Journal of Machine Engineering, Vol. 10, No. 2, 2010

reuse,
laser, machining

Paul MATIVENGA[1], Mohamad RAJEMI[1],
Sundar MARIMUTHU[1], Lin LI[1],
S. YANG[2], K. COOKE[2]

ESTABLISHING A BASIS FOR SUSTAINABLE RE-USE OF CUTTING TOOLS THROUGH LASER DECOATING

There is an urgent and growing need to reduce the environmental footprints of products and manufacturing processes and to support sustainable material consumption. For engineering applications this implies the need to develop low energy/carbon footprint manufacturing processes that utilise extended life tooling. In machining, nano-structured coatings can be used to extend service life of cutting tools. However, hard coatings pose a challenge to the re-shaping and re-use of tools. This work investigated the use and re-use of cutting tools by developing selective tool coating removal using laser and conventional chemical de-coating technology. The laser de-coated tools were re-coated and their machining performance was compared to that of chemical de-coated and re-coated tools as well as first generation coated and uncoated tools. The paper presents a comparison of the energy footprints associated with the re-use of tooling. It is concluded that high value tooling can exploit material re-use procedures.

1. INTRODUCTION

To achieve sustainable development, there is a global need to develop competitive sustainable manufacturing [1]. This requires the simultaneous development of competitive manufacturing strategies and the reduction of environmental footprints. In engineering, sustainable use of strategic resources can be enhanced by developing tooling with extended life as well as where appropriate re-use of tools. To extend the life of cutting tools, promote the use of higher cutting speeds and in some cases dry machining, physical vapour deposition (PVD) coatings such as titanium nitride (TiN) are widely used in high performance machining. Compared to the use of uncoated carbide tools, TiN coating improves the surface finish, wear resistance and tool life during cutting [2,3]. TiN also improves the tribological conditions by reducing contact length and hence heat partition into the cutting tool [4]. However, when coatings need to be re-applied, e.g. when faults arise in

---

[1] School of Mechanical, Aerospace and Civil Engineering, The University of Manchester, UK, e-mail: P.Mativenga@manchester.ac.uk
[2] Teer Coatings Ltd, UK

the coating process (unacceptable material composition / uneven thickness), or when the tool needs to re-used after service, it is often necessary to remove the coatings and subsequently recoat the repaired surfaces.

The removal of these coatings from the substrate while preserving the latter's properties is always a challenging task due to strong adhesion to the substrate and low film thickness. The removal of such coatings is normally performed using wet chemical processes [5]. Although this method is widely used in industry, it has some concerns such as, processing of waste residue, uneven removal, long lead times (in the order of hours) and environmental issues associated with chemical residue disposal. To overcome these difficulties an alternative, dry technique is explored by using laser irradiation. Laser stripping has attracted much attention in science and engineering [6-8] because of its advantages of high speed of processing, selective removal on small areas and dry processing which eliminates the use of hazardous chemicals. The Excimer laser stripping of thin films, oxides, ceramics and paints [9-11] has gained increasing interest because of its ability to ablate materials in a well controlled manner. So far there is hardly any reported work focussing on the laser removal of coatings from cutting tools to facilitate re-use. For other applications not concerned with machining, the benefits and criteria for product re-use was articulated by Umeda et al in their CIRP paper [12].

The focus of the work reported in this paper was to investigate the use of an Excimer laser in removing TiN from coated carbide tools and then benchmark the machining and environmental performance of the new re-processing route compared to uncoated tools, first generation coated and chemically stripped tools.

2. EXPERIMENTAL DETAILS

2.1. LASER DE-COATING AND CUTTING TESTS

To prove the de-coating concept carbide cutting inserts, CNMA 120404 HTi10 WC made by Mitsubishi were used. Some of the inserts were coated to 2 µm thickness of TiN by Closed Field Unbalanced Magnetron Sputter Ion Plating [13]. Experiments were performed to determine the process window for removing the TiN coating without damaging the carbide substrate. A schematic diagram of the experimental arrangement for laser de-coating is shown in Fig. 1. A GSI Lumonics IPEX 848 Excimer laser with an output wavelength of 248 nm was used. A redirecting mirror, a beam shaper (aperture mask with an opening of 8 × 8 mm) and a spherical fused silica lens of focal length 100 mm were used as the optical system to obtain a square beam of 0.5 × 0.5 mm on the surface of the workpiece. The experiments were carried out at room temperature and atmospheric pressure. The insets were irradiated in a vertical orientation with perpendicular beam incidence. The workpiece was held on a computer numerically controlled (CNC) X–Y–Z stage set. During the de-coating process, the electrical power consumed by the laser was evaluated using a DT-266 digital clamp meter.

