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Review

Causes of failure and repairing options for dies and molds: A review

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ABSTRACT

The life of industrial dies and molds can be efficaciously increased by timely repair of damaged surfaces. The degree and severity of damages of these vital production tools depend on the service conditions and requisite precision in shape and size of dies and molds. The failure analysis of these damaged surfaces is important for the selection of most appropriate process and processing parameters leading to longer mean time between failures. This paper comprehensively depicts the global scenario of the dies and mold industries, various materials used for manufacturing of dies and molds, their modes of failures under different duty conditions and various repairing options. The global market of dies and molds is more than a hundred billion US dollars with wide spread in BRIC nations, European Union and North America. Various designations of tool steels with/without surface treatment and aluminum alloys are used for the manufacturing of dies and molds. The major causes of failures during operations are due to high thermal shocks, mechanical strain, cyclic loading and corrosion resulting in heat checking, wear, plastic deformation and fatigue. Other cause failures are due to faulty design, defective material, mishandling and force majeure due to accidental conditions. These issues are traditionally repaired using gas tungsten arc welding, electro-spark and cold spray technique depending on the material. Laser, electron beam and micro-welding are recent repairing options attractive mainly due to low heat input and controlled material deposition. The comprehensive study presented in this paper is relevant to the die and mold repairing industries and will assist the selection of the most appropriate process depending upon the availability of resources with thorough knowledge of the advantages and limitations.

Contents

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1. Introduction

Dies and molds are widely used for mass production of plastic parts, die cast components, sheet metal components, shape formed components and forged products. The key position of dies and molds in mass production are primarily due to globalization and demand for a continuous competitive improvement in terms of increasing their complexities and reduction in mold cost. The scenario is further compressed in time scale due to shorter delivery period, shrinking time to market and particularity of one-of-a-kind production. The need of die and mold repairing is originated by design and/or manufacturing errors, material defects, plastic deformation and wear. The design, manufacturing and material defects pops up during the earlier part of die and mold life. Later, it is mainly due to plastic deformation, wear and combination of both. The combination of plastic deformation and wear leads to various surface defects, like-surface cracks, dig, scratches, broken and blunt edges. The frequency and magnitude of repair is mainly governed by requisite tolerances on the product. As the die and mold industries are more than 100 years old, there have been numerous attempts to repair these manufacturing tools. The availability of high power machines (like-lasers, electron beam, plasma sources etc.) integrated with precise manipulators (like- robots, multi-axis workstation etc.) has changed the very basic idea of die and mold repairing. This paper consolidates the discrete information and ratiocinates an integrated picture of global scenario of the dies and mold industries, various materials used for manufacturing of dies and molds, their modes of failures under different duty conditions and various repairing options in niche specialty area of dies and mold. It also prognostics the repairing trend in the die and mold industries for the immediate future.

2. Global scenerio

The estimated global market for small and medium enterprises (SME's) all over the world is more than \$120 billion. The changes in global manufacturing scenario are directly affecting the die and mold industries. The total sales of US in 2010 has been reported as US \$11.7 billion as compared to that of US \$13.35 billion in 2006, witnessing a drop of about 15% within a time span of 4 years and about 36% between 1998 and 2010. Moreover, China's die and mold industry association indicated that the sales revenue of dies and molds for the year of 2010 amounted to about US \$17 billion with more than 30,000 mold manufacturers, employing about one million people. China also claimed in its 12th 5-year plan for the die and mold industry to grow up to \$26 billion by 2015 [1]. Wall Street Journal reported this change of guard as "US toolmakers withstood growing competitions from lower cost foreign producers for years. But China's sudden emergence as a manufacturing power house and an unbeatable pricing opponent has them reeling" [2]. The shift of the die and mold manufacturing from developed nations to developing nations is mainly due to availability of low wage workers, competitive environment and shifting of major automobile manufacturing companies. Also frequent design changes, multiple trials and exchanging complex information hinders boundaries of the dies and mold makers to stay in close proximity to their parent companies. The recent statistics shows the growth of the die and mold sector in China, India, Thailand and Japan was about 15% per year during the last decade. In which, India alone is expected to reach INR 236 billion (US\$ 4.7 billion) by the end of 2015 amounting to a growth of about 15% in the next 5 years [3].

Traditionally, dies and molds are customized to produce the improved products with advanced features leading to extended life. The precision and accuracy of these dies and molds are important as they impart these attributes to the products during the processing. Therefore, the manufacturers are forced to invest high value in the production of complex and long-lasting dies and molds. These dies/molds undergo a large number of local impacts, cyclic loading, thermal stresses and corrosion affecting their life significantly. Problems, like worn-out geometries, plastic deformation or dimensional instability and surface cracks, appear sometimes within few working cycles during introduction phase leading to premature failure. On the contrary, many times they take several thousand cycles leading to failure at maturity. Life of dies and molds depends upon various factors such as quality of design, appropriate material selection, right manufacturing, correct heat treatment and designed operating conditions [4]. Due to above described problems, dies and molds loose the accuracy, size and shape at critical locations resulting in products out of shape and tolerances. As downtime equals lost profit in industrial economics, one of the two options: stand-by system and quick-repairing mechanism are only the possible solutions [5]. The high cost of dies and molds due to costly materials with higher precision in manufacturing make the quick-repairing mechanism as only economically viable solution [6,7]. This has encouraged the development of various dies and mold repairing techniques.

3. Die and mold materials and their failures

The selection of the die and mold materials is an important decision in the production of precise components, as appropriate selection of materials is imperative to get acceptable life of dies and molds at reasonable cost. There are two important

Table 1
Various materials used in die and mold industries.

Material designation AISI	Material composition	Industry and end application	Ref.
H10	0.4%C, 0.3%Mn, 3.25%Cr, 2.5%Mo, 0.4%V	Brass extrusion	[9]
D2	1.5%C, 0.4%Mn, 12%Cr, 0.95%Mo	Medical product packing strip	[10–13]
O1	0.9%C, 1.15%Mn, 0.5%Cr, 0.5%W	Cutting die used for making car racks	[14]
H13	0.35%C, 0.3%Mn, 5.1%Cr, 1.5%Mo, 1%V	Brass window handles, brass gas valves	[15–27]
D3	2.2%C, 0.35%Mn, 12%Cr	AISI-1008 carbon steel blank	[28,29]
P20	0.35%C, 0.3%Mn, 1.7%Cr, 0.4%Mo	Forming fixture	[7,30]

criteria for the selection of materials for dies and molds. A first criterion is from the design point of view where ductility, toughness, fatigue strength, wear resistance and corrosion resistance are important. The second is from the manufacturing point of view, where hardness, machinability, polishability and dimensional stability are the prime concerns. Tool steel is one of the most widely used die and mold material. Classification of tool steel provided according to AISI (American Iron and Steel Institute) standards are well known and widely followed in the industries. While wide range of tool steel materials are available, the most popular and commonly used classes of defined standards are hot work tool steel (H series), cold work tool Steels (D series), plastic mold tool steels (P series), shock resistance (S series), special purpose (L series), and water hardening (W series) [8]. As it is not possible to select a single material with maximum wear resistance, resistance to softening at elevated temperatures and toughness for all the applications, there is always a trade-off for material selection considering the various applications. Table 1 presents the various materials used in the dies and mold industries.

Various materials subjected to different service conditions leads to different type of failure of dies and molds. In general, die and mold are said to be failed when their performance deteriorates due to changes in shape, dimensions and material properties leading to unsatisfactory functioning. The causes of failure reported in the literature can be categorized as catastrophic, manufacturing and operational defects [7]. Fig. 1 depicts the classification of the causes of failure for dies and molds.

