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# Fundamental aspects and recent developments in metal surface polishing with energy beam irradiation

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ABSTRACT

Energy beam polishing technologies have revolutionised the metal surface precision finishing procedure of various materials owing to their specific capability to provide non-contact, selective, and automated polishing processes; further, these technologies help enhance the mechanical properties of the materials. However, the inadequate understanding of the fundamental mechanism of the energy beam finishing process may limit the practical application of such technologies. Furthermore, to cope with the rapid development in various technologies associated with energy beam surface finishing, there is a strong requirement for researchers to highlight the current obstacles and predict promising trends. In this review paper, the main benefits and characteristics of energy beam surface finishing are first summarised. The various parameters that influence the energy beam finishing results are then discussed. For different metallic materials, the experiment parameters are not very identical; therefore, the discussions will be conducted in a sequence. The surface roughness level that can be obtained for the assigned material is considered a key aspect for evaluating the finishing effect, and the variation in mechanical property is considered as a supplement. We also review the fundamental evolution of the energy beam finishing models, existing applications in various fields, and limitations that stand in the way of satisfying industry requirements. The paper will be concluded by introducing the future development trends in energy beam surface finishing technologies, for instance, the large-area and short-time finishing, which play a decisive role on whether the current research can be applied for factory production and provide economic benefits.

## 1. Introduction

The application of energy beam technologies such as laser beam, electron beam, ion beam, and plasma beam in the field of metal surface finishing has attracted increasing attention from scholars globally. As already known, the removal procedure of metallic materials is widely applied in various industries to obtain sophisticated products. The conventional removal mechanism of metal surface depends on the mechanical strength of the tool to surmount the resistance of the coarse surface [1,2]. The brittleness and wear resistance of a few metals will bring difficulties to the application of mechanical polishing, and a few flammable metallic dust particles generated during the friction process may produce potential safety hazards [3,4]. As for the chemical and electrochemical polishing technologies, the original products become smooth by dissolving the surface peaks, during which the material removal rates are primarily dependent on the working distances of electrical potential and uniformity of chemical agents [5,6]. For complex geometries, inconsistent surfaces may be produced due to variations in the working distance/internal cavities or the stagnation of fluid flow caused by certain features [7]. Additionally, these parts must be immersed in polishing solutions, ineluctably restricting the processing of large components [8]. Hence, developing new finishing technologies to improve these circumstances is highly required. Back in the 1970s, Lester et al. [9] made use of a low-energy ion beam to polish metal surfaces. However, this technology had not been well developed at that time until Draper et al. [10] were affected by the laser fused silica polishing experiment conducted in 1982 [11]; the micro-melting research on metal surface was then studied the following year. After that, electron beam and plasma beam joined the field of metal surface finishing, and these techniques are continuously being redefined, expanded, and tailored to requirements. These technologies have revolutionised the surface finishing procedure of metallic materials by smoothing the surfaces via melting and evaporation rather than removal.

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From the perspective of technology performance, energy beam surface treatments, which have been researched back in the early 1960s [12–14], refer to the technologies that use high energy density sources to irradiate or inject the materials for transforming the composition and structure of the treated surface. For conventional metal surface treatments, the reinforcement of the physico-chemical properties may be regarded as the most important purpose. However, these surface technologies can produce modified layers of up to several millimetres in depth, resulting in significant variations in the microstructure of the bulk material. Although further post-processing such as heat treatments can be adopted to mitigate the negative effects, these surface technologies still have difficulties of meeting polishing requirements [15]. Quite to the contrary, the energy beam finishing technology has obvious differences from the conventional energy beam machining patterns consisting of quenching, cladding, and alloying. This polishing method has high requirements for the surface morphology, depth of material removal, and modified layer thickness, rather than the chemical and mechanical properties [16–18]. Hence, energy beams have been extensively investigated to satisfy the surface polishing demands. Ramos et al. [19] conducted $CO_2$ laser polishing experiments (spot diameter = 0.35 ± 0.05 mm) and obtained the arithmetic average roughness value (i.e. Ra) using an automated profilometer device. The Ra value increased from ~0.82 to 1.13 μm to ~2.56–4.18 μm as the laser power was reduced from 420 W to 220 W. Kim et al. [20] presented that under the same experimental conditions, the thickness of the modified layer obtained by the pulsed electron beam (PEB) process could be controlled within a few microns, while the thickness of the modified layer gained by the continuous electron beam (CEB) process was over 100 μm.