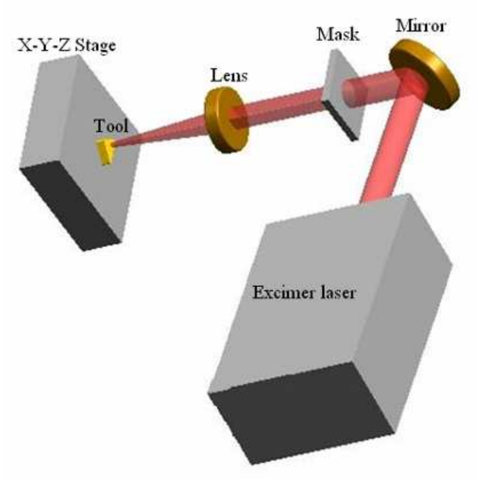


Fig. 1. Schematic diagram of the experimental set-up

The optimal process window was evaluated by first de-coating a small area (i.e. limited to the laser spot size) using a stationary laser beam. This beam was then translated linearly and then scanned with offsets to de-coat larger areas. The samples were analysed using a Veeco-Wyko NT1100 optical surface profiling system for both de-coated depth profiles and roughness values. Imaging of the samples was performed by optical microscopy and a scanning electron microscope (SEM), while Energy Dispersive X-Ray (EDX) analysis was used to confirm coating removal.

2.2. CHEMICAL ETCHING OF TIN COATINGS

The stripping of Ti-based coatings using a hydrogen peroxide-based mixture was reported in literature [5] where the mixture comprised of H_2O_2 and potassium oxalate ($K_2C_2O_4.H_2O$). A variant of the process was applied in the de-coating of TiN inserts as reported in this current work. In this case H_2O_2 plus EDTA (ethylenediaminetetraacetic acid) was used. In this context EDTA is described as a novel molecule for complexing metal ions. EDTA accelerates the etching of titanium. An H_2O_2/EDTA mixture for etching of Ti is described in a US 1985 patent [14]. The solution attacks the coating interface where it reacts with titanium, thus removing the thin metallic bonding layer and degrading the coating’s adhesion. The effectiveness of the process depends on process time and temperature. Optimum de-coating was achieved in around 60 minutes at room temperature. The chemical stripping process can be scaled up to treat large numbers of similar tools in one process.

2.3. EVALUATION OF MACHINING PERFORMANCE

The evaluation of machining performance was carried out on an MHP CNC lathe. The cutting tests were performed at various cutting speeds and a constant depth of cut and feedrate of 1 mm and 0.08 mm/rev respectively on EN8 steel. The cutting speeds were kept at relatively low values since uncoated tools were also being evaluated. The response variables measured were flank wear, component surface finish and the power consumed during machining.

3. RESULTS AND DISCUSSIONS

3.1. LASER DE-COATING OF TIN COATINGS

Fig. 2 shows the variation of ablation rate with laser fluence for TiN coating and the carbide insert, as established from the experiment. It can be seen that the removal of TiN and carbide insert material can be achieved above certain distinct threshold fluences. This variation in threshold fluence can be exploited to selectively remove the coating from the substrate. The minimum threshold fluence was approximately 1.62 J/cm^2 for the TiN coating and 2.36 J/cm^2 for the carbide tool material. After a series of experiments the best processing conditions were found to be a fluence of 2 J/cm^2, scanning speed of 0.5 mm/s, frequency of 50 Hz and laser beam was overlapped by 80% of its width (to provide increased area coverage).