The catastrophic failure of dies and molds are attributed to faulty design, force majeure, improper storage and mishandling during transportation. Faulty design is one of the important aspects leading to catastrophic failure. It can be avoided by taking extra care while designing sharp corners, notches and sudden change in cross section which can lead in increase of high contact pressure and negatively affect fatigue behavior and surface wear [5,31,32]. Use of computer based design and analysis programs can ensure perfection in specific design of such tools. The prediction of die damage mechanism through the simulation played a vital role to avoid premature failures [13,33]. Force majeure causes the failure due to unpredictable unwarranted events that happens during the operation of dies and molds. These events include the failure of primary supplies (like-water, electricity etc.) and natural disasters (like-earth quake, flood etc.). Many times the dies and molds failure just takes place due to improper storage during the lean time of the manufacturing. Improper location of storage may cause of chemical reactions due to other stored items/consumables leading to oxidation/corrosion of surfaces of dies and molds. Improper handling during transportation of dies from one station to another may cause damage to the dies and molds. These errors can accidently occur due to extreme thermal shock, extreme mechanical strain, operators fault and errors during transportation or mishandling. It is reported that inappropriate applications of such dies results in 62% reduction its

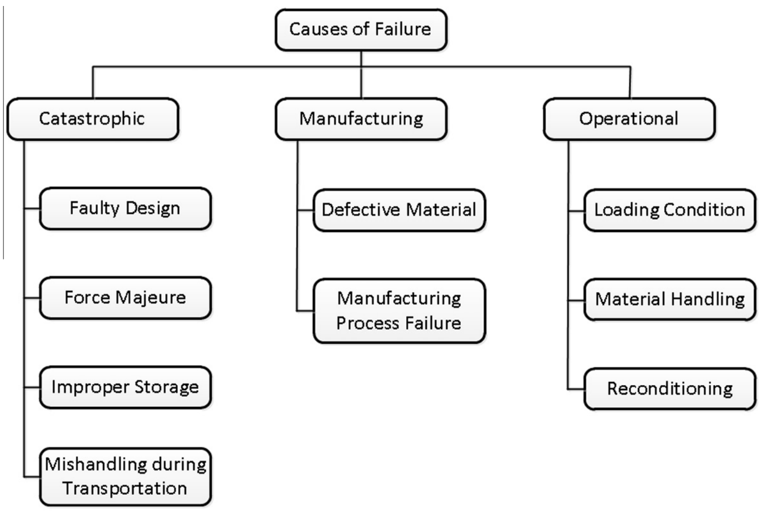

Fig. 1. Classification of the causes of failure for dies and molds.

performance in case of cold working dies [34]. Most of the time, the mishandling further exaggerates wear and tear leading to premature failure of dies and molds.

Manufacturing failures are occurred due to non-conformity of specified material and manufacturing process. Though the material procured was as per the desired specification, the fault during post-machining processes also caused the failure of dies and molds. Post machining heat treatment and other finishing operations like surface grinding and electro-discharge machining are critical because tool steels are susceptible for cracking during these operations. An improper heat treatment causes inferior toughness and low fatigue strength. Furthermore, misalignment in such case may exaggerate the stress state produced during operation of die and mold leading to its failure [35]. Improper grinding particularly lack of lubrication during grinding may also lead to the formation of small hairline cracks in a wider area [14]. Therefore, to ensure accurate functioning, dies and molds should undergo critical in-process quality-checks after various manufacturing and heat treatment cycles. The rate of quenching and heat treating environment majorly affects the microstructure produced after heat treatment in order to maintain adequate hardness matrix. All of these metallurgical properties are important for longer life of dies and molds. Therefore, it is very crucial to develop user friendly database for the shop floors particularly for material matrix, heat treatment and surface treatment related to particular application [10]. The manufacturing of dies and molds are still challenging in many cases, though there is the availability of multi-axes machines and the latest software for manufacturing of dies and molds. Improper direction of machining due to lack of accessibility or time-saving approach leading to uneven and unusual stress pattern leads to failure of dies and molds.

Operational failures are the leading causes for failure of dies and molds. In most of the cases the mechanism of failure (heat checking, mechanical fatigue, wear or plastic deformation) are related to their applications (hot working, cold working and plastic parts manufacturing). Hot working dies are more prone to cracks, thermal fatigue, plastic deformation and corrosion due to its additional application of repetitive heating and cooling cycles apart from general mechanical loading. On the contrary, the cold working dies usually fail due to impact loading and initiation of fatigue cracks at stress concentrated areas [36]. However, with the availability of finite element modeling and analysis approach, a prior estimation of plastic deforma-

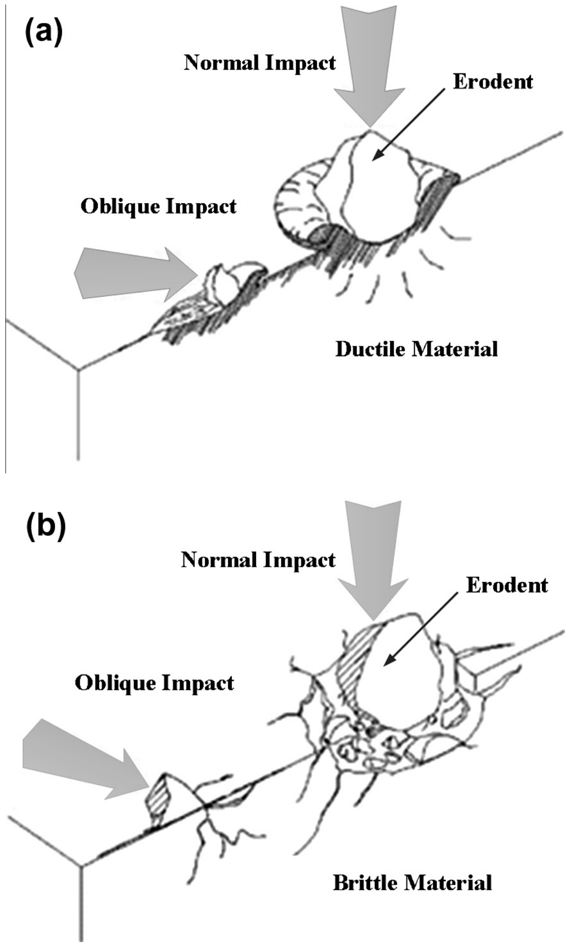

Fig. 2. Modes of erosion wear (a) on ductile materials and (b) on brittle materials [38].

tion and wear can be made. Such estimations are proven to be helpful for making a judgment about selection of work-piece/die material, die shape, operating speed and temperature [11,37]. A detailed study about all the above are also discussed in subsequent sections of this paper focusing on its relevance in die/mold life. Wear is the most obvious and prominent phenomenon that occurs due to the interactions of two or more surfaces. It causes deformation and elimination of surface elements as a result of mechanical action and subsequently developed stresses. Various factors and their combinations such as complex geometry, die/mold material, inadequate heat treatment, surface impurities, working environment, pressure and temperature affects wear type and behavior. Fig. 2a and b presents the mode of erosion wear in ductile and brittle materials respectively [38].

In ductile material, the erosion wear is initiated with the plastic deformation. This plastic deformation occurs owing to molecular dislocation over the slip plane within the crystal where the shear stress (τ) is above the yield stress. Such deformation may occur under the extreme pressure or high temperature that leads to deformation of die and mold from its original shape. During hot working processes, the prolonged contact period between die/mold surfaces and the working material leads to plastically deform die/mold along with the high pressure and temperature. Fig. 3 presents dislocation principle of plastic deformation.

