On the mechanisms of wetting characteristics modification for selected metallic materials by means of high power diode laser radiation

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ABSTRACT

This work elucidates and analyses the factors responsible for modifications to the wettability characteristics of metallic materials after high power diode laser (HPDL) treatment. It was found that interaction of EN3 and EN8 mild steel with HPDL radiation resulted in the wettability characteristics of the mild steels altering to various degrees depending upon the laser processing parameters. Such changes in the wettability characteristics of the mild steels were found to be due essentially to: (i) modifications to the surface roughness; (ii) changes in the surface O$_2$ content and (iii) the increase in the polar component of the surface energy. All of these factors were seen to influence the wettability characteristics of the mild steels, however, the degree of influence exerted by each was found to differ. Work was therefore conducted to isolate each of these influential factors, thereby allowing the magnitude of their influence to be determined. This analysis revealed that surface roughness was the primary influential factor governing changes in $\theta$ and hence the wettability characteristics of the mild steels. Surface energy, by way of microstructural changes, was also shown to influence to a lesser extent changes in the wettability characteristics, whilst surface O$_2$ content, by way of process gas, was found to play a minor role in inducing changes in the wettability characteristics of the mild steels.

Key words: high power diode laser (HPDL), wettability, metal
I. INTRODUCTION

Both scientists and engineers alike have a great interest in understanding the interfacial phenomena between coatings and metal substrates, since in many practical applications where the coatings are applied onto metals, the performance of the article is directly linked to the nature of the coating-metal interface. The interfacial phenomena of wetting is often the primary factor governing whether a coating will adhere and bond to a substrate in practical applications such as enamelling and thermal spray coating. To date, very little work exists pertaining to the use of lasers for altering the surface properties of materials in order to improve their wettability characteristics.

Notwithstanding this, it is recognised within the currently published work that laser irradiation of material surfaces can effect their wettability characteristics. Previously Zhou et al. [1, 2] have carried out work on laser coating of aluminium alloys with ceramic materials (SiO\textsubscript{2}, Al\textsubscript{2}O\textsubscript{3}, etc.), reporting on the well documented fact that generated oxide layers often promote metal/oxide wetting. Furthermore, Heitz et al. [3], Henari et al. [4] and Olfert et al. [5] have found that excimer laser treatment of metals results in improved coating adhesion. The improvements in adhesion were attributed to the fact that the excimer laser treatment resulted in a smoother surface and as such enhanced the action of wetting. But, the reasons for these changes with regard to changes in the material’s surface morphology, surface composition and surface energy are not reported.

In contrast, work by Lawrence et al. on the laser modification of the wettability characteristics of a number of different composite [6-11], ceramic [12], metallic [13-15] and polymeric [16, 17] materials has shown that the wettability performance is affected by changes in the surface roughness, the surface O\textsubscript{2} content and the surface energy. Likewise, much detailed work has been carried out with excimer lasers which has shown the lasers to be a very effective means of enhancing the wettability characteristics of many polymeric materials. Much research has been carried out to study the effects of excimer laser radiation on the wettability characteristics of polyethylene terephthalate (PET) in both film [3], fibre [18] and sheet [19] form. The work on PET sheet by Andrew et al. [19] revealed that excimer laser treatment resulted in surface roughening. It was suggested that this was probably due to the differential etching of crystalline and amorphous regions in the material. Surface roughening was also obtained on polyparaphenylene terephthalamide (PPTA) fibres after excimer laser treatment by Watanabe.
and Takata [20]. Watanabe et al.[18] reported that after excimer laser treatment of PET films and fibres, an increase in adhesion was occasioned. It was proposed that such improvements were the result of the laser generating a more polar surface. Laurens et al. [21, 22] also concluded that a more polar surface resulted from the excimer laser treatment of polyetheretherketon (PEEK). Yet despite the large amount of work conducted with excimer lasers, no published literature to date exists pertaining to the use of other industrial lasers to modify the wettability characteristics of polymer materials.

The use of the high power diode laser (HPDL) to effect changes in the wettability characteristics of many materials, including metals, is a field of ongoing research. But, despite the fact that much understanding has already been acquired regarding the basic process phenomena and the numerous mechanisms involved, knowledge of the predominant influential factors, namely morphology, microstructure and surface chemistry, and the individual effects thereof on the HPDL modified wettability characteristics of metals is limited. This work describes the employment of a number of techniques to isolate these factors, thereby allowing their singular effect on changes to the wettability characteristics of a number of common engineering metals (EN3 and EN8) treated with a 1.2 kW HPDL to be ascertained.