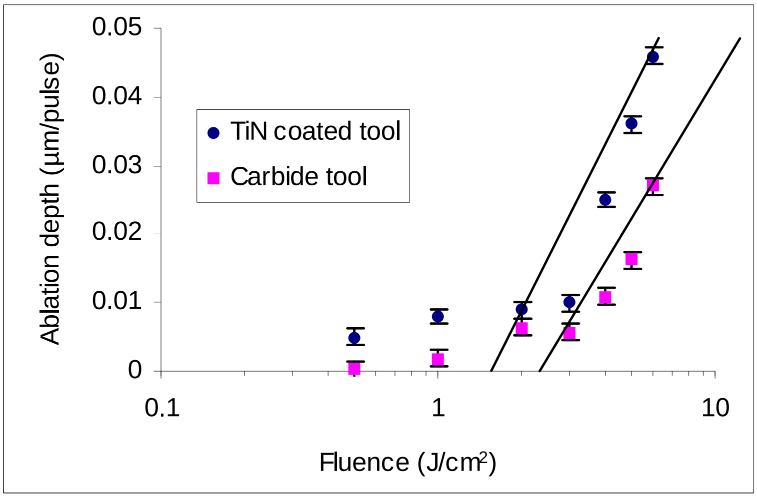


Fig. 2. Ablation depth in µm/pulse using an Excimer laser a frequency of 50 Hz and 200 pulses

Removal of the TiN coating was confirmed by the Energy Dispersive X-Ray (EDX) analysis. Fig. 3 shows that the coated insert (Fig. 3a) had a significant percentage of Ti as expected; the de-coated insert (Fig. 3b) revealed the underlying tungsten in the carbide substrate and no noticeable titanium content was recorded.

Fig. 4a shows images of a rhombus insert with laser de-coated cutting edges. The contrast between the TiN coated and de-coated surfaces can be seen clearly. Additionally, a close up view on an insert edge in Fig. 4b shows that the de-coating process still manages to maintain excellent edge definition.

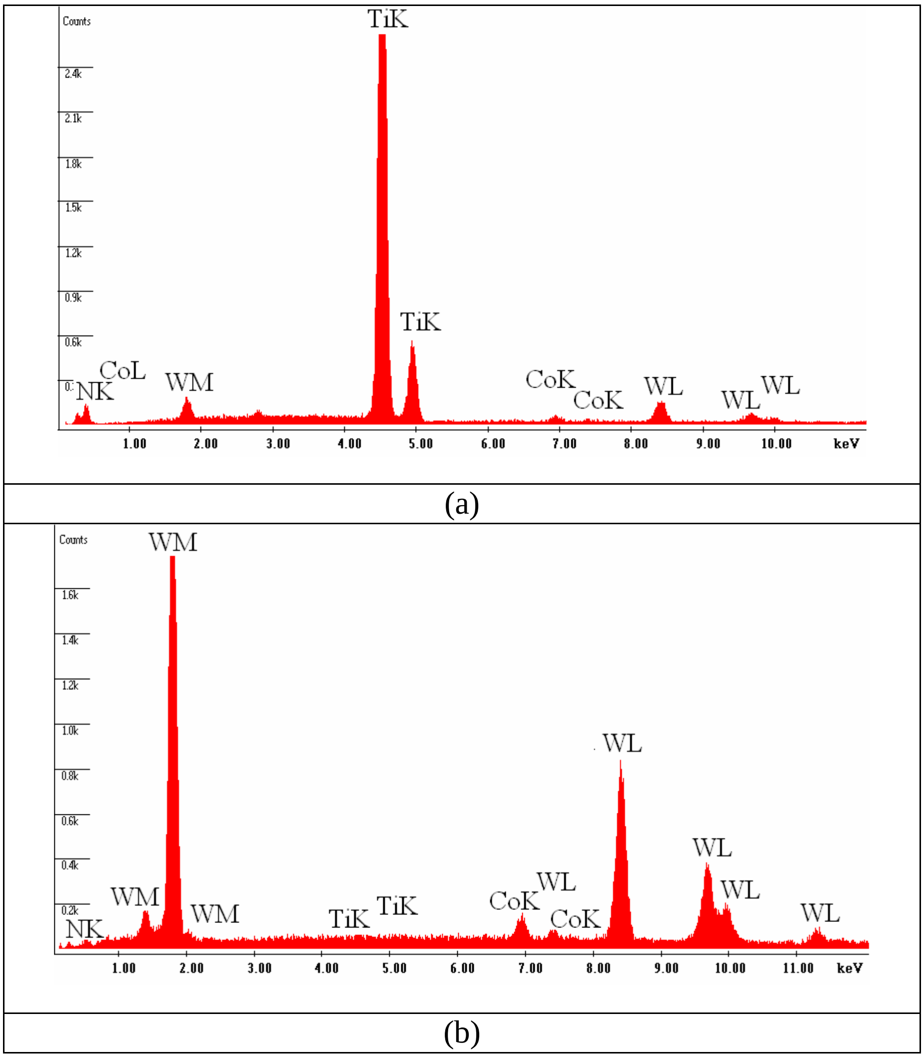
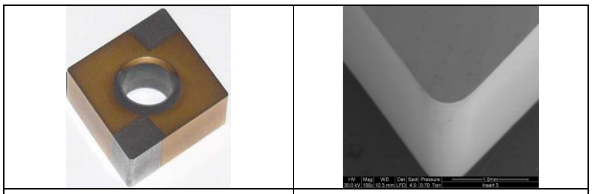


