Laser surface remelting and alloying of aluminium alloys

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Abstract
Aluminium alloys offer notable advantages in the manufacture of structural components, but generally they have poor tribological behaviour characteristics.
Such disadvantages can be lessened by adequate surface treatments, which do not compromise the over–all properties of the material used.
Laser surface remelting and alloying treatments enable the obtainment of surface layers of an adequate thickness, characterized by distinct metallurgical properties.
By laser surface alloying it is possible to alter the metallurgical and mechanical characteristics of the sublayer submitted to radiation by addition on its surface of a predetermined quantity of chemical elements melted together with the base material.
By suitable techniques, it is possible to achieve sound alloyed layers of no less than one millimetre thick, with hardness values of over 200 HV, obtained with laser powers that are industrially acceptable in decidedly short treatment times.
By simply remelting it is possible to drastically reduce or even eliminate pre–existing porosity in the material submitted to laser radiation by exploiting the rapid solidification of thin surface layers, and consequently remarkable benefits in terms of tensile strength and ductility are achieved and hence, also thermical fatigue resistance.

Riassunto
Trattamento superficiale di leghe di alluminio mediante laser
Le leghe di alluminio offrono notevoli vantaggi nella costruzione di componenti strutturali, ma possiedono in generale mediocri caratteristiche di comportamento tribologico.
Questi svantaggi possono essere ridotti con opportuni trattamenti di superficie che non compromettono le proprietà globali del materiale utilizzato.
I trattamenti di alligazione e di rifusione laser consentono l'ottenimento di strati superficiali di spessore adeguato e caratterizzati da spiccate proprietà metallurgiche.
Con il processo di alligazione è possibile alterare la composizione chimica e, conseguentemente, le caratteristiche metallurgiche e meccaniche del substrato sottoposto a irraggiamento mediante apporto sulla sua superficie di quantità prefissate di elementi chimici fusi assieme al materiale base.
Impiegando adeguate tecniche di trattamento risulta possibile l'ottenimento di strati alligati sani, di spessore non inferiore al millimetro, possedenti valori di durezza superiori ai 200 HV, ottenuti con potenze laser industrialmente accettabili e con tempi di trattamento decisamente contenuti. Mediante la semplice rifusione è possibile, sfruttando la rapida solidificazione di sottili strati superficiali, operare una drastica riduzione o addirittura una completa eliminazione delle porosità preesistenti nel materiale sottoposto a irraggiamento laser con conseguenti notevoli benefici in termini di resistenza a trazione e duttilità e quindi di resistenza a fatica termica.

Introduction

The following are some of the most outstanding results of this work, which aims at local modification of the properties of an aluminium alloy for castings by laser surface remelting and alloying.
The objective can be attained through local modification of the microstructure with remelting followed by fairly fast solidification.
If, however, the surface of the aluminium alloy is to possess mechanical and metallurgical properties not inherent in the original alloy, modification of the microstructure must be accompanied by modification of its chemical composition, also through remelting, but in this case with the addition of alloying material to the molten bath before solidification.
This paper covers certain aspects of the process which tends on the whole, to be fairly complicated, as the laser treatment of aluminium alloys gives rise to a large number of metallurgical problems, connected with the peculiar physical properties of the material; these tend to make the actual process critical (high thermal conductivity, low density, low melting temperature, compared with the added materials).

Materials and treatments

The tests were made using G–Al Si 7 Cu 3 (DIN) aluminium alloy as substrate in the form of plane specimens or components.
The experiments were made using the 15 kW Avco HPL 6 laser as the source, and consisted in a set of penetration tracks, with variation of the parametric conditions each time.