Heat checks are a large number of cracks generated under thermal fatigue cracks due to cyclic heating and cooling of the die or mold. This regular exposure to cyclic heating and cooling leads to temperature gradient and subsequent thermal stresses across the adjacent layers that further amplifies crack generation on the surface. As the distance from the surface increases the effect of thermal cycling also decrease and it invariably stops the propagation of these cracks into the bulk material of dies and molds. Thus, there is formation of a large number of small cracks with shallow depth forming checker like pattern on the die and mold surface. Therefore, these cracks are named as Heat checks. The higher depth of these cracks has also been reported by several researchers for the cases, where the local stresses are higher due to other global stresses present during the operational phase. These are often the first and fastest emerging signature of failure in hot working dies and molds and are also known as thermal fatigue [25,33]. The formation of oxides is inevitable in hot working dies. These oxides and residual casting material gets filled in the heat checks formed on the die/mold surfaces during the processing. This filled material generates high stresses and subsequent plastic yielding which leads to further opening of cracks during the cooling phase of the operation [17]. The regular cycle of this process results in erosion, corrosion or oxidation, plastic deformation and soldering of the surfaces [25,39]. The effect of temperature rise leading to such failure has been experimentally demonstrated using fatigue testing machine and it was established that the working temperature is one of the key parameter promoting crack initiation and growth [40]. A similar observation was reported and it was shown that a little modification in hot-forging process parameters like modification in billet temperature and forging rate can significantly improve life of hot forging die [41,42]. The effect of porosity, ductile dimples and oxide layer present over the surface of die was also investigated and it was found that these features also promoted the initiation of cracks and develop an internal oxidation zone inside the crack [43,44]. The presence of oxide layers certainly causes the weakening and plastic deformation of die [45]. Fig. 4 depicts steps involved in heat checking.

The another form of the failure mechanism is mechanical fatigue that initiates from various surface defects like–inclusions, porosities and oxide layers etc. present over the surface. Corrosion stirring due to chemical reaction between the working environment and die/mold surface also helps in the initiation of such damage. These defects help in the development of

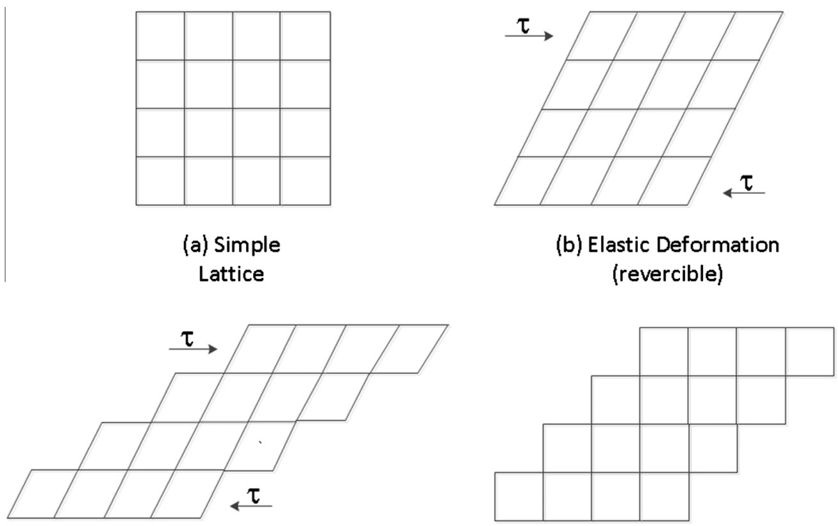

Fig. 3. Dislocation principle of plastic deformation.

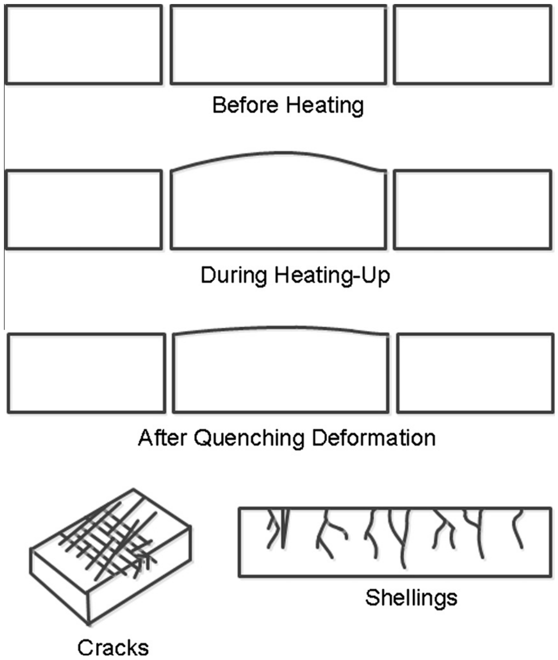

Fig. 4. Steps involved in heat checking.

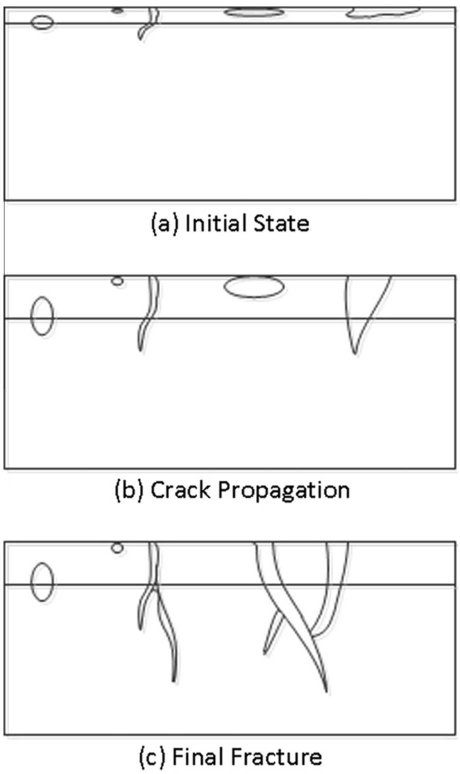

Fig. 5. Mechanism involved in mechanical fatigue.

internal oxidation zones leading to the initiation of crack and its enlargement. As several stresses involved during the operation, coalescence of these propagating cracks results in the final fracture of die/mold. Fig. 5 presents mechanism involved in mechanical fatigue.

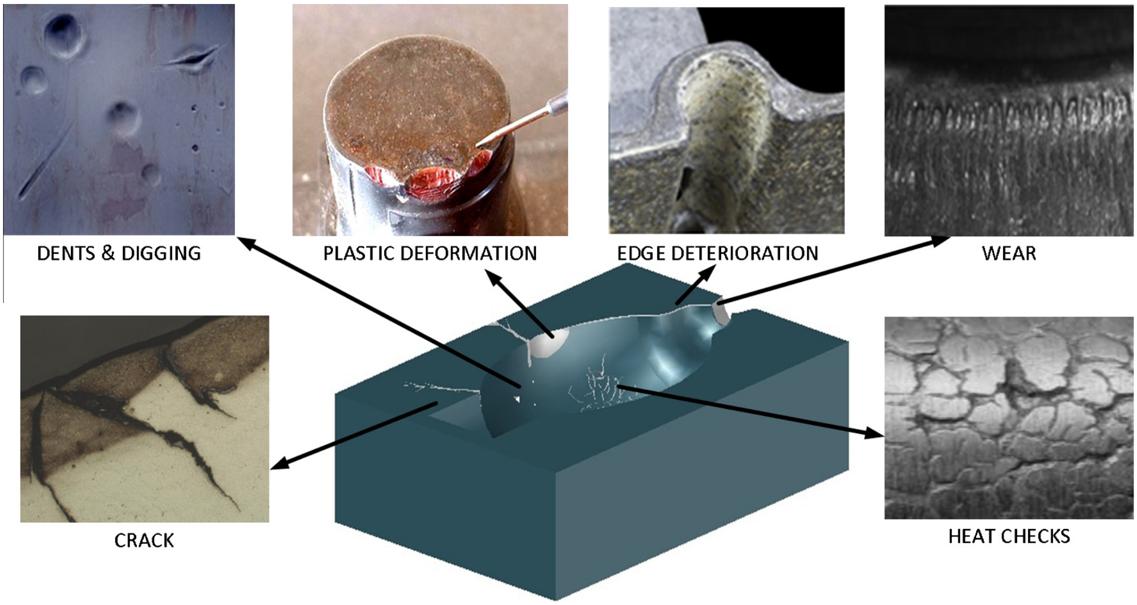

Fig. 6. Types of defects in dies and molds [18,23,42].