II. EXPERIMENTAL PROCEDURES

A. Materials processing procedures

The solid materials used as substrates in the wetting experiments were rectangular billets (50 x 100 mm$^2$ with a thickness of 3 mm) of common engineering low carbon mild steel (EN3 and EN8). The contact surfaces of the materials were used as-received in the experiments. The general laser processing experimental arrangement comprised of the defocused laser beams being fired back and forth across the surfaces of the mild steel by traversing the samples beneath the laser beam using the x- and y-axis of the CNC gantry table. The laser used in the study was a 1.2 kW HPDL (Rofin-Sinar, DL-012), emitting at 940 nm. The laser beam was focused directly onto the samples to a 6 x 20 mm$^2$ rectangular beam with a fixed power of 500 W. The beam was traversed across the samples by means of mounting the assembly head onto the z-axis of a 3-axis CNC table as shown in Fig. 1. The focused laser beam was thus fired across the surface of the mild steel by traversing the samples beneath the laser beam using the x- and y-axis of the CNC table at speeds of 250-2000 mm min$^{-1}$. In order to study the effects of gas
type, Ar, N$_2$ and O$_2$ were blown through the gas box at a rate of 8 l min$^{-1}$. In order to analyse the laser treated specimens, they were examined using optical microscopy, scanning electron microscopy (SEM) and X-ray photoemission spectroscopy (XPS) techniques.

**B. Contact angle and surface energy analysis procedure**

To investigate the effects of HPDL processing parameters on the wetting and surface energy characteristics of the mild steels, wetting experiments were conducted. The experiments were comprised of control experiments carried out using the sessile drop technique with a variety of test liquids with known surface energy properties. Thus it was possible to quantify any surface energy changes in the mild steel resulting from laser interaction.

The sessile drop control experiments were carried out, using human blood, human blood plasma, glycerol and 4-octanol. Details of the test liquids are given in table 1. The experiments were conducted in atmospheric conditions at a temperature of 20$^\circ$C. The droplets were released in a controlled manner onto the surface of the test substrate materials (laser treated and untreated) from the tip of a micropipette, with the resultant volume of the drops being approximately 6 x 10$^{-3}$ cm$^3$. Each experiment lasted for three minutes with profile photographs of the sessile drops being obtained every minute. The contact angles were then measured with a mean value being subsequently determined. The standard deviation due to experimental error was calculated as being ±0.2$^\circ$.

**III. THE EFFECTS OF LASER OPERATING CONDITIONS ON WETTABILITY CHARACTERISTICS**

An optical micrograph of a sessile drop of a vitreous enamel (20$^\circ$C) placed on the surface of EN8 mild steel before (a) and after (b) HPDL irradiation with the contact angle superimposed is shown in Fig. 2. As one can see from Fig. 2, HPDL irradiation of the mild steel surface effected a considerable reduction in the enamel contact angle, $\theta$. Furthermore, as is evident from table 2, under the experimental laser parameters employed and processing in an O$_2$ atmosphere, HPDL irradiation of the surfaces of the mild steel samples resulted in changes in $\theta$. It can be seen that in general, interaction of the mild steels with the HPDL beam resulted in $\theta$ between the mild steel and the control liquids reducing.
A. The effects of surface morphology

According to Neumann et al. [23, 24], a model similar to that for heterogeneous solid surfaces can be developed in order to account for surface irregularities, being given by a rearrangement of Wenzel’s equation:

\[
\gamma_{sl} = \gamma_{sv} - \left( \gamma_{lv} \cos \theta_w \right) \frac{1}{r}
\]

(1)

where, \(\gamma_{sl}\) is the surface energy at the solid-liquid interface, \(\gamma_{sv}\) is the surface energy at the solid-vapour interface, \(\gamma_{lv}\) is the surface energy at the liquid-vapour interface, \(r\) is the roughness factor defined as the ratio of the real and apparent surface areas and \(\theta_w\) is the contact angle for the wetting of a rough surface. Eq. (1) shows clearly that if the roughness factor, \(r\), is large, that is the solid surface is smooth, then \(\gamma_{sl}\) will become small, thus, a reduction in the contact angle will be inherently realised by the liquid if \(\theta < 90^0\). In contrast, if \(\theta > 90^0\) then the opposite will be.