Surface remelting – Results and discussion

The surface remelting tests were assessed on the basis of metallographic inspections, to determine the maximum depth, the hardness, soundness and microstructure of the remelted layer.
Fig. 1 shows the melted depths obtained with a single pass, detected at the centre of sections drawn at 20 and 40 mm from the starting point of the treatment.
As expected, the high thermal conductivity of the material led to a noticeable increase in the depth of penetration (and generally in the melted volume) as the treatment proceeded; this increase became more and more significant as the time of interaction increased.
From a metallurgical point of view, the most remarkable effect of fast solidification induced by laser is the refinement of the dendritic structure, as revealed by the metallographic examination (Fig. 2).
Generally, it is possible to distinguish three different areas with differing microstructure in the treated part: an interface between the remelted area and the basic

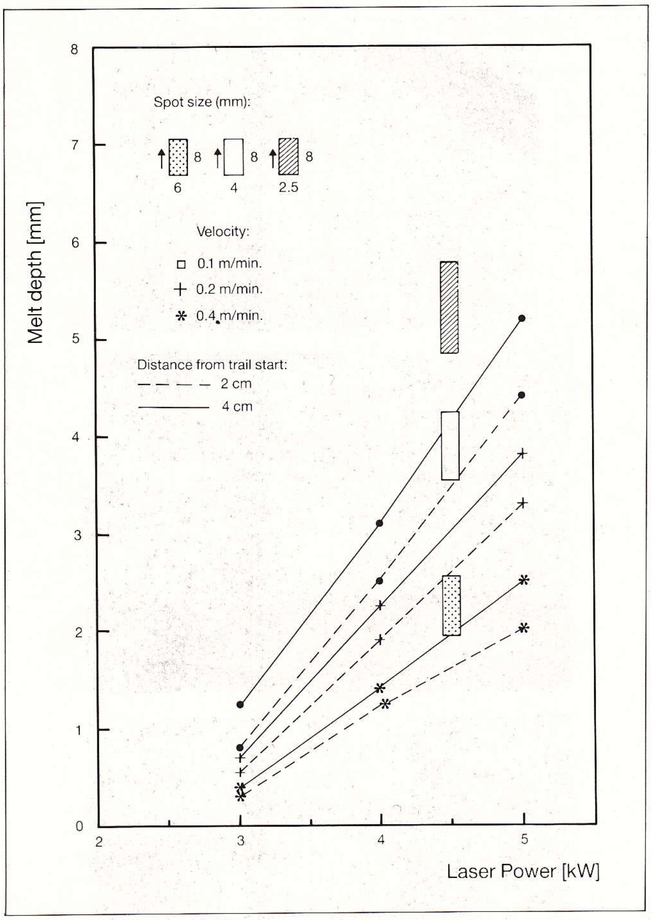


Fig. 1 - Laser surface remelting. Melt depth with regard to process parameters.

