloys," CIRP Annals – Manufacturing Technology, Vol. 63, pp. 273-276.

[54] Kinsey, Cullen, G., Jordan, A., Mates, S., 2013, "Investigation of electroplastic effect at high deformation rates for 304SS and Ti-6Al-4V," CIRP Annals – Manufacturing Technology, Vol. 62, 279-282.

[55] Mai, J., Peng, L., Lin, Z., Lain, X., 2011, "Experimental study of electrical resistivity and flow stress of stainless steel 316L in electroplastic deformation," Materials Science and Engineering A, Vol. 528, pp. 3539-3544.

[56] Ruszkiewicz, B., Akhavan Niaki, F., Mears, L., Gendreau, E., 2017, "An investigation of electroplastic drilling of mild steel," Proceedings of the ASME 2017 International Manufacturing Science and Engineering Conference (MSEC 2017), Vol. 1, paper number MSEC2017-2766, pp. V001T02A013+14.

[57] Tang, G., Zhang, J., Zheng, M., Zhang, J., Fang, W., Li, Q., 2000, "Experimental study of electroplastic effect on stainless steel wire 304L," Materials Science and Engineering A, Vol. 281, pp. 263-267.

[58] Xie, H., Dong, X., Liu, K., Ai, Z., Peng, F., Wang, Q., Chen, F., Wang, J., 2015, "Experimental investigation on electroplastic effect of DP980 advanced high strength steel," Materials Science and Engineering A, Vol. 637, pp. 23-28.

[59] Ruszkiewicz, B.J., Gendreau, E., Akhavan Niaki, F., Mears, L., 2018, "Electroplastic drilling of low- and high-strength steels," Journal of Manufacturing Science and Engineering, Vol. 140, pp. 061017+14.

[60] Vakili Azghandi, B., Kadivar, M.A., Razfar, M.R., 2016, "An experimental study on cutting forces in ultrasonic assisted drilling," Procedia CIRP, Vol. 46, pp. 563-566.

[61] Celaya, A., López de Lacalle, L.N., Campa, F.J., Lamikiz, A., 2010, "Ultrasonic assisted turning of mild steels," International Journal of Materials and Product Technology, Vol. 37(1/2), pp. 60-70.

[62] Sharma, V., Pandey, P.M., 2016, "Study of ultrasonic assisted turning of 4340 steel with plane and self-lubricating cutting inserts," Proceedings of the ASME 2016 International Manufacturing Science and Engineering Conference (MSEC 2016), Vol. 1: Processing, paper number MSEC2016-8565, pp. V001T02A015+9.

[63] Zou, P., Xu, Y., He, Y., Chen, M., Wu, H., 2015, "Experimental investigation of ultrasonic vibration assisted turning of 304 austenitic stainless steel," Shock and Vibration, Vol. 2015, pp. 1-19.

[64] Ruszkiewicz, B.J., Mears, L., 2016, "Electrically assisted compression of tungsten carbide and its implications for electrically assisted machining," Proceedings of the ASME 2016 International Manufacturing Science and Engineering Conference (MSEC 2016), Vol. 1: Processing, paper number MSEC2016-8554, pp. V001T02A013+5.

[65] Ulutan, D., Özel, T., 2011, "Machining induced surface integrity in titanium and nickel alloys: a review," International Journal of Machine Tools and Manufacture, Vol. 51, pp. 250-280.

[66] Ayed, Y., Germain, G., Ben Salem, W., Hamdi, H., 2014, "Experimental and numerical study of laser-assisted machining of Ti6Al4V titanium alloy," Finite Elements in Analysis and Design, Vol. 92, pp. 72-79.

[67] Yang, J., Sun, S., Brandt, M. Yan, W., 2010, "Experimental investigation on 3D finite element prediction of the heat affected zone during laser assisted machining of Ti6Al4V alloy," Journal of Materials Processing Technology, Vol. 210, pp. 2215-2222.

[68] Bermingham, M. J., Palanisamy, S., Dargusch, M.S., 2012, "Understanding the tool wear mechanism during thermally assisted machining Ti-6Al-4V," International Journal of Machine Tools & Manufacture, Vol. 62, pp. 76-87.

[69] Joshi, A., Kansara, N., Das, S., Kuppan, P., Venkatesan, K., 2014, "A Study of Temperature Distribution for Laser Assisted Machining of Ti-6Al-4V Alloy," Procedia Engineering, Vol. 97, pp. 1466-1473.

[70] Liu, C., Shi, Y., 2014, "Modelling and Simulation of Laser Assisted Milling Process of Titanium Alloy," Procedia CIRP, Vol. 24, pp. 134-139.

[71] Bunget, C.J., Salandro, W.A., Mears, L., 2013, "Thermomechanical modeling sensitivity analysis of electrically assisted forming," Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, Vol. 227(8), pp. 1089-1098.

[72] Honarpisheh, M., Abdolhoseini, M.J., Amini, S., 2016, "Experimental and numerical investigation of the hot incremental forming of Ti-6Al-4V sheet using electrical current," International Journal of Advanced Manufacturing Technology, Vol. 83, pp. 2027-2037.

[73] Magargee, J., Morestin, F., Cao, J., 2013, "Characterization of flow stress for commercially pure titanium subjected to electrically assisted deformation," Journal of Engineering Materials and Technology, Vol. 135, pp. 041003+10.

[74] Salandro, W.A., Bunget, C.J., Mears, L., 2011, "Several factors affecting the electroplastic effect during an electrically-assisted forming process," Journal of Manufacturing Science and Engineering, Vol. 133, pp. 064503+5.