Thus, premature failures/defects of dies and molds can also be attributed to factors related to both classes – catastrophic or manufacturing failures [46] whereas, post-operational defects of dies and molds are mainly observed when subjected to several local impacts, cyclic loading, thermal stresses and corrosion [47]. Fig. 6 presents the type of defects in dies and molds. The study about the causes of failure indicates that all stages from design to field applications are equally important for the long-term performance of dies and molds. It has been observed that many of the die and molds under goes failure/damage before their affirmed and anticipated life span due to unexpected errors. When these errors are below certain threshold, their restoration/reclamation/repair remains the solution in most of the cases considering the techno-economic feasibility.

4. Steps involved in repair

Once the type and extent of damage is assessed and it is always practice to estimate the techno-economic feasibility of the repair. Initial flaw can be detected at very early stages through regular inspection. The preventive maintenance procedure will increase the useful life. The omnipresent surface contaminants present over the surface should be removed at the time of inspection. Primary cleaning procedure is important for the removal of organic, inorganic and soils (e.g. rust, oils,

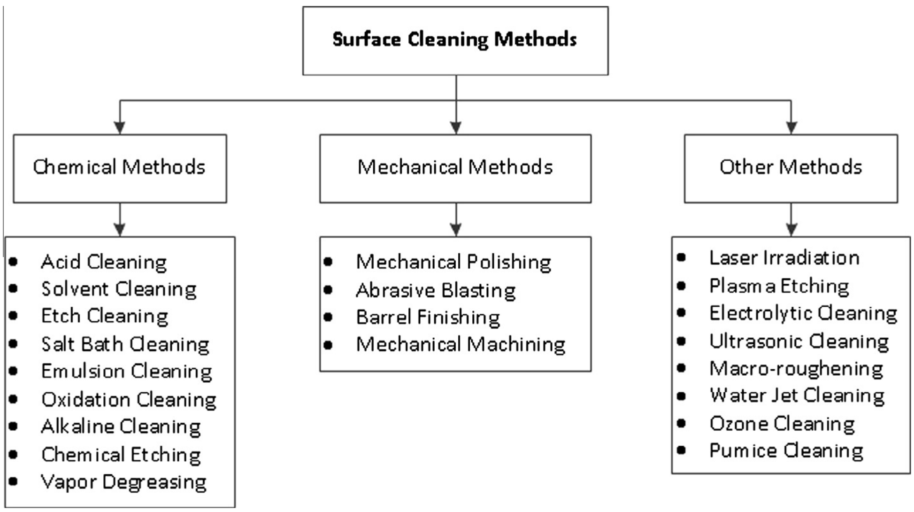

Fig. 7. Detailed classification of various cleaning processes.

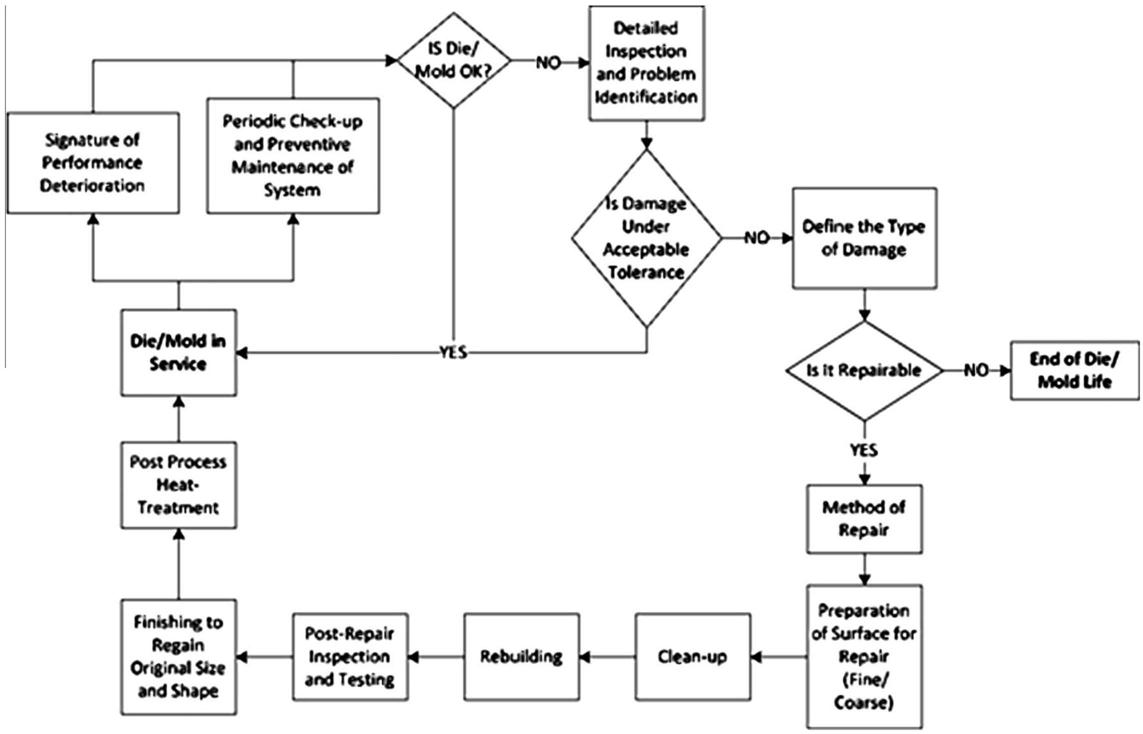

Fig. 8. Steps involved in repairing of die/mold.

pigments etc.) present over the surface of die and mold in operation. There are several physical, chemical and their combinations are available for these purposes. Fig. 7 presents a detailed classification of various cleaning processes. Most of these processes are traditionally being used by several researchers and several well set procedures are available in the literature. In most of the cases, mechanical machining is considered to primarily clean the affected area and also to prepare surfaces before deposition. The amount of material is to be removed depends on type of flaw present, the selection of repairing process and accessibility of the equipments to be used during deposition. Other processes shown in Fig. 7 can be used for surface cleaning purposes where deeper excavation is not required. Preference to these processes are also depends upon type of repair processes are to be used, repair complexity and ease or accessibility towards the repair zone. The amount of material is to be removed is dependent of these factors. The key purpose of cleaning is complete removal flaw made over the surface of die/mold. Moreover, the minimum amount of material deposition taking place depends on macro/micro deposition capability of the repair process is being applied. This can also be important criteria while selecting surface cleaning method and amount of material is to be removed. Fig. 8 depicts steps involved in repairing of die/mold.