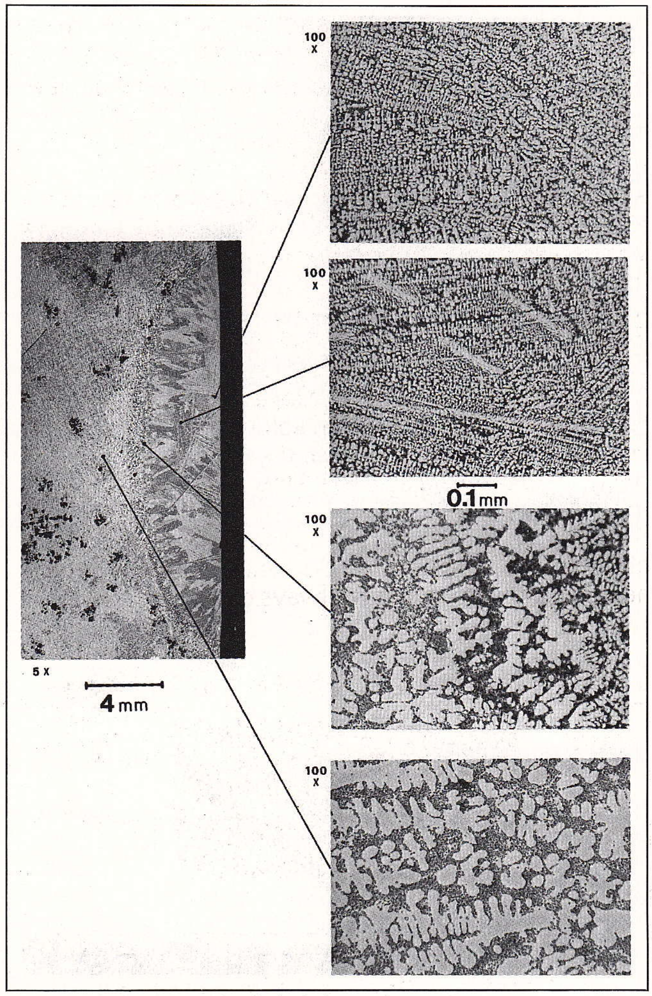


Fig. 2 - Laser surface remelting. Optical micrographs.

material, with a somewhat coarse structure, and with a tendency towards concentrations of microporosities and interdendritic shrinkages; an area close to the surface, with a very fine structure with equiaxial growth of the dendrites, and an intermediate area between the two outlined above, which reveals a basically columnar behaviour of the dendritism. There, both metallographic and ultrasonic (C-Scan) inspection revealed almost complete removal of the original porosities.
Tests with partially overlapping tracks showed structural and sclerometric faults at the edge of the overlapped area (Fig. 3), where there was also a tendency towards the formation of fairly large porosities. However, hardness values proved to be, on average, 25% higher than in the basic material.

Surface alloying - Results and discussion

This process differs from the simple remelting process in that it modifies the chemical composition of the irradiated material, through the application of pre-established quantities of alloying powders melted together with the basic material, on its surface.
In our experiment, the iron-based powders were sprayed on; laser parameters were set as follows: incident power 5 kW with speeds between 60 and 120 cm/min.
The single pass was obtained by reducing the scanning speed every 40 mm during the course of the treatment. This condition must always be taken into account when interpreting the results given below, in that each step treated is affected by the preheating induced by the previous steps (a similar effect to that already found in remelting).
Fig. 4 shows the optical and electronic micrographs of a typical alloyed layer.

Hardening mechanisms

Tests made with an electronic microprobe on the

various test specimens treated always showed a rather high percentage of aluminium (over 60%) in the alloyed layer, even though high hardness values were achieved (up to 600 HV).
This is possible because the rapid solidification induced by the laser beam makes it possible to obtain supersaturated solutions of the alloying elements in aluminium, characterized by a wide range of hardness values. In the case under consideration, taking into account the melted masses and volumes, the cooling rate was estimated to be around 10^4 K/s.
Fig. 5 shows, as an example, the hardness and total of alloyed elements trends according to the distance from the surface in a typical laser-alloyed layer.
Hardening by supersaturated solutions must be considered, at present, one of the possible hypothesis but not the only one able to justify the hardening mechanism.
Another hypothesis, strengthened by new observations, may be based on the formation of needlelike phases that are always observed in all the

Fig. 3 - Laser surface remelting: a) overlap of two trails; b) C-Scan inspection.