[75] Maurotto, A., Muhammad, R., Roy, A., Silberschmidt, V., 2013, "Enhanced ultrasonically assisted turning of a β-titanium alloy," Ultrasonics, Vol. 53(7), pp.1242-1250.

[76] Muhammad, R., Hussain, M.S., Maurotto, A., Siemers, C., Roy, A., Silberschmidt, V.V., 2014, "Analysis of a free machining α+β titanium alloy using conventional and ultrasonically assisted turning," Journal of Materials Processing Technology, Vol. 214, pp. 906-915.

[77] Muhammad, R., Maurotto, A., Roy, A., Silberschmidt, V.V., 2012, "Hot ultrasonically assisted turning of β-Ti alloy," Procedia CIRP, Vol. 1, pp. 336-341.

[78] Pujama. J., Rivero, A., Celaya, A., López de Lacalle, L.N., 2009, "Analysis of ultrasonic-assisted drilling of Ti6Al4V," International Journal of Machine Tools and Manufacture, Vol. 49, pp. 500-508.

[79] Maurotto, A., Roy, A., Babitsky, V.I., Silberschmidt, V.V., 2010, "Recent developments in ultrasonically assisted machining of advanced alloys," Proceedings of 4th CIRP International Conference on High Performance Cutting.

[80] Patil, S., Joshi, S., Tewari, A., Joshi, S.S., 2014, "Modelling and simulation of effect of ultrasonic vibrations on machining of Ti6Al4V," Ultrasonics, Vol. 54, pp. 694-705.

[81] Cakir, F.H., Gurgen, S., Sofuoglu, M.A., Celik, O.N., Kushan, M.C., 2015, "Finite element modeling of ultrasonic assisted turning of Ti6Al4V alloy," Procedia – Social and Behavioral Sciences, Vol. 195, pp. 2839-2848.

[82] Tadavani, S.A., Razavi, S.R., Vafaei, R., 2017, "Pulsed laser-assisted machining of Inconel 718 superalloy," Optics & Laser Technology, Vol. 87, pp. 72-78.

[83] Venkatesan, K., 2017, "The study on force, surface integrity, tool life and chip on laser assisted machining of Inconel 718 using Nd:YAG laser source," Journal of Advanced Research, Vol. 8, pp. 407-423.

[84] García Navas, V., Arriola, I., Gonzalo, O., Leunda, J., 2013, "Mechanisms involved in the improvement of

Inconel 718 machinability by laser assisted machining (LAM)," International Journal of Machine Tools & Manufacture, Vol. 74, pp. 19-28.

[85] Azarhoushang, B., Akbari, J., 2007, "Ultrasonic-assisted drilling of Inconel 738-LC," International Journal of Machine Tools & Manufacture, Vol. 47, pp. 1027-1033.

[86] Baghlani, V., Mehbudi, P., Akbari, J., Sohrabi, M., 2013, "Ultrasonic assisted deep drilling of Inconel 738LC superalloy," Procedia CIRP, Vol. 6, pp. 571-576.

[87] Nath, C., Rahman, M., 2008, "Effect of machining parameters in ultrasonic vibration cutting," International Journal of Machine Tools & Manufacture, Vol. 48, pp. 965-974.

[88] Anderson, M., Patwa, R., Shin, Y.C., 2006, "Laser-assisted machining of Inconel 718 with an economic analysis," International Journal of Machine Tools & Manufacture, Vol. 46, pp. 1879-1891.

[89] Salandro, W., Jones, J., Bunget, C., Mears, L., Roth, J., 2015, "Introduction to Electrically Assisted Forming," in Salandro, W. et al., eds, Electrically Assisted Forming – Modeling and Control, First Edition, Springer International Publishing.

[90] Molotskii, M.I., 2000, "Theoretical basis for electro- and magnetoplasticity," Materials Science and Engineering A: Structural Materials Properties Microstructure and Processing, Vol. 287, pp. 248-258.

[91] Ruszkiewicz, B.J., Grimm, T., Ragai, I., Mears, L., Roth, J.T., 2017, "A review of electrically-assisted manufacturing with emphasis on modeling and understanding of the electroplastic effect," Journal of Manufacturing Science and Engineering, Vol. 139(11), pp. 110801+15.

[92] Machlin, E.S., 1959, "Applied voltage and the plastic properties of 'brittle' rock salt," Journal of Applied Physics, Vol. 30(7), pp. 1109-1110.

[93] Troitskii, O.A., 1969, "Electromechanical effect in metals," ZhETF Pis. Red., Vol. 10(1), pp. 18-22.

[94] Xu, Z.S., Lai, Z.H., Chen, Y.X., 1988, "Effect of electric current on the recrystallization behavior of cold worked α-Ti," Scripta Metallurgica, Vol. 22(2), pp. 187-190.

[95] Conrad, H., Okazaki, K., 1979, "A study of the electroplastic effect in metals," Final Report to Air Force Office of Scientific Research (AFSC). AFOSR Grant Number 77-3203.

[96] Andrawes, J.S., Kronenberger, T.J., Perkins, T.A., Roth, J.T., Warley, R.L., 2007, "Effects of DC current on the mechanical behavior of AlMg1SiCu," Materials and Manufacturing Processes, Vol. 22(1), pp. 91-101.

[97] Sánchez Egea, A.J., González Rohas, H.A., Montilla Montaña, C.A., Kallewaard Echeverri, V., 2015, "Effect of electroplastic cutting on the manufacturing process and surface properties," Journal of Materials Processing Technology, Vol. 222, pp. 327-334.