The HPDL induced surface effects on EN8 mild steel are clearly discernible from Fig. 2. From the microstructures shown in Fig. 3, it would appear that HPDL treatment occasioned surface melting and resolidification. What is more, table 3 shows that reductions in the surface roughness of both EN3 and EN8 mild steel were observed (using a Taylor-Hobson Surtronic 3+ profileometer) after interaction with the HPDL beam when using any of the selected process gasses, with the reductions in surface roughness being relatively similar in value.

B. The effects of process gasses

The effects of different process gasses will play a significant role in influencing \(\theta\) since the \(O_2\) content of a material’s surface is an influential factor governing the wetting performance of the material [25, 26]. Experiments were therefore conducted to investigate the effects of using Ar, \(N_2\) and \(O_2\) process gasses on \(\theta\). In order to study exclusively the effects of process gas on the wettability characteristics of the mild steels, the remaining laser operating parameters were set such that a similar degree of melting and solidification occurred and a similar surface roughness was achieved. Now, wetting is governed by the first atomic layers of the surface of a material, so, to determine the element content of \(O_2\) at the surface of the mild steels, it was necessary to examine the surface using XPS.
Figure 4 shows the results of the XPS analysis of both EN3 and EN8 mild steel in terms of the surface O$_2$ content when processed with selected gasses. As is evident from Fig. 4, increases in the surface O$_2$ content of both the EN3 and EN8 mild steel after HPDL interaction were observed only when processing was carried with an O$_2$ processing gas. In all other cases the surface O$_2$ content of both materials was seen to decrease markedly. Moreover, the assertion that surface O$_2$ content is an important factor in determining $\theta$ is borne out somewhat by Fig. 4, in which the effects of the differences in surface O$_2$ content appear to have a noticeable influence on $\theta$. It is clearly evident, however, from Fig. 5 that the reductions in $\theta$ do not correlate with the surface O$_2$ content results given in Fig. 4. Indeed, Fig. 5 shows that reductions in $\theta$ were occasioned after HPDL treatment regardless of the process gas employed, with the reductions being similar in value. Nevertheless, Fig. 5 shows quite clearly that the largest reduction in $\theta$ occurred when O$_2$ was used as the process gas and the surface O$_2$ content was subsequently the highest.

C. The effects of surface energy.

The intermolecular attraction which is responsible for surface energy, $\gamma$, results from a variety of intermolecular forces whose contribution to the total surface energy is additive [27]. The majority of these forces are functions of the particular chemical nature of a certain material, and as such the total surface energy, $\gamma$, comprises of $\gamma^p$ (polar or non-dispersive interaction) and $\gamma^d$ (dispersive component; since van der Waals forces are present in all systems regardless of their chemical nature). Therefore, the surface energy of any system can be described by [27]

$$\gamma = \gamma^d + \gamma^p$$

(2)

Similarly, the total work of adhesion, $W_{ad}$, can be expressed as the sum of the different intermolecular forces that act at the interface [27]:

$$W_{ad} = W_{ad}^d + W_{ad}^p = 2\left(\frac{\gamma^d_{sv} \gamma^d_{lv}}{\sqrt{\gamma^d_{sv} \gamma^d_{lv}}}\right)^{1/2} + 2\left(\frac{\gamma^p_{sv} \gamma^p_{lv}}{\sqrt{\gamma^p_{sv} \gamma^p_{lv}}}\right)^{1/2}$$

(3)

where $W_{ad}^d$ is the dispersive component of the work of adhesion, $W_{ad}^p$ is the polar component of the work of adhesion, $\gamma^d_{sv}$ is the dispersive component of the surface energy at the solid-vapour interface, $\gamma^d_{lv}$ is the dispersive component of the surface energy at the liquid-vapour interface, $\gamma^p_{sv}$ is the polar component of the surface energy at the solid-vapour interface and $\gamma^p_{lv}$ is the
polar component of the surface energy at the liquid-vapour interface. By equating Eq. (3) with the Young-Dupre equation:

\[ W_{ad} = \gamma_n (1 + \cos \theta) \] (4)

the contact angle for solid-liquid systems can be related to the surface energies of the respective liquid and solid by

\[ \cos \theta = \frac{2\left(\gamma_{sv}^{d}\gamma_{lv}^{d}\right)^{1/2} + 2\left(\gamma_{sv}^{p}\gamma_{lv}^{p}\right)^{1/2}}{\gamma_{lv}} - 1 \] (5)