5. Repairing options

Traditionally, materials used for manufacturing dies and molds possess considerably high amount of carbon and alloying elements thereby making the material difficult to weld due to substantial metallurgical concern and low weldability [7,30,48,49]. Among the various material deposition techniques, fusion welding is the only reliable technology available that can improve the mechanical properties so as to extend lifespan of dies and molds. During fusion welding, the metallurgical relationship between base metal and deposited material varies with respect to time, volume and pattern of deposition. The post repairing life of dies and molds depends on the quality of repair, in addition with pre and post repair treatments; thereby the repair process should be escorted by highly specialized knowledge. Demand of precise and fastest modes of repair at considerably low investment enforces researchers to develop enhanced processes for mold and die repair. The repair method usually involves excavation/gauging, followed by cleanup of the damaged area and subsequent material deposition. Fig. 9 presents the various options for material deposition during dies and molds repair.

5.1. Gas tungsten arc and plasma transferred arc welding

Gas tungsten arc welding (GTAW) is one of the oldest and most commonly methods used in the repair industries. It is preferred as its welding setup is easy to operate, highly portable and less time consuming [50]. It is also widely deployed for the repair of dies and molds due to some special qualities like–high arc stability and concentration provides accurate

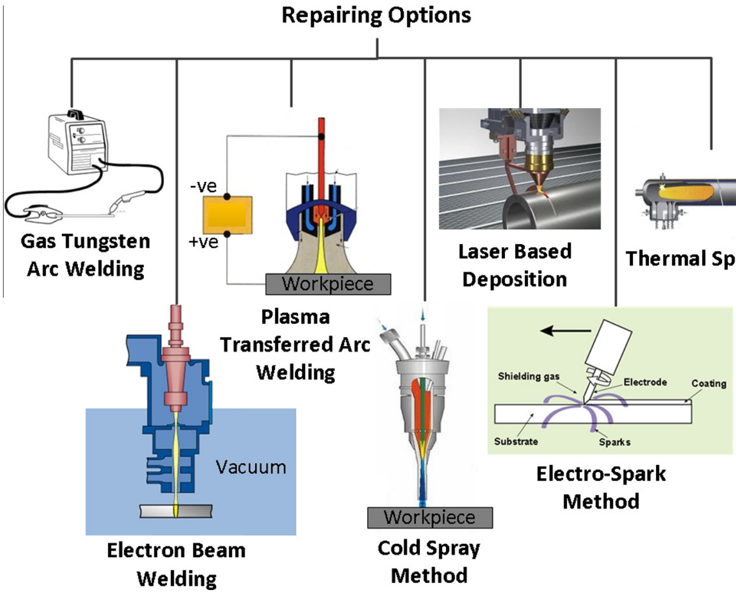

Fig. 9. Options for material deposition during dies and molds repair.

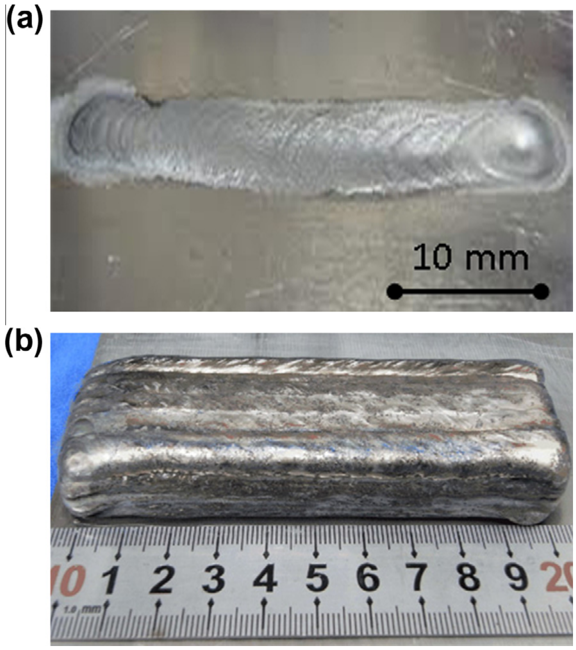

Fig. 10. Typical surface repaired using (a) gas tungsten and (b) plasma transferred arc welding [57].

and controlled bead deposition [33,51]. Generally, GTAW equipment used for dies and mold repair are manually operated, hence highly flexible to approach in complex geometries and intricate parts thereby requiring highly skilled operators [50,52]. As most of the dies and molds are made of heat treatment sensitive tool/high alloy steels, pre-heating and post welding heat treatment is mandatory to avoid the formation of very hard and brittle phases leading to solidification cracking and high residual stresses. Several authors have reported successful repair of dies and molds in literature [48,53–55]. Fig. 10a presents a typical deposition using GTAW.

Plasma transferred arc welding (PTAW) produces better results than GTAW in terms of efficiency and the quality of deposition produced at lower cost [56]. PTAW process ensures deep penetration and narrow heat affected zone with comparatively small weld bead through high velocity plasma jet when compared to the GTAW process. PTAW has the liberty to be operated in straight, reversed and variable polarities. The plasma jet of PTAW also restricts atmospheric gases to enter into the deposited zone and thereby provides a better shield to avoid atmospheric contamination. Fig. 10b presents a typical material deposited using PTAW method [57]. It also provides higher deposition rate in comparison to other arc welding methods [58]. On the other hand, during GTAW process, flow is induced by magneto-hydrodynamic pumping of arc which provides free burning. As there is no direct contact of tungsten electrode with the work-piece, problems like tungsten particle inclusion can be avoided.

5.2. Laser based material deposition

Material deposition using lasers as heat source are preferred choice over conventional processes due to low heat input. This material deposition process leads to small heat affected zone, negligible undercut and very small volume weld [59–61]. Laser based material deposition methods with filler material in the form of wire or powder are successful and used for die and mold repair applications [62,63]. The recent development of compact solid state lasers qualified this technology at par with conventional processes in terms of space, maneuverability and adoptability [64]. Besides these, the laser based deposition methods have advantages in terms of flexibility, ease of control and automation with the help of CNC-work stations or robotic arms. Due to these, more precise and accurate material deposition with very small thickness starting from tens of microns can be done with least change in the parent material composition [65]. Initially, CO_2 laser was only the industrial work horse and was used for the demonstration of reconditioning of various prime components. However, industry was rather reluctant to adopt this technology, mainly due to high investment and running costs. Since high power diode lasers diode pumped Nd:YAG lasers and high power fiber lasers were developed and introduced to the market the situation has changed due to significant reduction in running and maintenance costs. Laser based material deposition mainly uses material either in powder or in wire form [66]. Wire feeding is preferred for fabrication of components involves continuous deposition, as intermittent start/stop results in discontinuity in deposited material. In wire feeding, the wire is always in direct contact with the melt pool on the substrate. Any inaccuracy in wire positioning and wire-feed rate disturbs the shape and size of melt pool. This disturbance leads to non-uniform/unsymmetrical shape of deposited materials/tracks. Moreover, a definite ratio between beam diameter and wire diameter (>3) are used for good quality deposition. Here, good quality deposition means the deposited material has good bonding to the substrate and the fed material spreads out during deposition resulting in a uniform smooth surface. Therefore, the positioning of the wire to the substrate and its size is critical in laser based material deposition involving wire feeders. In powder feeding, the major advantage is in terms of flexibility and precise control during the material deposition. Among the powder feeding methods, three different concepts of powder injection are reported in literature (as shown in Fig. 11): (1) Off-axis powder injection (a single powder stream is red lateral into the laser beam); (2) Continuous coaxial powder injection (a powder stream cone is produced which encloses the laser beam); (3) Discontinuous coaxial powder injection (three or more powder streams are fed coaxial to the laser beam). The major difference between off-axis powder injection and continuous coaxial powder injection is advantage of omni-directional deposition at the cost of slightly lower powder utilization efficiency. Discontinuous coaxial powder injection is superior to continuous coaxial powder injection for three-dimensional deposition involving tilt of the deposition head [67].