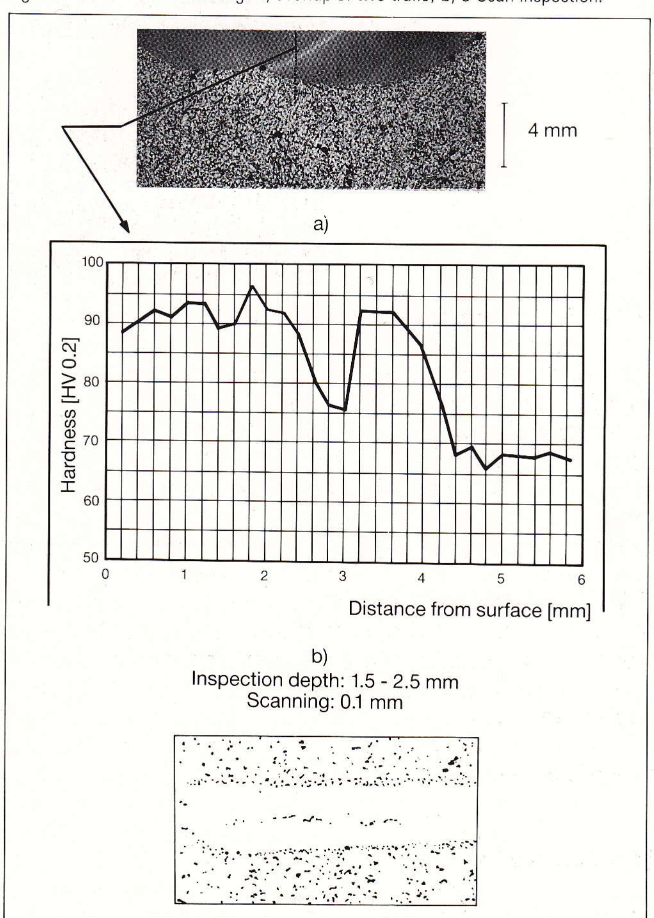


Fig. 4 - a) Cross-section of an alloyed trail; optical micrograph. b) and c) Sem micrographs.

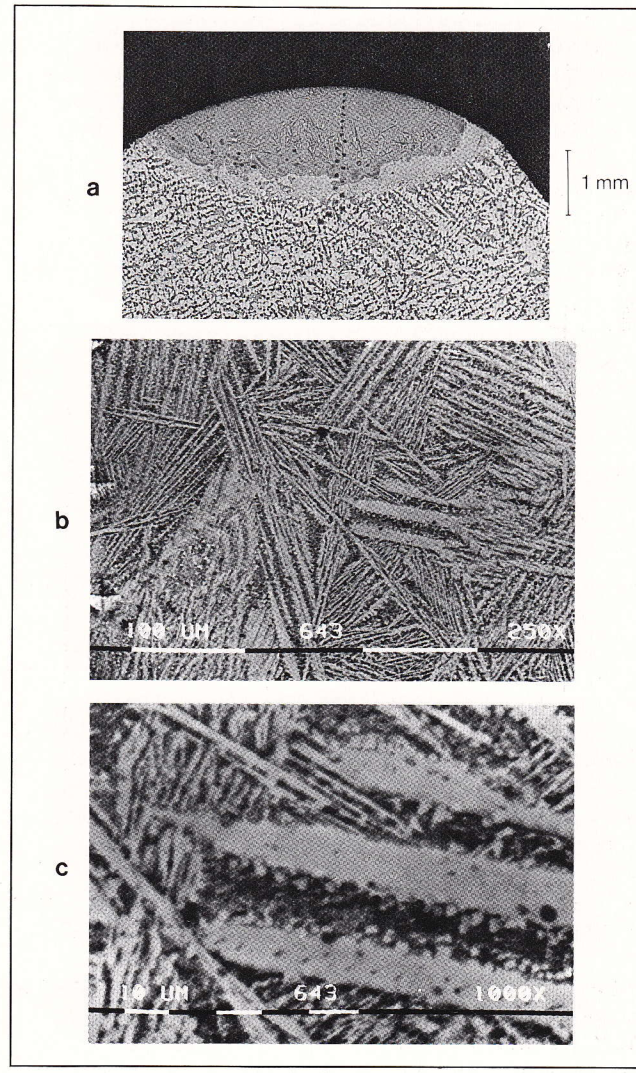
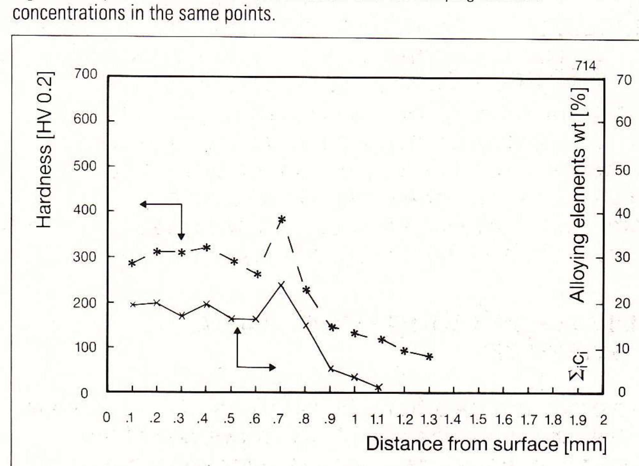