In accordance with studies conducted by Fowkes [27] and Agathopoulos et al. [28], it is possible to estimate reasonably accurately the dispersive component of the surface energy of the mild steels, \( \gamma_{sv}^{d} \), by plotting the graph of \( \cos \theta \) against \( \left(\gamma_{lv}^{d}\right)^{1/2}/\gamma_{lv} \) in accordance with Eq. (5), with the value of \( \gamma_{sv}^{d} \) being estimated by the gradient (\( -2\left(\gamma_{sv}^{d}\right)^{1/2} \)) of the line which connects the origin (\( \cos \theta = -1 \)) with the intercept point of the straight line (\( \cos \theta \) against \( \left(\gamma_{lv}^{d}\right)^{1/2}/\gamma_{lv} \)) correlating the data point with the abscissa at \( \cos \theta = 1 \). Fig. 6 shows the best-fit plot of \( \cos \theta \) against \( \left(\gamma_{lv}^{d}\right)^{1/2}/\gamma_{lv} \) for the untreated and HPDL treated EN3 and EN8 mild steel-experimental control liquids system from which the values of \( \gamma_{sv}^{d} \) given in table 4 for the mild steels were deduced.

It is perhaps not surprising when one considers the similarities in the measured contact angles that the plots shown in Fig. 6 for the EN3 and EN8 are very similar. It can see clearly that the best-fit straight lines for both HPDL treated mild-steel-liquid systems intercept the ordinate higher above the origin than those of the untreated mild steel samples. This is of great importance since interception of the ordinate close to the origin is characteristic of the dominance of dispersion forces acting at the mild steel-liquid interfaces of the untreated samples, resulting in poor adhesion [27, 19]. On the other hand, an interception of the ordinate well above the origin is indicative of the action of polar forces across the interface, in addition to dispersion forces, hence improved wettability and adhesion is promoted [27, 29]. Furthermore, because none of the best-fit straight lines intercept below the origin, then it can be said that the development of an equilibrium film pressure of adsorbed vapour on the mild steel surface (untreated and HPDL treated) did not occur [27, 29].
Again, in accordance with studies conducted by Fowkes [27] and Agathopoulos et al. [28], it is not possible to determine the value of the polar component of the surface energy of the mild steels, $\gamma_{sv}^p$, directly from Fig. 6. This is because the intercept of the straight line (cos $\theta$ against $(\gamma_{lv}^p)^{1/2}/\gamma_{lv}$) is at $2(\gamma_{sv}^p\gamma_{lv}^p)^{1/2}/\gamma_{lv}$, and thus only refers to individual control liquids and not the control liquid system as a whole. However, it has been established that the entire amount of the surface energies due to dispersion forces either of the solids or the liquids are active in the wettability performance [27, 30]. As such, it is possible to calculate the dispersive component of the work of adhesion, $W_{ad}^d$, using only the relevant part of Eq. (3) thus

$$ W_{ad}^d = 2(\gamma_{sv}^d\gamma_{lv}^d)^{1/2} \quad (6) $$

The results reveal that for each particular control liquid in contact with both the untreated and HPDL treated mild steel surfaces, both $W_{ad}$ and $W_{ad}^d$ are related by the straight line relationship

$$ W_{ad} = aW_{ad}^d + b \quad (7) $$

where $a$ and $b$ are constants unique to each control liquid system. Also, for the control test liquids used a linear relationship between the dispersive and polar components of the control test liquids surface energies has been deduced which satisfies the equation

$$ (\gamma_{sv}^p)^{1/2} = 1.3(\gamma_{sv}^d)^{1/2} + 1.15 \quad (8) $$

By introducing Eq. (7) into Eq. (3) and rearranging, then

$$ W_{ad}^p = (a - 1)W_{ad}^d + b \quad (9) $$

or alternatively,

$$ (\gamma_{sv}^p)^{1/2}(\gamma_{sv}^p)^{1/2} = (a - 1)(\gamma_{sv}^d)^{1/2}(\gamma_{sv}^p)^{1/2} + \frac{b}{2} \quad (10) $$