Because the energy beam surface machining is a novel concept that complex shapes of various metallic materials can be polished by non-contact automation, this technology has attracted researchers in a wide range of areas such as aerospace, biomedicine, and manufacturing. For instance, in the die and mould industry, semi-finished products should be polished as the final procedure [1], and their finishing processes generally require expert labourers [21,22]. However, companies all over Europe are struggling to recruit an adequate number of experienced workers [23], and it is difficult to carry out repeatable quantitative machining processes by manual polishing. High energy density beam, which is an efficient choice to achieve surface roughness in a few nanometres to tens of nanometre range [24,25], brings the possibility of providing finishing processes without being limited by human resource insufficiency. There are also other advantages of the newest energy beam finishing techniques: scrapless machining, no micro-crack formation, mechanical reinforcement, high precision, and selective and automated processing [1,17,26,27]. Meanwhile, the specific demands of diverse industries for different materials are promoting the progress of this technology. Additive manufacturing, also known as three-dimensional (3D) printing, has helped to advance the interest and investment in energy beam polishing to some extent [17,28]. Although additive manufacturing has gained great popularity owing to its superiority in fabricating components with complex 3D geometry [29], it is not capable of controlling the surface appearance at the microscale level [6]. The 3D-printed parts would not satisfy the operation requirements due to rough surfaces. Lamikiz et al. [30] used laser irradiation to attain the surface polishing of parts produced by selective laser sintering in 2006. To improve the efficiency, Yasa et al. [31] proposed a laser remelting polishing method, which entails re-scanning of the upper layer before putting a new layer of powder, or re-scanning the outer skin of the part behind finishing the last layer. Consequently, the investment of energy beam polishing has been facilitated by the motivation of receiving 3D-printed parts that conform to the surface quality requirements.

The further breakthrough of the energy beam finishing technology is closely related to relevant factors such as technology selection, processing adjustment, simulation optimisation, and application demands. As shown in Fig. 1, these energy beam technologies provide new methods for metal surface finishing and are continually optimised to promote their industrial application. However, energy beam polishing technologies remain less competitive in the actual application market, and the investment in basic research on these technologies from various manufacturers is extremely limited (the dashed lines in the figure indicate that they have not been fully realised). With the increasing demand from various industries and the rapid development in technology, energy beam finishing technologies have been greatly promoted, and these technologies are in the key phase of large-scale adoption. In this review paper, the fundamentals and obstacles of the energy beam metal surface finishing technologies are summarised. The review of available important discoveries and feasible expansion capacities will be of great benefit to researchers in related fields. The rest of this article will start with the presentation of the basic mechanism of energy beam finishing technologies. The protection measures and the processing strategies of these technologies are then introduced in Section 2. The evolution of the energy beam finishing processes and their polishing effects (e.g. surface roughness, specular reflectance, corrosion resistance, wear resistance, hardness, elastic modulus, fatigue strength, wettability, and releasability of moulded resin) achieved at different stages are discussed in Section 3. The development of the energy beam metal finishing modelling technology is reviewed in Section 4 as a serviceable supplement to the empirical experiments. After that, in Section 5, the paper will sum up not only the capacities afforded by the application of energy beam finishing processes in the fields of aerospace, biomedicine, and manufacturing, but also the limitations of the current technologies. Finally, a discussion of feasible future trends and the conclusions are presented in Section 6.

## 2. Background of energy beam metal finishing technologies

The basic principles of energy beam metal finishing technologies are presented in this section. Other information on energy beam polishing techniques can be referred to previous overviews [32,33]. According to the heat source, energy beam techniques can be divided into laser beam, electron beam, ion beam, and plasma beam. To clearly demonstrate the differences between these technologies, the basic mechanism of each energy beam will be introduced accordingly. Furthermore, studies on the energy beam protection measures and their tool processing strategies may further expand their technical capabilities, thereby accelerating the industrialisation of energy beam polishing technologies [34]. Therefore, these two aspects will also be presented.

### *2.1. Fundamentals of laser beam metal finishing*

#### *2.1.1. Mechanism of laser beam metal finishing*

Laser beam polishing is the leader in the adoption of remelting to smooth metal surfaces with high energy density beams, although it was studied approximately 10 years later than ion beam metal surface polishing [9,10,26,35]. According to the lasing medium, lasers can be divided into gas laser, solid laser, liquid laser, and semiconductor laser. The high-power $CO_2$ gas laser and Nd:YAG solid laser were the lasers used in the very beginning [36,37]; the new type of semiconductor laser then emerged in the early 21st century [38]. Irrespective of the laser selected, the laser metal polishing process includes the following phenomena: the laser beam energy radiates to the workpiece surface producing an extremely shallow molten pool, and the liquid phase is driven to move away from the convex peaks and flow into the gullies by surface tension. Ultimately, a glossy metal surface could be obtained [39]. An illustration of the laser beam finishing is shown in Fig. 2. Compared with other energy beams having only an approximate Gaussian intensity distribution, laser beams exhibit their superiority in the aspect of providing both Gaussian and top-hat intensity distribution. For a Gaussian heat source, the intensity at the central region of the beam is much greater than that at the edge of the irradiated region, and this inhomogeneous intensity distribution appears to be less efficient in