Fig. 5 - Comparison between microhardness and the alloying element concentrations in the same points.



alloyed layers. Examinations by electronic microprobe pointed out that such phases are characterised by nearly constant chemical composition indifferently to be localized in alloyed layers very differently hardened. So we can't exclude that such phases are, as a matter of fact, intermetallic compounds that confer hardness according to their distribution density and not, by definition, according to their level of saturation.
In any case it should be noted how the cooling rate at the solid-liquid interface ($\dot{\varepsilon}$) and the sum of the concentrations of all the alloying elements ($\Sigma\, c_i$) represent the independent variables responsible for the hardness:

$$H = H\,(\Sigma\, c_i,\ \dot{\varepsilon}) \tag{1}$$

with

$$\dot{\varepsilon} = \dot{\varepsilon}(\vec{r},\ V_f) \tag{2}$$

where $\vec{r}$ is the vector that indicated the single positions inside the treated area and V_f is the melted volume.
The high-density laser power used for the alloying treatments leads to a negligible functional dependence between $\dot{\varepsilon}$ and $\vec{r}$ just as negligible is the dependence of $\dot{\varepsilon}$ on the amount of the melted volume, the variations of which, at least in the cases under consideration, were very limited. Therefore, in our case, there is a mere functional dependence between the hardness values and the sum of the concentrations of the alloyed elements, that is:

$$H = H\,(\Sigma\, c_i) \tag{3}$$

where $\Sigma\, c_i$ clearly depends on the amount of powder used and on the melted volume which, in turn, depends on all the independent variables of the process.

Fig. 6 - Hardening of the alloyed layer at progressive distances (1 ⟶ 2 ⟶ 3) from start.

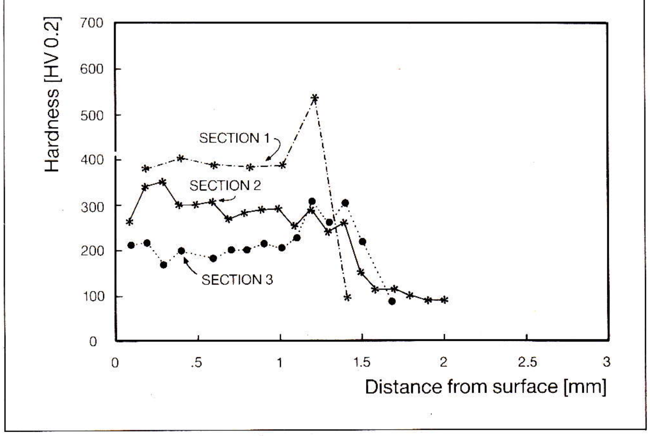


Fig. 5 confirms the one-to-one correspondence between hardness and composition of the layer, as defined by (3). Note that the composition values given in the graph were obtained from micro-analyses made inside the hardness test impressions.
Fig. 6 shows the hardness values taken on transverse sections of a single alloyed track, drawn at a distance of 10 mm from each other, beginning from the start-of-treatment area.
The fairly constant behaviour of the hardness values in the single sections is particularly noteworthy, confirming structural homogeneity (see the micrographs of Fig. 4) as a result of the strong convective flows generated in the liquid pool.
A comparison of the three curves shows that the mean hardness values tend to drop off gradually as the treatment proceeds. This phenomenon can be ascribed, not to the effect of postheating, which leads to redistribution of the elements in the various phases

Fig. 7 - Hardness versus velocity at different powder mass flows.

