Application of surface modification Technologies to improve performance of hot sheet metal forming tools: A review

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Abstract. Hot sheet metal forming tools are exposed to severe operating conditions which cause adhesion, abrasive wear and fatigue. This causes a reduction in tool life and increased tool maintenance costs. On the other hand, the need for eco-friendly tools has arisen. Surface modification technologies have created opportunities in the tooling industry because of their capability to reduce the thermal and mechanical wear of hot sheet metal forming tools hence extending tool life. However, the technologies have some challenges which limit their wide application and there is need for further development. The purpose of this paper is to give a review on the application of surface modification technologies in hot sheet metal forming tools. The paper also discusses future research areas in the modification of tool surfaces to reduce wear and friction in hot sheet metal forming tools.

Keywords: Surface modification, sheet metal forming, tool life

1 Introduction

Hot sheet metal forming of materials such as high strength steels, titanium and aluminium alloys requires the use of efficient lubrication systems since these materials are tribologically difficult to work on [1]. Lubricants are useful in metal forming to reduce friction, forming loads and prevent corrosion. Some of the lubricants such as chlorinated paraffin oils used to prevent breakdown and galling are hazardous to the environment [1]. Reduction in lubricant usage results in reduction of environmental impact and an avoidable health burden. In order to overcome the above mentioned limitations, researchers have investigated the use of environmentally friendly lubricants [1,2]. However, there is need for further research on the use of minimum lubricant and alternative technologies for improving the tribological

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performance of the tools. From an economic and ecological point of view, there is need to reduce or eliminate the amount of lubrication.

Apart from the enviromental hazards, hot forming is costly due to tool replacement costs, maintence costs and production interuptions attributed to the excessive wear and failure of tools. The tools are exposed to adhesion, thermal fatigue, abrasive wear and thermal stresses as a result of the elevated temperature and this causes reduction in tool life and high maintenance costs [2]. The quality of the tools affects the accuracy and mechanical properties of the formed parts. In order to overcome the harsh working conditions, hot forming tools should have high hardness to resist abrasive wear, the ability to prevent thermal shock, oxidation resistance properties and good load-bearing capacity to prevent plastic deformation [3].The purpose of this paper is to give a review on the application of the technologies investigated to improve the tribological efficiency of hot sheet metal forming tools. Firstly, the paper explores the surface modification technologies. For each technology, an analysis and evaluation is given. This is followed by a conclusion and discussion of opportunities for future research on the subject.

2 Surface Modification technologies

A lot of research was conducted to develop ways of improving the wear and corrosion resistance of hot forming tools. The following section discusses some of the methods.

2.1 Surface texturing

Surface texturing is one of the most effective methods used to improve tribological performance. Surface texturing is the modification of the surface topography to create uniformly distributed pockets or grooves (dimples) with controlled geometry [4]. This offers advantages such as improved load capacity, wear resistance, reduced lubricant consumption, increased tool life and reduced coefficient of friction [5]. This is necessitated by the lubricant retention ability of the grooves (dimples), which act as lubricant reservoirs and trap debris hence reducing abrasive wear [6], [7]. The dimples also act as hydrodynamic pressure pockets thus reducing friction [7]. Figure 1 shows the surface topography of a laser textured surface. Methods of creating surface textures include electric discharge texturing, micro-machining and laser texturing [7],[8]. Other methods explored include photochemical texturing and masking surfaces by inkjet printing followed by electrochemical machining [4]. Laser texturing involves the use of heat generated from a laser to create dimples and it is the most successful texturing method developed [5]. [6] studied the effects of laser texturing of hot stamping dies. Stamping tests were conducted on textured dies that had different dimple parameters. The results of the study revealed that laser texturing improved the tribological performance of the dies since all textured surfaces resulted in improved wear resistance when compared to surfaces which were not textured.