Fig. 3. EDX Spectrum (a) before and (b) after de-coating (fluence of 2 J/cm^2, speed of 0.5 mm/s, frequency of 50 Hz, and laser beam overlap of 80%)



(a) selectively de-coated insert

(b) smooth laser de-coated insert edge

Fig. 4. Sample laser de-coated insert (at fluence of 2 J/cm^2, speed of 0.5 mm/s, frequency of 50 Hz and laser beam overlap of 80%)

The surface finish of the de-coated inserts is shown in Fig. 5, where it is compared to that of the coated inserts. The results show that inserts de-coated by the Excimer laser de-coating process has a smoother surface finish compared to that of chemically de-coated inserts. De-coating the inset marginally increases the surface roughness of the tool. A smooth surface profile is beneficial for minimising the coefficient of friction during the cutting process.

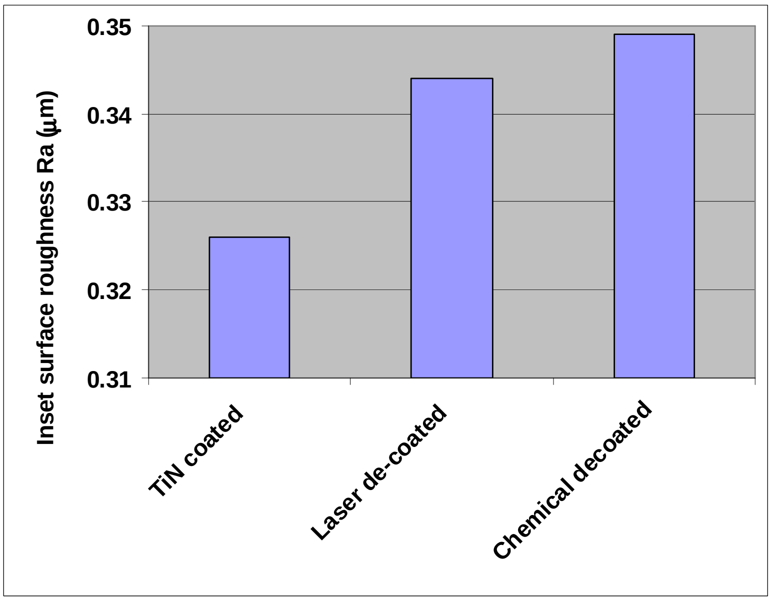


Fig. 5. Effect of de-coating on insert roughness

The chemical and laser de-coated inserts were then re-coated with 2 μm thickness of TiN (by the same process discussed in section 2.1) so as to compare the machining performance with uncoated and first generation coated insert.

3.2. EVALUATION OF WEAR PERFORMANCE

To test the effectiveness of using re-coated tools, cutting tests were performed on an MHP CNC lathe. Traditional wear assessment is often based on average flank wear or tool life however this comparison is not standardized or normalized because it may not take into account the true length of cut or the amount of material removed. One such approach of normalizing the effect is based on taking the logarithm of a ratio of the flank wear to the actual length of cut for material removed. This normalises the variability in the spiral length of cut as experienced when the workpiece diameter changes in turning. The assumption here is that the width of the flank wear land will be the same as the width of cut. From Fig. 6 it is clear that compared to the coated tools, the uncoated tool experiences a higher wear rate especially at higher cutting speeds. Compared to the first generation (i.e. not previously re-worked) coated tools, the tools coated after laser and chemical de-coating show a relatively comparable wear rate. At higher cutting speeds the first generation coated tools give the best wear performance while the laser de-coated and re-coated tools are the second best. It is clear from these results that re-coating of tools after laser or chemical de-coating does not significantly compromise the wear performance when compared to first generation coated tooling.