Laser based material deposition have been researched and deployed for Ni, Co and Fe based alloys [68–70]. Fig. 12 presents typical material deposited using laser based material deposition method [71]. It also produces little distortion and results in high-quality coatings. Because the process is additive, repairs and modifications to existing molds and dies are achievable, resulting in a production-worthy tool from a prototype or obsolete tool. Reduced post-processing requirements, reduced cycle time, increased part quality and increased mold and die lifetimes are all benefits of the laser based material deposition process.

5.3. Micro-GTAW and micro-plasma

Micro-GTAW and micro-plasma welding are advanced form of conventionally GTAW and plasma welding, capable of producing a smaller, softer, bell shaped arc, precisely controlled through digital power supply. These power supplies are usually inverter based, controlling welding current with a precision up to 0.1 A and can weld areas as small as 100 μm wide using filler rod with diameter range starting from few microns. The results of such precision welding are comparable to that of laser based processes. Recently, microwelding processes have been deployed for the layered deposition exploring to manufacture smaller few mm sized 3D metallic parts. In this process, the tip of a metallic wire is melted to form a track and then subsequently a number of adjacent tracks forms a layer and a number of layer forms a 3D object. Its precision is controlled with the help of CNC units, thereby confirming accuracy with quality [72]. Successful deposition of Inconel 600 super-alloy and Titanium Aluminide have been reported, where the deposited materials various mechanical properties and their microstructures were tested. The results depicted the deposited material to be fully dense and free from any cracks and pores thus reinstating the process capabilities [73,74]. Ti–Ni and Ti–Fe inter metallic alloy were also tested to create pinned objects by stacking beads and there microstructures were observed showing no cracks in the formed objects [46,75]. Furthermore Ti beads were examined in respect to diameter, height and contact angle for the formation of 3D Ti objects like–arch arabic numerals and pyramidal shapes developed. The deposited geometry was examined and its microstructure was studied and their results revealed that no cracks were formed between the substrate and the deposited material [46]. Fig. 13 presents a typical material deposited using micro-GTAW deposition method.

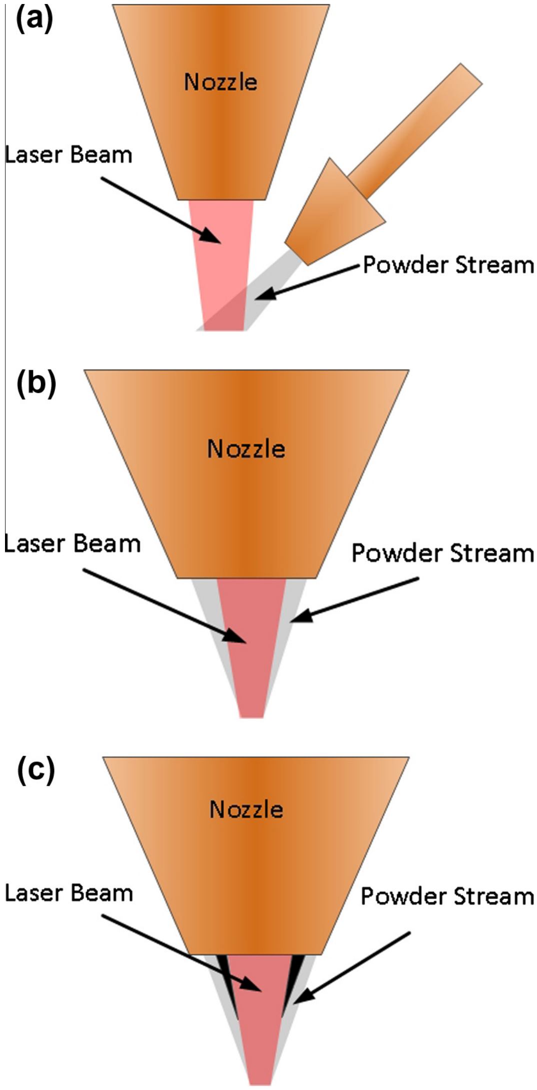

Fig. 11. Different powder injection method of laser based material deposition.

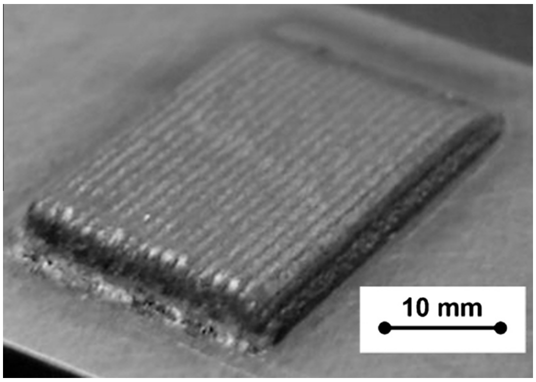

Fig. 12. Typical material deposited using laser based material deposition method [71].

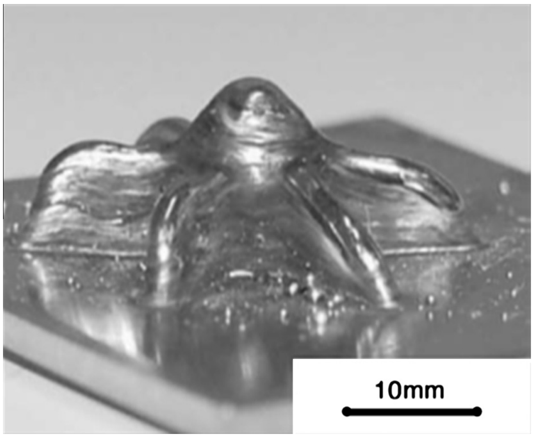

Fig. 13. Typical material deposited using micro-GTAW deposition method [72].

5.4. Other processes

Among the other deposition methods for the repair of dies and molds, Electron Beam Welding (EBW) is also being used for the welding of gas turbine stationary nozzles, combustion components and shaft seals. The major advantage is derived in EBW due to high energy low heat process providing narrow HAZ in the weld zone. With the advancement in the technology, electron beams can be generated with characteristic having high peak current density ($\sim 10^4$ A/cm^2) with low energy (10–35 keV) and short pulse ($\sim$1 μs) [76]. During the interaction of material with high energy processes like–laser and electron beam welding, very fast heating, melting and possible evaporation of the surface layers over the substrate is produced. The composition [77], stress-state [78] and micro-structure [79] of the surface layers witness quick alteration due to heat conduction towards the cold substrate. The repair through EBW is restricted to straighter and less complex joint geometry which must fall in the same plane. Hence the process can be used on confined weld paths only highlighting the major limitation of the process, also the weld being performed requires a vacuum chamber for its execution and thereby is not used very popularly because of these restrictions.

The method of cold spray was developed in early 1980s in Soviet Union by Papyrin and his team, this method involves deposition of material over a substrate through supersonic jet of powder spray at lower temperature. Successful repair of a mold made-up of ductile aluminum alloy using cold spray method shown good deposition and wear properties [80]. The process ensures minimum plastic deformation and low thermal stresses during deposition. The major application of cold spray method is in repairing of aluminum and magnesium alloyed components. Although there are many advantages of using cold spray method for deposition but major limitation while using the process over hard, brittle, usual die cast material.

Thermal coatings are also commonly used to extend service life of dies and molds. These coatings are usually applied to improve temperature, wear, corrosion, surface texture and surface appearances of dies and molds for overall improvement in fracture toughness. Thermal coatings are usually applied again at the end of repair process with the help of similar technology and equipment so as to recover the surface properties and texture of the original parts of dies and molds [81,82]. The long-established coating methods being used are chemical vapor deposition, low pressure plasma spraying, high velocity oxy-fuel spraying and electron beam physical vapor deposition technologies, which are practically beyond the most repair facilities due to high overhead costs. Also the major limitation of thermal spraying are low bonding strength, porosity in deposited material and low loading capacity. The availability of these coating facilities and technology licenses restrict the number of vendors capable of performing hot section repairs on the more advance parts.