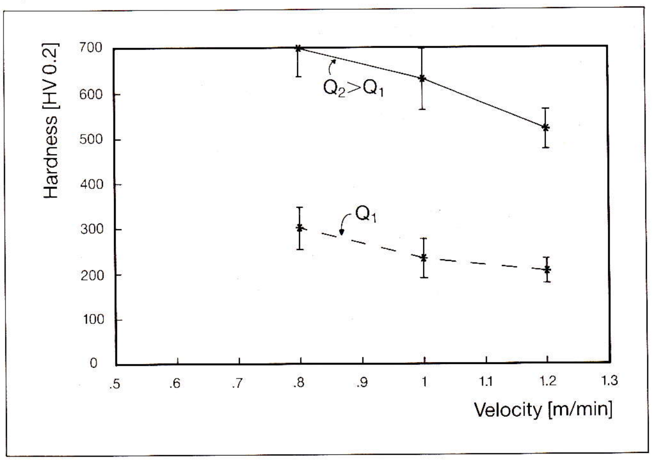
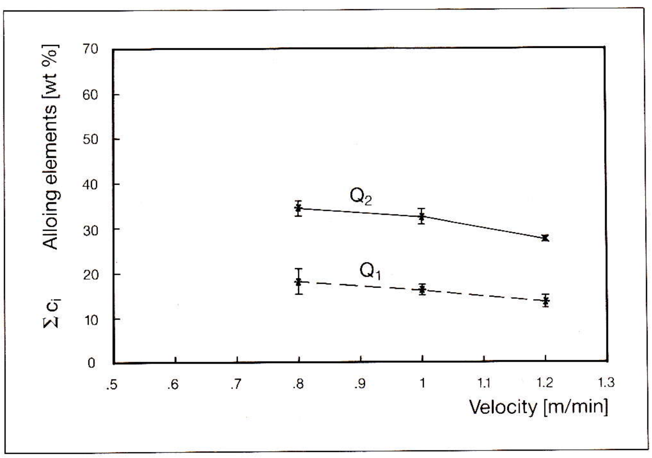


Fig. 8 - Alloying element concentrations versus velocity at different powder mass flows.



or a partial resolubilization, but rather to a greater dilution of the alloying elements due to the gradual increase in the melted volume during the course of the treatment. This phenomenon is obviously emphasized in the case of specimens with limited mass (as in Fig. 6) while, with larger specimens, there is no great difference between the mean hardness of the individual sections.

Correlation of hardness/scan rate

Fig. 7 gives the mean values and the standard deviations in the hardness values measured on the transverse sections of alloyed layers, obtainded by varying the traversing speed of the specimens during treatment. The two curves refer to two different amounts Q of sprayed powder.

Note that, for a given amount of powder, the hardness of the alloyed layer increases as the traversing speed is reduced. This is to be ascribed to the combination of two contrasting effects: if we reduce the scanning rate while keeping the amount of powder sprayed constant, the amount of powder involved in the process increases, and this leads to enhancing the hardness; however, if we reduce the scanning rate, the melted volume increases, the concentration of the alloyed elements reduces and, in consequence, the hardness decreases. The predominance of one or other of the two factors depends on the mass of the specimen involved: if the mass is fairly small, the second factor tends to dominate, and the hardness is progressively reduced; otherwise, if the mass is large, the first factor prevails and there is a notable increase in hardness.

The case shown in Fig. 7 refers to a large specimen in which there is very limited increase in melted volume as the treatment speed is reduced. Fig. 8 gives the sums of the concentrations of the alloyed elements according to the treatment speeds. Note that a 25% increase in the amount of powder sprayed ($Q_2 = 1.25\ Q_1$) does not lead to a proportional increase in concentration. This phenomenon can be explained by considering that a larger amount of powder tends to enhance the screening effect on the radiated surface, and this leads to a lower melted volume.

Similar conclusions to those set forth above make it possible to anticipate the effect of variation in the size of the laser spot. It is clear from what has been outlined above, that if the diameter of the spot is reduced, the treatment speed and the amount of powder sprayed remaining constant, there is a reduction in the melted volume, with a consequent increase in the concentration of alloyed elements and hence in hardness (Figs. 9 and 10).

Fig. 11 shows hardness trends according to concentrations of alloyed elements. The curve plotted

Fig. 9 - Hardness versus velocity at different spot laser diameters.