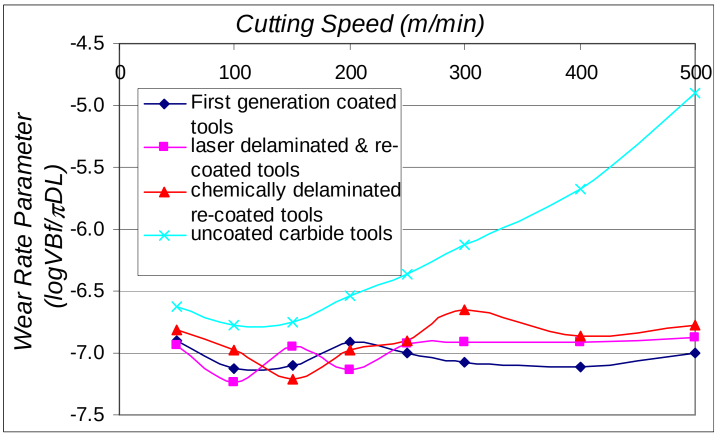


Fig. 6. Wear rate parameter in turning

3.3. SURFACE ROUGHNESS OF MACHINED PARTS

Fig. 7 shows the average surface roughness of the machined EN8 steel surfaces measured using a Taylor Hobson Surtronic 3+ surface roughness measuring instrument with a cut-off value of 0.8 mm and transverse length of 8 mm. As expected the coated inserts generated superior surface finish on the workpiece compared to uncoated tools throughout the range of cutting speeds investigated. At higher cutting speeds, the laser de-coated inserts gave a marginally better performance than the first generation coated tools and chemical de-coated/re-coated tools. Compared to first generation coated tools, re-coating tools after laser or chemical de-coating does not significantly compromise the surface finish of the machined parts.

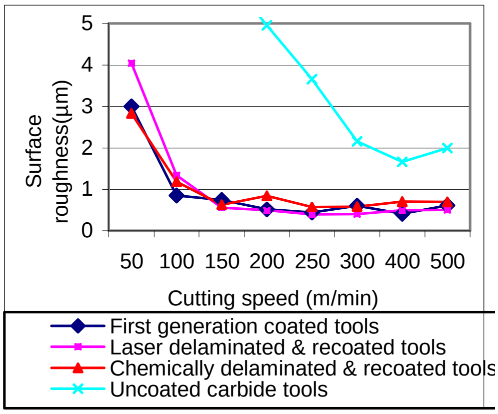


Fig. 7. Surface roughness of the machined surface

3.4. ENVIRONMENTAL FOOTPRINTS IN CUTTING

Sustainable re-use of materials should be developed with a goal of reducing the environmental footprints in re-use of materials. Energy and carbon footprint analyses are important considerations for green manufacturing. The energy requirement for the machining process depends on the energy consumed by the machine tool and the specific energy in cutting operations. Following on earlier work by Gutowski [15], the electrical power P, and energy requirement, E, for machining can be calculated from equation 1 and 2 respectively.

$$P = P_0 + k\dot{v} \tag{1}$$

$$E = (P_0 + k\dot{v})t = E_0 + E_{cutting} \tag{2}$$

where, P_o is the idle power (or power consumption for a machine tool before engaging the cutting tool) in watt (W), k is the specific energy requirement in cutting operation in Ws/mm^3 and $\dot{v}$ is the material removal rate (MRR) in mm^3/s, t is the total cycle time for machining, E_o is the energy consumed by a powered machine before engaging the cutting tool and $E_{cutting}$ is the energy for actual material removal in joules. From equation 1 and 2 the total power or energy for machining can be divided into two terms, the idle and machining loads. The idle power is the power required for the equipment features that support the machine. The power, P, consumed by a machine using a three phase motor can be calculated from the measured current using equation 3:

$$P = V \cdot I \cdot \sqrt{3} \tag{3}$$

where V is the voltage and I is the Current.

Fig. 8 shows the energy that would be required to remove 1 cubic centimetre of the material. Machining at higher cutting speeds leads to shorter cycle times and reduced energy footprints. The use of TiN coated tools reduces the energy footprint compared to the uncoated tools for most of the higher cutting speeds tested. Moreover re-coating the tools after either laser or chemically stripping does not significantly compromise the reduction in energy footprints to be gained from the use of coated tools. On average the energy required for material removal (excluding that consumed by machine modules) was evaluated to be 13% of the total energy for the machining process.