6. Other aspects of die and mold repair

The properties of die and mold material is govern by the amount of different microstructural constituents during cooling and their individual properties. The microstructures that are formed with increasing cooling rate from austenizing temperature are ferrite–pearlite, bainite and martensite along with retained austenite. The individual hardness of these microstructure depend primarily on chemical composition of material specially the carbon content, the cooling rate and the formation temperature. As the different deposition process leads to different cooling rates, different sets of microstructures are formed. At high cooling rates achieved during laser, plasma and electron beam processing etc., in some of the tool steels austenite fully get transformed into martensite with hardness value exceeding 850 VHN. At lower cooling rate, as in case of GTAW, ferrite and pearlite are formed and resultant hardness is about 200 VHN. At medium cooling rates, the microstructure consisting of ferrite, pearlite, bainite and martensite are produced. Thus various deposition techniques give rise to the formation of different material properties leading to different die and mold life. Thus, the pre and post treatment of the dies and mold plays a vital role in the extended life.

There has been controversy in imposing pre and post deposition treatments due to large variety of methods, material and expectations with the repaired die and mold. A discoloration is a general consequence with pre and posts deposition heat treatment and can be avoided with no or lesser pre-heating, while deposition without pre-heat increases the susceptibility of cracking. It necessitates a negotiation between pre-heating and discoloration. The amount of heat produced during repair depends upon the local temperature and interaction time of the heat source with the base material. In fact, the dies and molds to be repaired, automatically gets heated up during material deposition generating enough heat to compensate for pre-deposition heat treatment. With this technique, surface re-melting passes can also be obtained using the same heat source without the use of filler metal; however this does not completely substitutes the benefits of pre heating for repair applications [49,83]. With the application of modern high power lasers, successful repair of die and mold without pre heating can also be obtained if the welding parameters used are appropriate along with suitable pulse shapes [29,84]. Post deposition, the microstructure and hardness values are found to be different from that of the base metal and in between intermittent layers. This problem is found to be more severe during the repair of large size dies and molds where the deposition is in bulk. In order to overcome these fundamental problems post deposition heat treatment is required to obtain sound microstructure and similar hardness between the base material and the deposited layers. Nevertheless smaller to medium sized dies and molds are often restrained from post deposition heat treatment in order to avoid the complexities of further machining and added costs since these die and mold are generally not subjected to very high thermal cycles and consequent stresses in compared to that of larger die and mold.

Generally repair welding processes are considered to have high cooling rates which give rise to the development of undesirable microstructures and residual stresses. These circumstances are painstaking when the residual stresses are nearly equal or higher than the yield point of the deposited material. Post repair heat treatment is often required to improve the properties of repair itself also it helps to relieve stresses produced during repair. The process parameters of post weld heat treatment (PWHT) are complex function of material, die/mold design, application type and duty conditions. There are dedicated standard industrial practices for PWHT [85]. PWHT produces resistance to brittle fracture, improved fatigue life through reduction in hardness and residual stresses [86]. These changes in the properties can be attributed to the decreasing in the proportion of hard phases, cementite and martensite, in the repair zones. These results have been proven through experimentation and FEA models [87]. After PWHT the base material displays basically a pearlitic/ferritic structure [88]. Another most important task of PWHT is to relieve diffusing hydrogen trapped in the repair zone as the metal cools and solidifies [89].

Vacuum heat treatments are also traditionally used during the repair process to restore the microstructure, improve weld-ability, apply brazes and diffused coatings. Significant metallurgical knowledge and experience are required to tailor the heat treatment steps. This ensures that the creep, fatigue and aging damage incurred during service are reversed as much as possible and that the correct microstructure and mechanical properties are produced after all welding and coating steps have been completed. Heat treatment cycles also result in a thermal etching effect, which serves to expose any tight cracks and strain edge cracking in welds. This improves the quality of the inspection and thus increases the reliability of the component in service.

Table 2
List of commercially available automatic die and mold repairing machines.

Machines	Company/website	Process	Features
AWS-6100	Weld Logic Inc. weldlogic.com	Micro-TIG/plasma	0.1–400 A adjustable current Automatic wire feed control Arc gap set & Arc distance control
NERTAMATIC 51	Airliquide www.airliquide.com	Micro-plasma	0.8–50 A adjustable current 107i Robot, 6 high precision axes Autonomous closed operator's cab
Micro-welds	ROFIN-SINAR Laser GmbH www.rofin.com	Laser	Small focus up to 0.1 mm diameter
Plasmamodule-10	FRONIUS USA LLC www.fronius.com	Micro-plasma	3–30 A adjustable current Robacta PTW 1500 Robotic system
The Orion PA230	Sunstone engineering R&D corporation www.sunstoneengineering.com	Pulsed arc and resistance welding	Adjustable power 1–230 J Three different weld modes Pulse arc mode Micro pulse arc mode Resistance arc mode
Micro plasma 20	EWM HIGHTEC WELDING GmbH www.ewm-group.com	Micro-plasma welding	Adjustable current 0.1–20A
Dual arc-82	Pro-fusion www.pro-fusiononline.com	Micro-plasma welding	Adjustable current 0.1–80 A
Micro PAW20	Liburdi dimetrics corp. www.liburdi.com	Micro-plasma welding	Adjustable current 0.1–80 A
PA-10/100-STD	WELDLOGIC, INC. weldlogic.com	Micro-TIG welding	Adjustable current 0.1–100 A Combined with a 45 × stereo zoom microscope
PA20	MACGREGOR SYSTEMS LTD www.macgregorsystems.com	Micro-plasma welding	Adjustable current 0.1–20 A
Ultima-150	Thermal arc www.victortechnologies.com/thermalarc	Micro-plasma welding	Adjustable current 0.5–15 A
PLASMAFIX 51	Airliquide www.airliquide.com	Micro-plasma welding	Adjustable current 80 m A – maxi 50 A

Table 3
Quick comparison of various material deposition processes.

Criteria	GTAW/ PTAW	Laser based deposition	Micro TIG /Plasma	EBW	Electro-spark welding	Cold spray	Thermal coatings
Rate of Deposition	●●●●○	●●●○○	●●○○○	●●●●●	●○○○○	●●○○○	●●●●●
Equipment portability	●●●●○	●●○○○	●●●●○	●○○○○	●●●●○	●●●○○	●●○○○
Access to intricate geometries	●●●●○	●●○○○	●●●●○	●○○○○	●○○○○	●○○○○	●●○○○
Cost	●○○○○	●●●●○	●●○○○	●●●○○	●○○○○	●●○○○	●●○○○
Metallurgical properties	●○○○○	●●●●○	●●●○○	●●○○○	●●●○○	●●○○○	●●○○○
Setup time	●●○○○	●●●●○	●●●○○	●○○○○	●●●○○	●●●○○	●●○○○
Requirement of heat treatment	●○○○○	●●●●○	●●●○○	●●○○○	●●●○○	●●●○○	●●○○○

High ●●●●●, Medium ●●●○○, Low ○○○○○.

Table 4
Base materials and recommended filler material compositions.

