Strategic Approach to Develop Solutions for Shaping Complex Workpieces of Exotic Materials

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Abstract. Exotic materials such as hardened steel and tungsten carbide tool steel have unique resistance and properties that make them hard-to-cut. Thus, research to find better ways to process such materials requires an innovative approach and new ideas. Therefore, the present study investigates the design of a novel WDEM combined with robotic machining to overcome limitations of traditional robotic machining. Wire EDM (WEDM) stands out as a non-traditional machining process able to cut complex profiles of hard-to-cut materials, achieving high dimensional accuracy and superior surface finishing. Unfortunately, WEDM is designed in rigid bed-based CNC machines which restrict design freedom in terms of size, shape and features due to machining envelope constraint. On the other hand, traditional machining processes such as drilling and milling using six-axis industrial robots have been investigated and some applications have successfully delivered cost efficiency, improved envelope and high flexibility. However, due to the structure and strength of the robot arm, accuracy, repeatability and finishing are not comparable to CNC machining outcomes. These researches are also restricted by the power of the robot arm holding the machining tool. This paper explores, identifies and selects suitable configurations and define research actions that must be taken to achieve a highly flexible, accurate machining system for exotic materials.

1. Introduction
The term exotic materials refer to superalloys, ceramics, reinforced plastics, semiconductors, and superconductors. Their application includes cutting tools [1], aerospace, automotive, military applications, medical equipment and bio-implants [2]. However, exotic materials properties are characterised by poor thermal conductivity, high toughness, ultra-hardness, and extremely high work hardening behaviour that combined will place exotic materials under the category of hard-to-cut materials [3].

To machine hard-to-cut materials, conventional processes need to be replaced by electro-discharge machining (EDM). EDM removes electrically conductive material by gradually melting and evaporating portions of the workpiece surface. A series of high-frequency discharges in the dielectric fluid between a conductive workpiece and an electrode by generated heat [4]. In EDM, there are no physical cutting forces between the electrode and the workpiece, avoiding mechanical stresses, chatter and vibrations [5].

EDM machines are numerically controlled. However, CNC machines are characterised by limited working space that often leads the workpiece to be segmented and processed in multiple stages, resulting in deterioration of dimensional precision with a substantial increase in costs and working time [6]. This characteristic makes it difficult to machine complex shapes on EDM. By following EDM
principles, a variant process called Wired EDM (WEDM) is found. WEDM cuts the surrounding contours of the workpiece by feeding a wire-electrode that moves as a band saw [7]. To control the wire path, WEDM is configured on computer numerically controlled (CNC) machines. In CNC context, most of the literature has focused on analysing WEDM over different materials at different process conditions [8] usually looking for less surface roughness (SR) or increased material removal rate (MRR) [9].

On the other hand, advantages in 6-axis Industrial Robotic arms (IR) are widely recognised and have been successfully used to replace many manufacturing techniques [10]. IRs with conventional machining tools have many advantages over CNC machines and has attracted significant research interest aiming cost-efficiency, flexibility, design, a multi-functionality [11]. However, IR machining has been severely limited, and most of the current research aims to overcome IR machining problems often originated from lack of IR stiffness and machining vibration [12].

The present research aims to investigate the feasibility of combining EDM with IR to produce complex-shaped workpieces on exotic materials. The research is organised as follows. Section 2 describes the study procedures. Section 3 presents the results and analysis of each field. In section 4, the combination results are presented and discussed; lately, section 5 is the conclusion.

### 2. Research methodology

To find answers, a systematic review of a two-stage is adopted [13]. Stage 1 search focused on literature in English language from 2009 to 2019. The databases were chosen considering affinity with the subjects of WEDM (1st research axis) and IR machining (2nd research axis), including Springer Link, Science Direct, Scopus, Web of Science, IEEE Xplore, and Google Scholar engine. Stage 2 search focused on industry articles, patents, and reports not include within the academic repositories [14]. To find appropriate keywords, the Web of Science database was first searched, looking for published texts, using the preliminary keywords in Table 1. After reading the titles and abstracts of the ten most cited papers, it was noticed that other strings were better aligned with the research, resulting in a final list of keywords in Table 2.