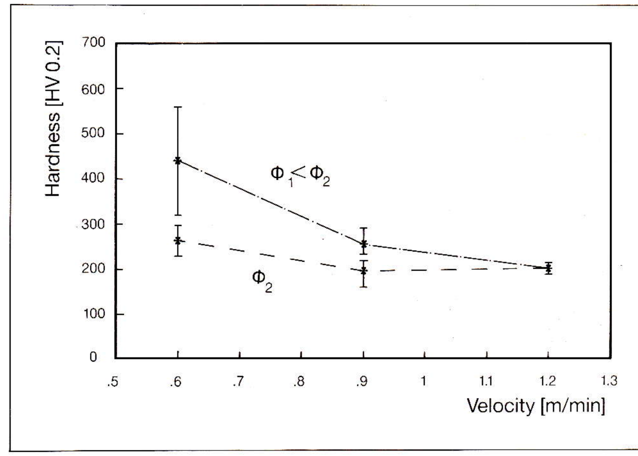


Fig. 10 - Alloying element concentrations versus velocity at different spot laser diameters.

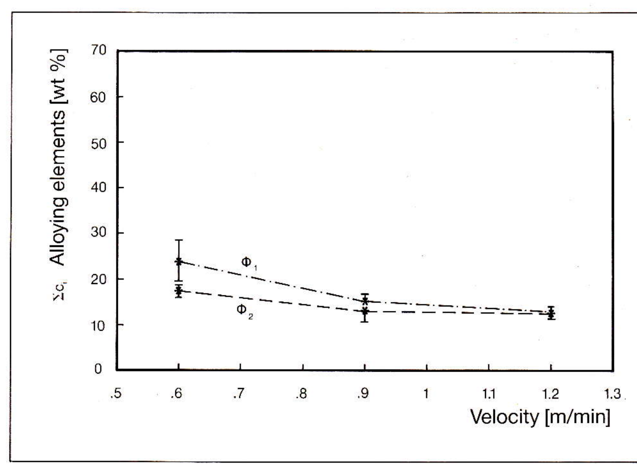
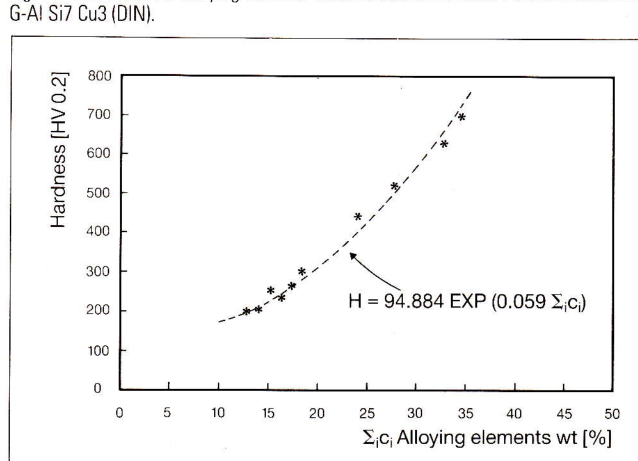


Fig. 11 - Hardness Vs. alloying element concentrations. Powder: Fe base. Substrate: G-Al Si7 Cu3 (DIN).



is the best fit of the experimental points, referred to the various process parameters considered (variation of treatment speed, amount of powder and diameter of the laser spot).
The analytical equation which expresses the functional dependence between hardness and the concentration of alloyed elements, valid for the type of powder used here, is as follows:

$$H = 94.884 \exp(0.059 \Sigma c_i)$$

Conclusions

An examination of some of the metallurgical aspects of the laser-beam surface alloying and remelting processes, revealed a number of correlations between the characteristics of the alloyed layer and the treatment conditions.
It is clear that, at least as far as alloying is concerned, the properties of the treated layer can be directly ascribed to the degree of dilution of the alloying elements; it follows, therefore, that if the correlation between this and the process parameters is known, it is possible to "design" the alloyed layer to suit the way in which the component is to be used.

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