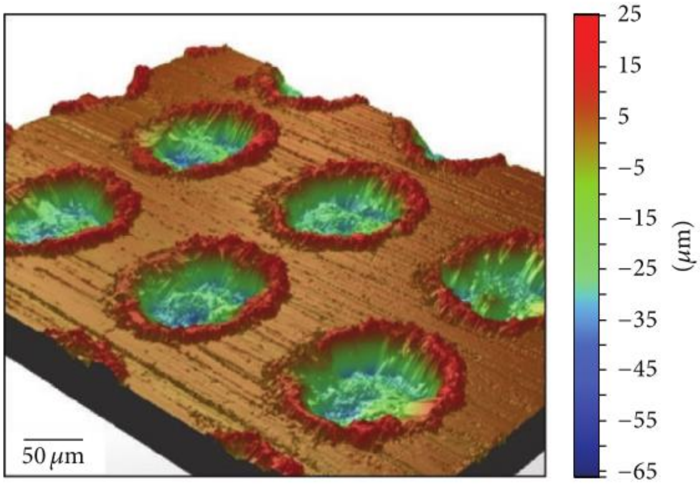

Fig. 1. Surface topography of a laser textured surface [6]

An increase in the number of dimples led to an increase in the retention of the lubricant. The texture with the highest dimple density had the best tribological performance due to the ability to retain more lubricant. According to [9], laser textured surfaces can control interface friction and prevent lubricant failure.

2.2 Coating of tool materials

Corrosion resistant coatings such as nitrides, carbides, titanium and chromium (TiN, TiCN, TiAlN, CrN) are also used to protect hot forming tools [10]. The coatings form a barrier between the tool and the work-piece thereby protecting the tool material from excessive wear, thus offering the opportunity for increasing hardness, wear resistance and chemical stability at elevated temperature [11]. Methods of applying the coatings include chemical vapour deposition, nitriding and physical vapour deposition [12]–[15]. Nitriding involves diffusion of nitrogen atoms on the surface of steels to form iron-carbo-nitrides which exhibit high hardness [16]. Physical vapour deposition (PVD) is the most common coating process developed. In PVD coating, heated material (CrN, AlCrN, AlTiN) is transported in the form of vapour through a vacuum or low pressure gaseous environment to the substrate as shown in Figure 2. This is followed by solidification of the material on the surface resulting in a hard coating [17]. The source of heat can be in the form of a laser beam or electron beam.

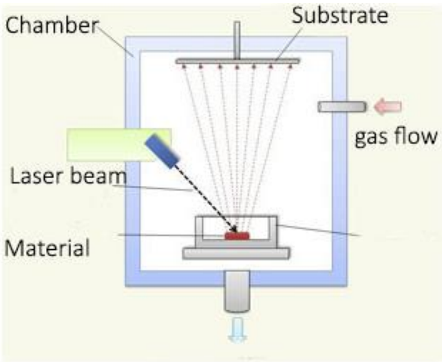

Fig. 2. Physical vapour deposition process [18]

PVD coatings are utilized to improve the wear resistance and hardness of hot forming tools. An evaluation was done by [11] on the wear rates of three coatings (CrN, AlCrN and AlTiN) for hot work steel in an aluminium extrusion process. The coatings for CrN, AlCrN and ATiN resulted in wear rates of 6.0, 0.5 and 0.004 $\mu m^3 N^{-1} m^{-1}$ respectively. Hence the AlTiN coating had the highest wear resistance properties [11].

2.3 Laser cladding

Laser cladding is a type of Direct Metal Deposition (DMD) processes which is used for enhancing wear, erosion, fatigue and corrosion resistance of a surface [19]. In laser cladding, a laser beam is focused on a work piece to create a melt pool. Metallic powder is then injected into the melt pool to build the coating as shown in Figure 3.

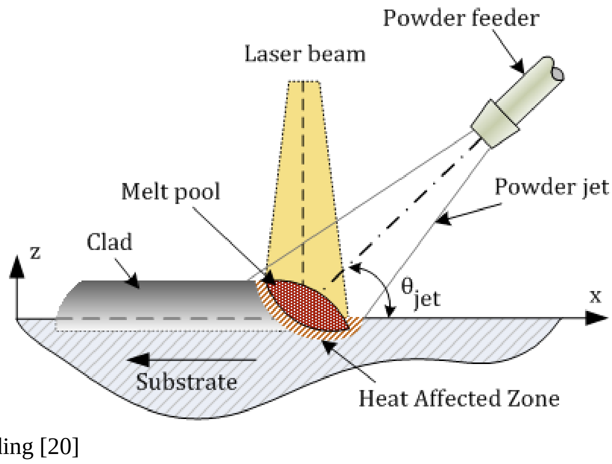

Fig. 3. Laser cladding [20]