| Table 1. Preliminary research strings |
|--------------------------------------|
| WEDM | IR machining |
| Exotic material | Machining |
| Electric discharge | Robotic |
| Hard to cut | Hard to cut |
| Wired EDM | |

| Table 2. Final research strings |
|---------------------------------|
| WEDM | IR machining |
| Exotic material | 6 axis robot |
| Hard to cut material | Industrial robot |
| Electric discharge | Wire cut |
| Wired EDM | Machining |
| High-speed WEDM | Grinding |

In the 1st research axis (i.e. WEDM), the first selection round resulted in 596 samples. Next, with restriction to each subject, parsing duplicates and categorisation, the sample resulted in 135 contributions. Lately, each paper was reviewed twice. The first review intent to compose the list of criteria that will judge and the second round selects the final literature. Additionally, the references were analysed and papers with potential contributions, not detected in the previous samples, were included in the final review round. The final selected literature on WEDM research axis was shortened to 94 samples. By following the same steps of the 1st research axis, for the 2nd research axis on IR machining, the literature was first screened to 485 papers, next to 108, and finally to 42 samples.

### 3. WEDM research outcomes and discussion

The literature on WEDM was categorised as a new Method, Process, or a Tool (MPT).
According to Figure 1, new methods and processes optimisation are prominent research fields in WEDM, while new methods are the typical outcome summing 58% of works. However, as in Figure 2, research is mostly process-related, being frequently limited to propose new approaches to optimise or predict WEDM processes parameters based on single or multi-response optimisation [15]. Hence, the derivative research for optimal process parametrisation is the majority and trend of publication, suggesting that new ways to increase process efficiency are necessary. By analysing the use of tools, it was observed that innovative tools are only 9% of research. Moreover, research innovations often focus on wire or dielectric composition, with few exceptions on taper angle and real-time process control, the later, also focusing on process parameters. Therefore, it is possible to suggest that the current literature lacks tools that can improve WEDM application.

In Figure 2, a breakdown of the literature objectives shown that nearly 85% of studies focus on MRR, SR. Regarding simulations, several methods have been identified as able to predict processes with 90 – 95% accuracy [16] thus, suggesting a high level of maturity with fewer research opportunities. Except for Micro-WEDM [17] and taper angle issues [18], no research was found focusing on dimensional accuracy. Therefore, is possible to suggest that conventional WEDM is delivering sufficient accuracy for straight cutting; however, the design is still limited by CNC constraints, and current solutions deliver reduced shape and accuracy [18, 19].

Regarding wire advances, higher performance wires rely on complex shaping and rare metals resulting in high-cost, damage to the wire chopper, straightness issues [20]. On the other hand, the evolution of pure brass wire to core brass-alloys next added with reduced Zinc content in coating alloys provides enhanced cooling and flushability and core brass wires persist as the best trade-off for cost, cut speed, surface roughness, and endurance [21]. As a solution to the high wire cost, an increasing interest in high-speed WEDM (HS-WEDM) is noticed. However, in HS-WEDM, when the MRR is near to 150 mm³/min, the workpiece surface presents burns and frequent wire breakage [22].

The common ways to improving MRR and SR are cooled fluids [23] or additives [24], also flushing combined with ultrasonic field [4]. To solve surface burning, a new dielectric fluid with higher vapourisation point was developed for HS-WEDM with increased MRR of 330 mm³/min, under higher average current of 15A and stable machining [22]. Concerning to ultrasonic combination, the principle behind the wire electrode activated with ultrasonic is to reduce or even eliminate the undesired effects of the electromagnetic field, resulting in higher dimensional and shape accuracy [25]. Regarding flush operation, the ultrasonic field helps to cope with the effects of gravity when the wire is working on non-vertical straight cutting [26], therefore, useful to improve design freedom, higher MRR and improved SR [25].

Lately, all found patents refer to wire development while only one journal article is directly related to the industry where a CNC machine is improved, and advantages argued on taper angle, increased workpiece thickness, and automatic wiring [19]. This distribution, combined with Figure 2 suggests that research focusing on new tools rather than processes parameters may be more relevant to the current industry needs.