By combining Eq. (10) with Eq. (3) and differentiating with respect to $(\gamma_{sv}^d)^{1/2}$, then the following can be derived:

$$ (\gamma_{sv}^p)^{1/2} = \frac{(\gamma_{sv}^d)^{1/2}(a - 1)}{1.3} \quad (11) $$
Thus, from the best-fit straight line plots of $W_{ad}$ against $W_{ad}^d$ for the mild steels when they are both untreated and HPDL treated, it was possible to determine the constants $a$ and $b$ for each separate condition of the mild steels. Since $\gamma_{sv}^d$ has already been determined for the untreated and HPDL treated mild steels from Fig. 6, then it is possible to calculate $\gamma_{sv}^p$ for untreated and HPDL treated mild steel using Eq. (11).

As one can see from table 4, HPDL treatment of the surface of the mild steels effected small increases in the polar component of the surface energy $\gamma_{sv}^p$ of the both EN3 and EN8. Such increases in the polar component of the surface energy of the mild steels will certainly have a positive effect upon the action of wetting and adhesion.

**IV. DISCUSSION OF LASER EFFECTED WETTABILITY CHARACTERISTICS MODIFICATION**

It is clear from the results presented previously that interaction of EN3 and EN8 mild steel with the HPDL resulted in the contact angle formed between the control liquids altering to various degrees depending upon the laser processing parameters. Such changes in the value of $\theta$ are influenced primarily by:

1. *Modifications to the surface roughness* - Regardless of the process gas used, HPDL treatment of the mild steels’ surfaces induced an ideal amount of surface melting and resolidification. This in turn resulted in reductions, to various degrees, in the surface roughness, thus directly reducing $\theta$.

2. *Surface $O_2$ content* - Changes in the surface $O_2$ content of the mild steels resulting from HPDL treatment in the various process gas atmospheres is an influential factor in the promotion of the action of wetting, since an increase in surface $O_2$ content inherently effects a decrease in $\theta$ and vice versa.

3. *Increase in the polar component, $\gamma_{sv}^p$, of the surface energy* - Resulting from the melting and resolidification of the mild steels’ surfaces, thus creating a different microstructure that quite possibly improved the action of wetting and adhesion.

From Fig. 3 it can be seen that the surface condition of the HPDL treated sample appears to be one indicative of melting and resolidification. Based on the observed $\theta$ measurements, it is
surmised that something like the optimum degree of surface melting is occasioned after HPDL surface treatment, resulting in a beneficial surface roughness. Similar laser induced surface smoothing effects were obtained by Nicolas et al. [31] and Henari et al. [4], who observed that excimer laser treatment of ceramics and metals could result in the generation of a smoother surface. Indeed, this supposition is borne out somewhat by Fig. 7, which shows that the surface condition of EN8 mild steel resulting from HPDL modification (with a number of different traverse speeds) greatly affected the measured contact angle between the mild steel and a vitreous enamel. As one can see from Fig. 7, at relatively low traverse speeds excess energy is deposited on the surface of the mild steel resulting in a high level of surface melting. This in turn causes porosities and a generally rough surface profile. As the traverse speed increases, however, the energy deposited on the surface of the mild steel reduces. Accordingly the degree of surface melting reduces ultimately to the optimum degree, resulting in the minimum surface roughness, and \( \theta \), at around 1500 mm min\(^{-1}\). Beyond this point the surface roughness, and contact angle, can be seen to increase, indicating that insufficient melting, and consequently smoothing, was achieved. Again, such results are in accord with those obtained by Feng et al. [32], who noted that under certain surface conditions, \( \theta \) reduction was inversely proportional to surface roughness. Further, Olfert et al. [5] found that excimer laser treatment of steel surfaces greatly improved the adhesion of a Zn coating. They asserted that laser treatment occasioned the smoothing of many of the high frequency surface features, resulting in more complete wetting by the Zn.