Materials deposited include cobalt and nickel-based super alloys [21]. Research was done to analyse the performance of laser cladded hot sheet metal forming tools. A study was done by [22] on the hardness and wear behaviour of hard-faced SKD61 hot work tool steel. The tool steel was cladded with super alloys (Satellite 6 and Norem02) at 700ºC. According to the results, the hardness of the tools coated with Satellite 6 and Norem02 was greater than the uncoated tool steel by factors of 2.8 and 4.4 times respectively.

Other authors have reported a slight difference in the performance of a laser cladded tool surface when compared to a conventional heat-treated tool. A study was done on the wear resistance of H13 laser clad coatings using a pin on disk test [23]. The wear resistance of the laser cladded tool steel was 1.06 and the wear resistance of an ordinary hardened tool steel was 1.0. The loss in volume caused by the wear was $0.13mm^3/Nm$ and $0.14mm^3/Nm$. Hence there was only a slight difference in the performance of the laser cladded tool steel when compared to the ordinary heat-treated tool steel.

Laser cladding presents attractive opportunities for creating functionally graded coatings to improve performance of hot sheet metal forming tools. Experiments on the use of a functionally graded coating to improve thermal properties of hot stamping tools were conducted by [24]. The coatings consisted of aluminium bronze and a cobalt based alloy. The functions of the aluminium bronze and the cobalt based coatings were to improve thermal conductivity and wear resistant properties at high temperature. The tools with laser cladding showed maximum heat flux of 400 kW/m^2 while the tool without cladding had a maximum heat flux of 18 kW/m^2.

2.4 Laser surface hardening

Laser surface hardening involves the laser assisted heating of a surface followed by self quenching to cause martensitic transformation [25]. This causes hardening of the surface and formation of a homogeneous stracture. When the surface is hardened, abrasion and corrossion resistance increase due to the formation of a dense and homogenous structure [26]. Figure 4 illustrates the laser surface hardening process. Advantages of laser surface treatment include short processing time, local treatment, low costs and the resulting smooth surface [26], [27]. Most studies focused on the laser surface hardening of hot work tool steels in order to improve thermal and mechanical resistance.

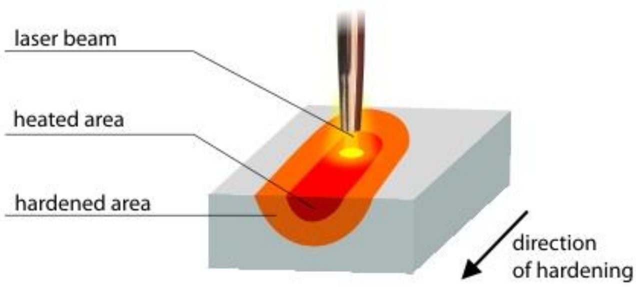

Fig. 4. Laser surface hardening [28]

Experimental i9nvestigations on the laser surface treatment of H13 tool steel were done by [26]. In the experiments, the intial hardness of the tool steel was about 240Hv and it increased to a range of 480-510HV after laser treatment. Similar work on H13 hot work tool steel was reported in [25]. The tool steel was firstly polished before it was heated with a 6KW diode laser. The optimum laser density which yeilded the best results in terms of the resultant tensile strength (2290 MPa) and yeild stress(1460 MPa) was 62.5 J/mm^2. Residual stresses developed due to the large temperature gradients especially when a high dense laser (75 J/mm^2) was used [25]. A study on the microstractural changes and hardness of laser surface hardened H12 tool steel was reported in [29]. According to the results, the laser treated layer had dense, fine microstructure and fine grains. Furthermore, a decrease in the coefficient of friction, hardness of 1100±30 HV and compresive residual stresses of 480±15 Mpa was archieved after laser surface hardening. The ability of laser surface hardening to produce smooth and honogeneous surfaces makes it attractive for the repair of damaged tool surfaces [27].