Reducing energy footprints is important for controlling cost as well as in minimising carbon footprints in machining. The latter is the case because the energy footprints can be used to evaluate the carbon footprints associated with the energy generation. However, the carbon equivalent for electrical energy delivered to a machine shop depends on the energy source mix (the balance between nuclear, gas, coal, hydro, and wind etc – i.e. power generation station suppliers). This erodes a basis for a universal quantitative comparison of carbon footprints for a product. However, since carbon footprints are evaluated from energy footprints by an appropriate geographical carbon intensity factor, the conclusions arrived at above with respect of energy footprints will be mirrored in comparing carbon footprints.

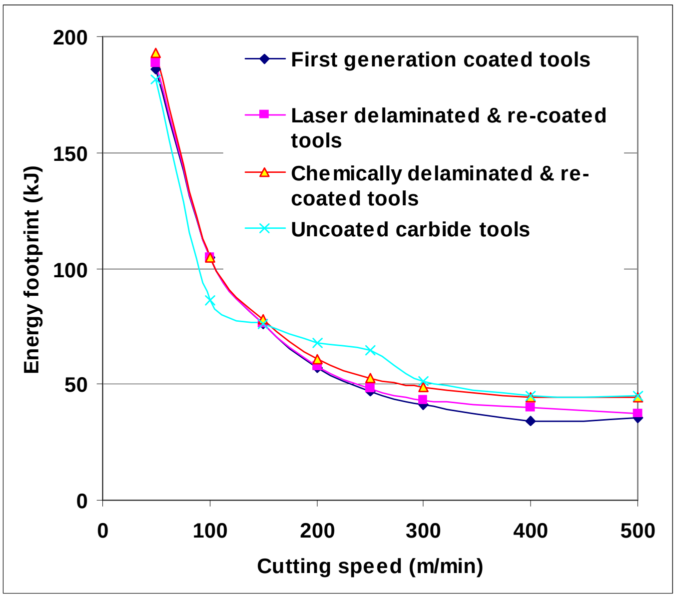


Fig. 8. Energy footprint for removing one cubic cm

3.5. ENERGY CONSUMPTION AND FOOTPRINTS FOR LASER DE-COATING

The power and energy consumed by the laser machine during the de-coating process was noted and is displayed in Fig. 9. This figure shows the variation of power consumption and laser output energy with various input voltage at a constant frequency of 50 Hz (corresponds to the operating condition for laser de-coating of tools). As shown in the

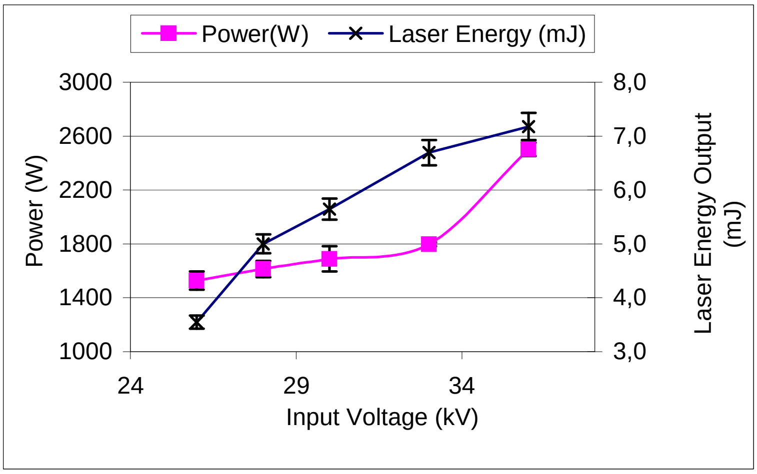


Fig. 9. Variation of power consumption with laser energy (frequency = 50 Hz)

figure the power consumption and output laser energy increases with increase in input voltage. During the de-coating process an input voltage of 28 kV corresponding to output laser energy of 5 mJ was used to obtain a laser fluence of 2 J/cm^2 at the irradiation spot.

With the operating parameters as discussed in section 3.1, the time required for de-coating 2 μm thick TiN coating was 20 seconds per mm^2. The area removed for each of the cutting edge using laser de-coating is 16 mm^2 hence time taken for de-coating was 320 seconds. Using 28kV input voltage, the total energy input was found to be 516.4 kJ. Comparing the energy required for the material re-use steps, it is clear that the energy consumed by the laser in the de-coating process (Fig. 9) is higher than the energy footprint for the machining process (Fig. 8). In case of chemical de-coating, it takes approximately 60 minutes for de-coating a batch of tools. As chemical de-coating process was done for a batch of tools, the de-coating rate cannot be compared directly. Additionally since no big machine tools are in the chemical stripping process, the energy consumption is not significant in relation to that of the laser process or metal cutting machine tools.