From the previous discussion it is unclear whether after HPDL surface treatment the surface roughness, the microstructural changes or the \( \text{O}_2 \) content alone, or a combination thereof, are the principal factors influencing the observed changes in the wettability characteristics of the mild steels. But by grinding the surfaces of the untreated and HPDL treated EN8 mild steel samples (treated in Ar, \( \text{N}_2 \) and \( \text{O}_2 \) atmospheres) down to 1 \( \mu \)m, whilst still retaining a HPDL treated surface, it was thus possible to isolate the effects of surface roughness by rendering them non-effective, and investigate at least the effects of the microstructural changes (and hence surface energy) and possibly those of the \( \text{O}_2 \) content (and hence process gas). Only the EN8 samples were analysed as it was assumed that since the wettability characteristics of two mild steels were seen to be similar, then the results obtained for the EN8 would be representative of not only both mild steels, but arguably of most metallic materials. An examination of the
contact angle characteristics of the ground EN8 mild steel samples using only glycerol revealed that $\theta$ was consistently around $30-34^0$ across the range of samples. In addition, from an XPS analysis the O$_2$ content of the EN8 samples it was found that O$_2$ content of the untreated sample remained around the original value at 33.8at%, whilst that of the HPDL treated samples was found to have reduced to a level similar to that of the untreated sample, 33.2-33.5at%. Since the measured contact angles of the ground samples varied by only $4^0$, despite the presence of the HPDL induced microstructures, then, combined with the fact that the O$_2$ content of the ground samples differed very little, it would appear from these findings that it is largely the surface roughness and quite possibly the surface O$_2$ content and the surface energy that are the main influential factors governing the changes in the wettability characteristics of the EN8 mild steel.

By grinding the samples further to remove the HPDL induced microstructures, one would be effectively removing the effects of surface energy from the previous investigation. The examination of $\theta$ between glycerol and EN8 samples was repeated and revealed that $\theta$ was consistently between $30-32^0$ across the range of samples. As before, the XPS analysis showed that the surface O$_2$ content on the untreated and HPDL treated samples were practically the same at 33.5-33.9at%. It is therefore reasonable to conclude that because the measured contact angles of the samples ground beyond the HPDL induced microstructures varied by only $2^0$, as opposed to $4^0$ when they were present, and that because the O$_2$ content of the ground samples was very similar, surface energy seems to play more of a role that surface O$_2$ in determining $\theta$. Additionally, these findings further confirm the assertion made previously that surface roughness is the primary influence in determining changes in the wetting characteristics of the EN8 mild steel. Further support for this proposition is apparent from an analysis of the surface O$_2$ content of the mild steels after HPDL treatment in the various atmospheres. As one can see from Fig. 3, the levels of surface O$_2$ content differ greatly across the range of process gasses used. Yet the observed reductions in $\theta$ after HPDL treatment were seen to be of a similar amount, regardless of the gas used. Nonetheless, as is evident from Fig. 4, the largest reduction in $\theta$ was obtained when processing was conducted in an O$_2$ atmosphere, which therefore generated the surface with the highest O$_2$ content. Such a finding implies that surface O$_2$ content does influence $\theta$, albeit to a limited degree, but surface roughness and surface energy play a more influential role.
V. CONCLUSIONS

This work has shown clearly that interaction of EN3 and EN8 mild steel with high power diode laser (HPDL) radiation resulted in the contact angle, $\theta$, and therefore the wettability characteristics of the mild steels altering to various degrees depending upon the laser processing parameters. Such changes in the wettability characteristics of the mild steels were found to be due essentially to: (i) modifications to the surface roughness resulting from HPDL treatment of the mild steels’ surfaces which, regardless of the process gas used, induced an ideal amount of surface melting and resolidification. This in turn resulted in reductions, to various degrees, in the surface roughness, thus directly reducing $\theta$; (ii) changes in the surface $O_2$ content of the mild steels resulting from HPDL treatment in the various process gas atmospheres since an increase in surface $O_2$ content inherently effects a decrease in $\theta$ and vice versa and (iii) the increase in the polar component, $\gamma^p_v$, of the surface energy resulting from the melting and resolidification of the mild steels’ surfaces, thus creating a different microstructure that quite possibly improved the action of wetting and adhesion.

All of these factors were seen to influence the wettability characteristics of the mild steels, however, the degree of influence exerted by each was found to differ. Work was therefore conducted to isolate each of these influential factors, thereby allowing the magnitude of their influence to be determined. This analysis revealed that surface roughness was the primary influential factor governing changes in $\theta$ and hence the wettability characteristics of the mild steels. Surface energy, by way of microstructural changes, was also shown to influence to a lesser extent changes in the wettability characteristics, whilst surface $O_2$ content, by way of process gas, was found to play a minor role in inducing changes in the wettability characteristics of the mild steels.