3 Discussion

Laser surface texturing has proved to improve the tribological performance of forming tools. However, the creating of dimples using laser causes the build-up of brittle undesirable buldges around the edge of the dimples. The buldges will have a high brittleness and hardness because of the microstructural transformation which occurs due to the large temperature gradients. When the textured surface comes into contact with a blank during a forming operation, the buldges tend to plough on the blank surface causing an increase in wear rate and surface roughness [30]. There is limited information regarding the selection of optimum dimple parameters (depth, distance between dimples) depending on a given application. Although some studies in literature involved selection of optimum parameters, it was revealed that there are conditions in which use of certain dimple parameters might be unfavourable to the sliding surfaces. Hence there is need for further research on the subject.

Literature analysis shows that surface irregularities are the major limitation with the PVD coatings. The irregularities cause delamination failure of the coated layer and development of cracks [21]. The steep thermal gradients in the PVD process give rise to residual stresses which weaken the bond between the coating and substrate [31].

Laser cladding is a complex process, in which the metallurgical and cooling process involves a lot of parameters. This makes it difficult to control or simulate the process in terms of the temperature fields, microstructure, stress heat transfer and solidification phenomena [19]. Literature analysis shows efforts done by other authors to optimize the parameters. According to [32], laser power and scanning speed are the most important parameters affecting heat input of the laser. However, there is need for more information regarding the performance of laser cladded tools to minimise residual stresses and optimize the hardness and wear resistance of the tools. The residual stresses lead to insufficient thermal shock resistance. As a result, thermal cracks develop in the base metal when the surface is exposed to high temperature [32]. Thus, post heat treatment is necessary to reduce the residual stresses.

In spite of the advantages brough about by the laser surface hardening, there is lack of clarity on the effect of the laser parameters on the performance of different tool steels. Although literature analysis shows some research efforts done to deternmine the effect of parameters, there is no available detailed information to provide guidance on the selection of optimum parameters.

Not much research was done regarding thermal fatigue resistance of laser surface treated tool steels. Thermal fatigue resistance is an importannt parameter in prolonging the service life of hot sheet metal forming tools. A study was done by [33] to measure thermal fatigue of laser treated H13 tool steel. According to the results, the laser surface treated H13 tool steel developed severe micro-cracks during the fatigue tests. Hence laser surface treatment was not able to improve the fatigue resistance of the H13 tool steel. The cracks which were developed during the fatigue tests could be caused by the large residual stresses which occured as a result of the steep thermal gradients induced during the laser surface hardening process.

4 Conclusion

The main objectives of the paper were to present and give an analysis of the surface modification technologies developed for improving the performance of hot sheet metal forming tools.The processes presented include surface texturing, application of coatings, laser cladding and laser surface hardening. The decrease in laser costs and its availability have prompted most researchers and manufacturers to focus on the laser based surface modification technologies. The following conclusions are derived:

- Laser texturing- There is need to establish optimum process parameters (dimple size, depth and distance between dimples) for a given application. Furthermore, the speed of the process and its cost are still issues of great concern. The challenge of raised features could be eliminated through the development of cost effective post processes. On the hand, other manufacturing process can be used in the texturing. One way of addressing that could be through the application of micro-machining technologies .
- Coatings- The major drawback lies on the weak bond between the substrate and coating. This leads to peeling of the coated layer under severe operating conditions. There may be need for further research on the pre-treatment of the tool surfaces before application of the coatings. Another issue of concern is the uneven roughness which leads to an increase in the coefficient of friction. There is need for cost effective post processes to improve the resultant surface toporgraphy.
- Laser cladding-There is need to do further research on the application of laser cladding to create functional layers with properties which enhance the performance of the tools. This could be achieved through the development of materials with special properties (high thermal conductivity, wear resistance

and corrosion resistance). Furthermore, there might be need to apply laser cladding in specific die areas depending on the required property. For example, applying wear resistant layers in areas that are wear intensive. There is also need to identify optimum laser cladding parameters for a given application in order to reduce the formation of residual stresses.

- Laser surface hardening- Regarding the laser surface hardening technology, there might be need for research on the post processing of the laser treated surface to reduce the effect of residual stresses as well as the identification of the influence of laser parameters on the resultant mechanical properties of the surfaces.[34]

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