In establishing the process window for laser de-coating, minimum energy footprint was not the key objective. The results show that there is need for further work to improve the efficiency of the laser de-coating process. However, these results are in agreement with the work reported by Gutowski [15] who asserted that the newer processes are generally less energy efficient.

On the whole, de-coating remains more energy efficient compared to recycling the materials by re-melting. This works show that cutting tool re-use is possible by laser assisted de-coating or chemical de-coating and further improvements in the energy usage in processing may be possible through research.

3.6. ENERGY SUMMARY COMPARISON FOR THE DIFFERENT STEPS

A comparison of the energy footprints was undertaken for the process steps involved in the study. This comparison shown in Fig. 10, was based on the information presented before, the use of a laser in the de-coating process and the energy footprints for cutting tools as presented by Dahmus and Gutowski [16]. The graph shows the embodied energy for the carbide material is the highest footprint followed by the energy for sintering and coating of the inserts. The energy for de-coating is the third largest with the energy used in machining being the smallest footprint. Again, thee data show that manufacturing processes such as machining despite being traditional, and no longer considered as innovative are actually very competitive with regards to energy footprints and environmentally emissions. More importantly the data shows that the laser de-coating process utilises far less energy compared to the sintering process or material extraction from ore. Thus use of laser ablation in cleaning cutting tools for re-coating does not appear to compromise machining performance and is more energy efficient compared to primary processes for tooling manufacture.

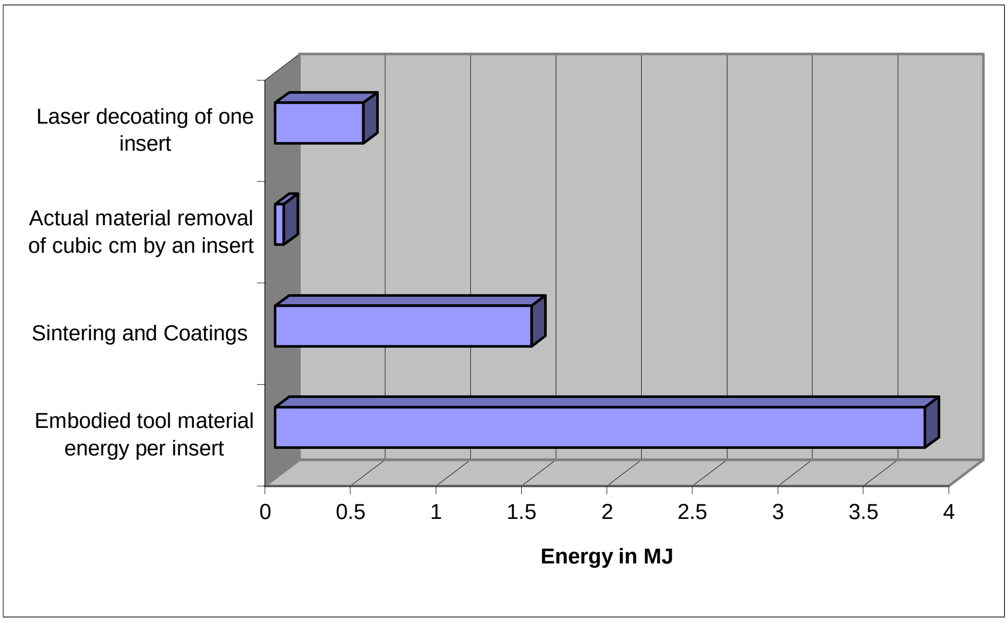


Fig. 10. Comparison of energy footprints for different process steps

4. CONCLUSIONS

Laser de-coating has the advantages of dry processing and selective removal. Excimer lasers can be used to successfully de-coat cutting tools. De-coating of coated tools through laser processing generates a superior surface finish compared to the established chemical stripping process. Re-use of recoated tools after laser or chemical de-coating does not significantly compromise machining performance (e.g. tool wear and workpiece surface finish) compared to first generation coated tools. For higher cutting speeds, compared to uncoated carbide tools, the use of first generation and re-coated tools reduces the energy footprint and hence the carbon footprint of the machining process. Re-coated tools after laser de-coating show some tool wear reduction and workpiece surface finish improvement at higher cutting speeds compared to those produced via a chemical de-coating route. Given the wide use of machining in industry, re-use of cutting tools could have significant resource utilisation and environmental benefits. Solutions for sustainable manufacturing and product re-use require the exploitation of multi-process expertise as demonstrated by this study.