Based on the results of this work, it is perhaps reasonable to assume that these findings are generic and therefore could be applied to most metallic materials in terms of wettability characteristics modification by means of laser radiation.
REFERENCES


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FIG. 1. Schematic representation of the 1.2 kW HPDL head assembly.

FIG. 2. Contact angles for a vitreous enamel on (a) the as-received EN8 mild steel surface, and (b) the HPDL treated mild steel surface (1500 mm min\(^{-1}\) traverse speed, O\(_2\) atmosphere).

FIG. 3. Typical SEM surface images of the EN8 mild steel (a) as received and (b) after HPDL treatment (1500 mm min\(^{-1}\) traverse speed, O\(_2\) atmosphere).

FIG. 4. Surface O\(_2\) content of the EN3 and EN8 mild steels before and after HPDL treatment in the various process gas environments (1500 mm min\(^{-1}\) traverse speed).

FIG. 5. Mean values of contact angle formed between glycerol at 20\(^{\circ}\)C and the EN3 and EN8 mild steel before and after HPDL treatment in the various process gas environments (1500 mm min\(^{-1}\)).

FIG. 6. Plot of \(\cos \theta\) against \(\left(\frac{\gamma_a}{\gamma_w}\right)^{1/2}\) /\(\gamma_w\) for the untreated and HPDL treated EN3 and EN8 mild steel in contact with the wetting test control liquids (1500 mm min\(^{-1}\), O\(_2\) atmosphere).

FIG. 7. Relationship between surface roughness, \(\theta\) (enamel) and traverse speed for the HPDL treated EN8 mild steel (O\(_2\) atmosphere).
FIG. 1.

- Cooling water connection
- Power supply connection
- Diode stacks
- De-focused laser beam
- Mounting holes
- Sealed box
- Mild steel (EN8) sample
- Gas Inlet
- Gas Outlet
FIG. 2.

(a) $\theta = 64^0$

(b) $\theta = 23^0$
FIG. 3.
FIG. 4.
FIG. 5.
FIG. 6.
FIG. 7.

Contact Angle, $\theta$
Surface Roughness, $Ra$

Laser Power: 500 W
Shield Gas: Oxygen
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Table 1. Total surface energy ($\gamma_{lv}$) and the dispersive ($\gamma_{lv}^d$) and polar ($\gamma_{lv}^p$) components for the selected test liquids.

Table 2. Mean values of contact angles formed between the selected test liquids at 20°C and the EN3 and EN8 mild steel before and after interaction with the HPDL in an O$_2$ atmosphere.

Table 3. Surface roughness values (Ra) of the EN3 and EN8 mild steel before and after interaction with the HPDL in the various process gas environments (1500 mm min$^{-1}$).

Table 4. Determined surface energy values for the EN3 and EN8 mild steel before and after HPDL irradiation.
Table 1

<table>
<thead>
<tr>
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<th>$\gamma$</th>
<th>$\gamma'_s$</th>
<th>$\gamma'_{lv}$</th>
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<td>(10$^{-3}$ Jm$^{-2}$)</td>
<td>(10$^{-3}$ Jm$^{-2}$)</td>
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<tr>
<td>Glycerol</td>
<td>63.4</td>
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<td>EN8 untreated</td>
<td>55</td>
<td>59</td>
<td>44</td>
</tr>
<tr>
<td>EN8 HPDL treated</td>
<td>41</td>
<td>39</td>
<td>32</td>
</tr>
</tbody>
</table>
Table 3

<table>
<thead>
<tr>
<th>Material</th>
<th>Surface Roughness, Ra</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Untreated</td>
</tr>
<tr>
<td>EN3 HPDL treated</td>
<td>1.51 µm</td>
</tr>
<tr>
<td>EN8 HPDL treated</td>
<td>1.46 µm</td>
</tr>
<tr>
<td>Surface Energy Component</td>
<td>Material Condition</td>
</tr>
<tr>
<td>-----------------------------------</td>
<td>--------------------</td>
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<tr>
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</tr>
<tr>
<td>Dispersive, ($\gamma^d_{sv}$) (mJ/m²)</td>
<td></td>
</tr>
<tr>
<td>Polar, ($\gamma^p_{sv}$) (mJ/m²)</td>
<td></td>
</tr>
</tbody>
</table>