S. No.	Base metal designation and composition	Filler material composition	Type of filler material (wire or powder)	Ref.
1.	AISI H13 – 0.35%C, 0.3Mn, 5.1%Cr, 1.5%Mo, 1%V	0.15%C, 1.5%Si, 2%Mn, 20%Cr, 7%Ni	Wire	[59]
2.	AISI P20 – 0.35%C, 0.3%Mn, 1.7%Cr, 0.4%Mo	0.35%C, 0.3%Si, 1.2%Mn, 7%Cr, 2%Mo	Wire	[59]
3.	AISI P20 – 0.35%C, 0.3%Mn, 1.7%Cr, 0.4%Mo	0.1%C, 0.6%Si, 1.3%Mn, 0.5%Mo	Wire	[59]
4.	AISI P20 – 0.35%C, 0.3%Mn, 1.7%Cr, 0.4%Mo	0.25%C, 1.4%Mn, 1.6%Cr, 0.3%Mo, 0.4%V	Wire	[59]
5.	AISI D2 – 1.53%C, 0.35%Si, 0.40%Mn, 12%Cr, 1%Mo, 0.85%V	0.73%C, 1.8%Si, 0.22%Mn, 9.2%Cr, 0.26%Mo,0.1%Ni, 0.28%V, 0.1%W	Wire	[7,30]
6.	AISI H13 – 0.41%C, 0.41%Mn, 5.2%Cr, 1.23%Mo, 1.1%V, 1.12%Si, 1.3%Ni	18.2%Cr, 7.6%Ni, 0.7%Al, 0.6%Si, 0.3%S, 1.2%Mn, 0.2%Mo	Powder	[61]
7.	Maraging steel – 12%Ni, 8%Co, 8%Mo, 0.5%Ti, 0.05%Al, 0.02%C	7.5%Ni, 6.25%Co, 6.25%Mo, 0.63%Ti, 0.12%Al, 3.81%Mn, 1.86%Si, 0.08%C	Powder	[6]
8.	1.2738 Steel – 0.48%C, 0.25%Si, 1.67%Mn, 2.2%Cr, 0.23%Mo, 1.26%Ni, 0.0026%S, 0.013%P	0.35%C, 0.3%Si, 1.2%Mn, 7%Cr, 2%Mo, 0.3%Ti	Wire	[49]
9.	1.2738 Steel – 0.48%C, 0.25%Si, 1.67%Mn, 2.2%Cr, 0.23%Mo, 1.26%Ni, 0.0026%S, 0.013%P	0.1%C, 0.6%Si, 1.2%Mn, 0.5%Mo	Wire	[49]
10.	AISI H13 – 0.39%C, 0.32%Mn, 5.15%Cr, 1.35%Mo, 1.03%V, 1.12%Si	0.31%C, 0.29%Mn, 4.97%Cr, 2.91%Mo, 0.61%V, 0.16%Si	Wire	[27]
11.	AISI H13 – 0.39%C, 0.32%Mn, 5.15%Cr, 1.35%Mo, 1.03%V, 1.12%Si	0.28%C, 0.33%Mn, 4.85%Cr, 4.05%Mo, 0.13%V, 0.25%Si	Wire	[27]
12.	AISI H13 – 0.39%C, 0.32%Mn, 5.15%Cr, 1.35%Mo, 1.03%V, 1.12%Si	0.13%C, 0.42%Mn, 6.35%Cr, 3.72%Mo, 0.04%V, 0.33%Si	Wire	[28]
13.	AISI H13 – 0.39%C, 0.4%Mn, 5.2%Cr, 1.3%Mo, 1%V, 1%Si	0.15%C, 1.5%Si, 2%Mn, 20%Cr, 7%Ni	Wire	[60]
14.	AISI P20 – 0.37%C, 1.4%Mn, 2%Cr, 0.2%Mo, 1%Ni, 0.12%Si	0.35%C, 0.3%Si, 1.2%Mn, 7%Cr, 2%Mo	Wire	[60]

7. Commercially available machines and filler materials

There are many material deposition machines are available commercially. Table 2 presents a list of commercially available automatic die and mold repairing machines. These machines can be suitably deployed considering the various advantages and limitations of the processes and most important available resources. Table 3 presents a quick comparison of various material deposition processes discussed above.

Among the stated deposition processes, availability of resources sometimes becomes the key factor while selecting a particular process. Some of the professional die and mold repairing shops may have multiple choices based on their available resources. Characteristics like–deposition rate, post repairing metallurgical properties and requirement of heat treatment are primarily important, on the other hand equipment portability, reach to make intricate geometry, set-up time and cost are also important on case to case basis. Traditional methods like–GTAW, PTAW and thermal coating provide higher deposition rate leading to poor metallurgical properties due to the involvement of high heat during deposition. On contrary, these methods are preferred for bulk deposition of large volume. Use of electro spark welding can be good for producing small volume deposition but the process limits itself with low deposition rates. Modern methods like laser based deposition, produces sharper, smaller deposition with focused and concentrated high energy beams resulting in good metallurgical properties after deposition. This method is successfully applied to the deposition of a very thin to large bulk deposition depending upon the application requirement. The process requires high investment and its running cost hinders the end application limited to repairing of higher value components only. Micro-GTAW/PTAW provided for a mid-way with a little compromise on the quality of repair, at an advantage of having lower setup and running cost. This wide range of available deposition processes increases effective repair possibility of most of the industrial components, reduces wastage and reproduction, saves energy and environment.

Once a suitable repair process is identified subsequently, the most significant aspect involving repair would be choosing an appropriate filler material. The standard practice usually followed by practitioners is selecting a filler material that has a matching chemical composition as that of the die or mold to be repaired whereas at times such a condition may not be true. In exceptional cases, hardness and edge retention may play more important role than chemical composition while choosing an appropriate filler material. Some examples are chosen to show the selection criteria of filler material by previous researchers with successful repair of mold/die in Table 4. Filler materials can be utilized in two forms i.e. wire or powder, having different setups and procedure of deposition. Advantages and disadvantages of these forms help researchers to choose one over the other. Powder filler materials are advantageous during deposition since it has low dilution <5% that of wire having <20% during deposition whereas disadvantageous during energy utilization and powder utilization efficiency. Filler material in the form of wire have nearly 100% deposition efficiency and less health hazardous than that of powder. Especially in case of laser depositions at low intensities filler materials in the form of wires absorbs laser poorly than that of powder and the deposited thickness also has a limited range.

8. Conclusions

This is well proven that the repair of the dies and molds is economical for the most of the cases. There is an increasing trend of dependence on the repairing methodology to be more competitive and environment friendly. BRIC nations are the major new players in the present scenario, but the importance of North America and European Union cannot be neglected. In changing industrial environment due to advent of computerized processing systems, compact and automated power supplies, feedback systems, high-end metallurgical characterization techniques have improved the basic understanding of changing material behavior during repair process. There are variety of developing materials generating demand to experiment with changing performance due to variety of filler materials, processes, individual process parameters, pre and post welding treatments. At the same time, the availability of multi-axes machining process, die and mold makers produces more attractive, hybrid shapes products which again leads to customer's exceeding expectations to produce more and more complex shaped products in day to day life. In such a competitive scenario, optimum utilization of expected die and molds life is of prime importance in view of quality and economic production runs. The major causes of failures during operations are due to high thermal shocks, mechanical strain, cyclic loading and corrosion resulting in heat checking, wear, plastic deformation and fatigue. Other cause failures are due to faulty design, defective material, mishandling and force majeure due to accidental conditions. These issues are traditionally repaired using gas tungsten arc welding, electro-spark and cold spray technique depending on the material. Laser, electron beam and micro-welding are recent repairing options attractive mainly due low heat input and controlled material deposition. Though the advent of newer processes has eased out the challenge of repairing, the selection of appropriate repair material and methodology is still an area needs a specialized attention and is dependent of various techno-economic factors.

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