4. IR research outcomes and discussion

Regarding IR machining, the criteria adopted to select the final literature sample were new MPTs.
As in Figure 3, IR machining is a growing research field, while new methods are the most frequent topic (50%), followed by new tools (31%) and new processes (19%). Besides, it was found that nearly all publications keep aiming to improve stiffness and suppress machining vibration [11]. However, as in Figure 4, solving the lack of stiffness and machining vibration are ways to improve IR machining accuracy. Since substantial research exist aiming to compensate errors, it is implied that the lack of stiffness and machining vibrations are problems not solved. Meanwhile, few studies were found focusing on machining efficiency in terms of MRR or SR [6]. On the contrary, improvements of MRR and SR are secondary effects observed when vibration, stiffness and simulation are managed [27], thus, suggesting that new ways to solve IR limitations must be achieved upon efficiency. As in Figure 4, the main approaches to improve IR machining can be found in four groups. The first and more common relies on simulations that allow offline programming [28] to convert 3D workpiece into cutting program [29] and avoid trajectory collision as well as IR singularities [30]. Hence, simulations deliver robot pose for maximised stiffness and embedded error compensation tailored for IR model and manufacturer [31].

5. Combination results and discussion

To identify feasibility, advantages and limitations, for both, WEDM and IR, the strengths and weakness were extracted and combined in Table 3, resulting in four scenario-quadrants.

Table 3. Combination matrix of IR & WEDM

| Strengths | Weakness | Wire EDM in CNC machines |
|-----------|----------|---------------------------|
| +IR1. Large envelope | -WE1. Low MRR | IR machining of hard-to-cut materials, higher accuracy, larger envelop, easier path programming, sensing processes, no vibration and stiffness problems. |
| +IR2. Design freedom | -WE2. Low design freedom | IR strengths & WEDM weakness: Same MRR, increased design freedom, flexible configuration, easier sensing, and similar wire cost. |
| +IR3. Path programming | -WE3. Limited envelope | Definition of strengths and weaknesses for EDM. |
| +IR4. Easier sensing | -WE4. Expensive wire usage | Definition of strengths and weaknesses for EDM. |
| WE1. High accuracy | +WE1. High accuracy | Definition of strengths and weaknesses for EDM. |
| WE2. High SR quality | +WE2. High SR quality | Definition of strengths and weaknesses for EDM. |
| WE3. Hard to cut material | +WE3. Hard to cut material | Definition of strengths and weaknesses for EDM. |
| WE4. No vibration or forces | +WE4. No vibration or forces | Definition of strengths and weaknesses for EDM. |

Due to the combined strengths, the resulting process should achieve improved design freedom, enlarged machining envelops, and flexible processes configurations potentially assisted by IR cut programming as well as sensing applied for WEDM parameters. Another two quadrants on weakness and strengths reveal some risks and many symbioses. One could argue in certain WEDM dimensional degradation; however, this conclusion is not straightforward. As most of IR dimensional error is
originated by conventional machining forces and vibration, the WEDM characteristic of non-contact and nearly zero forces shall improve IR precision machining into a level yet to be confirmed, since a few papers have quantified machining error sources coming from the IR exclusively. For WEDM, kinematics is recognised as a critical process parameter; thus, adapting WEDM into an IR shall enable electrode movement with superior smoothness and SR. As a risk, the WEDM feeding system is complex and potentially heavy to act as an EE. In this sense, a possible solution is to adopt HS-WEDM type that reuses the wire and thus, presents more possibilities to be reconfigured in a lighter design and yet deliver reduced costs for WEDM. Lately, since many weaknesses on WEDM are amended by IR and vice versa, most combinations do not necessarily result in deteriorated outcomes. For instance, low MRR of WEDM is prone not to be improved by IR; however, the low MRR will demand to the IR a low level of speed, which is desirable since high speed is a source of IR dimensional error.

6. Conclusion
By analysing the strengths and limitations of IR machining and WEDM, a combination was investigated, and possible outputs were identified. One of the key findings is that no previous studies have focused on combining WEDM into an IR. Lately, the results confirm that the combination is potentially feasible, and several problems found in IR machining are expected to be dramatically reduced by WEDM combination. Future research to this work is to design a new WEDM end effector, by leverage and adapt existing methods and tools associated with IR machining and WEDM to develop a hybrid approach that aligns those two fields with a specific focus on hard-to-cut metals.

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