ACKNOWLEDGEMENTS

The authors would like to thank the joint support offered by the Engineering and Physical Sciences Research Council (EPSRC) and the Technology Strategy Board (TSB), UK under the ELMACT grant DT/E010512/1 and Technology Programme grant TP/6/MAT/6/K1028G respectively and the Joule Centre grant JSGP408/09.

REFERENCES

[1] JOVANE F., YOSHIKAWA H., ALTING L., BOËR C.R., WESTKAMPER E., WILLIAMS D., TSENG M., SELIGER G., PACI A.M., 2008, *The incoming global technological and industrial revolution towards competitive sustainable manufacturing*, CIRP Annals - Manufacturing Technology, 57/2, 641-659.

[2] WIEDEMANN R., OETTEL H., BERTAM T., WEIHNACHT V., 2001, *Mechanical properties of TiN coatings*, Advanced Engineering Materials, 3/11, 865-870.

[3] MATIVENGA P., HON K.K., 2005, *Wear and cutting forces in high-speed machining of H13 using physical vapour deposition coated carbide tools*, Journal of Engineering Manufacture, 219/2, 191-199.

[4] AKBAR F., MATIVENGA P.T., SHEIKH M.A., 2008, *An evaluation of heat partition in the high-speed turning of AISI/SAE 4140 steel with uncoated and TiN-coated tools*, Journal of Engineering Manufacture, 222/ 7, 759-771.

[5] BONACCHI D., RIZZI G., BARDI U., SCRIVANI A., 2003, *Chemical stripping of ceramic films of titanium aluminum nitride from hard metal substrates*, Surface and Coatings Technology, 165/1, 35-39.

[6] NEVES P., ARRONTE M., VILAR R., BOTELHO DO REGO A.M., 2002, *KrF excimer laser dry and steam cleaning of silicon surfaces with metallic particulate contaminants*, Applied Physics A: Materials Science & Processing, 74/2, 191-199.

[7] KIM J., NA S., 2007, *Metal thin film ablation with femtosecond pulsed laser*, Optics & Laser Technology, 139/7, 1443-1448.

[8] TURNER M.W., CROUSE P.L., LI L., 2006, *Comparison of mechanisms and effects of Nd:YAG and CO2 laser cleaning of titanium alloys*, Applied Surface Science, 252/13, 4792-4797.

[9] HEITZ J., PEDARNIG J.D., BÄUERLE D., PETZOW G., 1997, *Excimer-laser ablation and micro-patterning of ceramic Si3N4*, Applied Physics A: Materials Science & Processing, 65/3, 259-261.

[10] DYER P.E., FARLEY R.J., GIEDL R., KARNAKIS D.M., 1996, *Excimer laser ablation of polymers and glasses for grating fabrication*, Applied Surface Science, 96/98, 537-549.

[11] LAPPALAINEN J., FRANTTI J., MOILANEN H., LEPPÄVUORI S., 1995, *Excimer laser ablation of PZT thin films on silicon cantilever beams*, Sensors and Actuators A: Physical, 46/1-3, 104-109.

[12] UMEDA Y., KONDOH S., SUGINO T., YOSHIKAWA H., 2006, *Analysis of Reusability using [`]Marginal Reuse Rate'*, CIRP Annals - Manufacturing Technology, 55/1, 41-44.

[13] SUN H., FIELD S., CHEN J., TEER D.G., 2004, *Study of deposition parameters, properties for PVD TixN and CrxN coatings using a closed field unbalanced magnetron sputter ion plating system*, Transactions of Materials and Heat Treatment, 25/5, 841-846.

[14] MINFORD W.J., MURPHY E.J., RICE T.C., 1985, Etching of titanium, United States Patent.

[15] GUTOWSKI T., DAHMUS J., THIRIEZ A., 2006, *Electrical energy requirements for manufacturing processes*, Proc. 13th CIRP International Conference on Life Cycle Engineering, Leuven, Belgium, 623-628.

[16] DAHMUS J., GUTOWSKI T., 2004, *An environmental analysis of machining*, Proc. ASME International Mechanical Engineering Congress (IMECE) and R&D Expo, Anaheim, California, 1-10.