Lasers in Manufacturing Conference 2019

Laser cladding with conical beams

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Abstract

The new approach in selective laser cladding using conical laser beams has been elaborated. Initial round laser beam is divided into two circular beams with regulated distribution of the laser power throughout the circular beams. Circular beams are transformed to conical beams, which are focused separately on the surface and on the deposited material for heating. The laser energy delivery to powder stream is very efficient because a total uniform absorption of laser energy in the dense powder stream (10^4-10^5 1/cm^3). Optimal regimes of cladding using multi-passage scheme were determined. Under wire deposition the heating of substrate reduces the residual stresses due the reduction temperature gradients and compensates heat losses from deposition zone by thermal conduction. The required power density for melt contact formation is significantly reduced.

Keywords: laser cladding; conical laser beams; separated heating; deposited material; high efficiency;

1. Introduction

The efficiency of using conical beams McLeod, 1954 in laser cladding was first shown by Chivel ,2004, 2005. However, the implementation of this innovative optical technology took about ten years. Recently, conical laser beams began to be introduced into the laser wire cladding technology Pitch, 2012. However, the developed devices use a single conical beam, which does not provide optimal heating of the wire and surface and energy-consuming. In addition, the proposed optical systems are inefficient when using a powder Kuznetsov, 2016.

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For separated heating of the deposited material and surface the method of laser cladding using conical laser beams has been elaborated Chivel , 2014,2018. Initial round laser beam is divided into two or more circular beams with regulated distribution of the laser power throughout the circular beams. Circular beams are transformed to conical beams, which are focused separately on the surface and on the deposited material (powder stream, wire, suspension stream) for heating . A focuses of conical beams are arranged along the optical axis by which the deposited material is fed.

2. Laser cladding method

The elaborated laser cladding method consists in feeding a cladding material into the focal region of a laser beam, located on the surface of an object to be treated. A series of parallel annular laser beams with an adjustable distribution of laser radiation power across the annular beams is formed from an initial circular laser beam, and are separately focused along a single optical axis, along which the cladding material is fed. The device (fig.1a) contains a laser, which is optically linked to a system for forming a series of annular laser beams with an adjustable distribution of laser radiation power across the annular beams, a focusing lens and system for feeding cladding material, a rotating mirror with an opening through which are passed tubes for feeding gas, cooling liquid and cladding material, and a system of conical focusing mirrors.

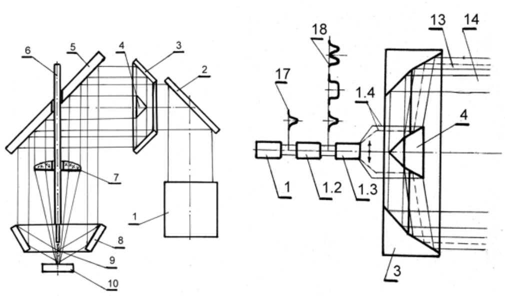

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Fig.1. (a) Laser cladding optical scheme. (b) Multi beam forming scheme

The device operates as follows. The laser beam 1 after passing through the adjustable beam expander is transformed into a two annular beams. One of the beams is focused by lens 7 on the product surface 10 to a irradiation spot and melt surface in spot. Cladding material is fed through the tube 6 in the form of a powder stream 9 or wire. Other conical beamare focused by means of conical mirrors 8 in the predetermined region of the stream 9 to heat this region.

Other optical system was elaborated for production series annular laser beams (fig.1b) with regulated distribution of laser energy across the beams.

By changing the dimensions of the beam 1.4 after the beam expander 1.3 can redistribute the power of the laser on areas 13 and 14 and thereby regulate the process of cladding and efficiency of the heating the surface and a stream of the material.

3. Laser cladding with powder

In the elaborated method Chivel,2018 the laser energy introduction to powder stream is more efficient because heating of small particles at stationary mode of operation and a total uniform absorption of laser beam energy is possible in the dense powder stream.

On powder injecting the structure of beam will be modified through laser light absorption and scattering. We consider the amplitude variations of the beam taking into account attenuation of laser light in snugpacking dispersed layer. The calculations are carried out for Ti spherical particles with diameter d=30µm under volume density $N=10^6 cm^{-3}$ accordingly. The radius of powder beam is taking to be R= 250 µm. For coherent light passing the exponential connection between coefficient of attenuation and layer's thickness can be used Ivanov et al., :

$$T=\exp(-Q\eta) \qquad (1)$$

where $\eta = 3Rn_1/2d$ – coefficient of layer's overlap, Q – effective factor of attenuation , $n_1=0,74(d/\delta)^3$ - dimensionless volume density of particles ($\delta=2d$ – average distance between particles).

For layer from optically hard large particles ($\pi d/\lambda>1$, $\pi d/\lambda(n-1)>>1$) the effective factor of attenuation may be written :

$$Q=1/1,5n_1 \ln[1+1,5n_1 Qi \exp(1,5n_1 Qi)] \qquad (2)$$

where Qi – attenuation factor of a single particle.

The transmission of powder stream has described by the relationship:

$$T=\exp[-\sigma(R-r)] \qquad (3)$$

where (R-r)- depth of laser light penetration into the powder stream in µm, σ—attenuation coefficient, Qi - factor of attenuation of insulated particle. Calculation values of attenuation coefficient for concerned powder streams are equal $\sigma= 45 cm^{-1}$ (D=500 µm). Laser intensity attenuation causes the Bessel beam peak intensity to fall and the distribution of laser intensity within powder stream level is leveled.

Intensity distribution of laser radiation within the powder stream in the absence of a interference excluding small center area has described by the following expression Shafer et al.,:

$$q=q_0(R/r)[e^{-\sigma(R-r)}+e^{-\sigma(R+r)}] \qquad (4)$$

The scattered laser radiation is effectively absorbed by particles under repeated scattering. The calculations of scattered radiation attenuation in the frame of transport theory Naumenko and Chivel, allows to determine diffuse transmission and reflection of powder stream.. For discussed above 100µm powder stream from 10µm particles Td = 0,16-0,30 for the length 50 µm , and Rd= 0,02-0,17, depending on the nature of reflection of diffuse radiation from the stream borders. The transmission of coherent light come to T=0,1 for the length 250 µm.

The potentials of the new method of laser radiation energy delivery to powder stream for production were investigated. In the model under study the dense stream ($10^6 cm^{-3}$) diameter 0,5mm from steel micropowders with particles 30 µm in size is injected into the focal region of conical beam 5-10 mm long at the rate of several m/s. Dynamics of heating and evaporation of spherical particles describe by equations:

$$4/3\pi r^3 \rho C(dT/dt)=\pi r^2 qQ_a - E - L\cdot G; \quad (5)$$

$$dr/dt=-G/4\pi r^2 \rho; \quad (6)$$

where r – particle radius, ρ – density of particle material, C – specific heat , q- laser radiation intensity, Qa – factor of absorption of particle, E – energy flow from particle surface, L – specific heat of evaporation, G – mass flow from surface.

Under initial step of particle heating the losses on evaporation and thermal conductivity are small and temperature dynamic may be write in view:

$$T=3q\cdot t\cdot Qa/4\rho\cdot Cr \quad (7)$$

According the calculations at particles duration of stay in the heating region ~ 10^{-2}s , the required laser power for heating to 1500 K not exceed ~ 200 -300W.

At low absorption of laser radiation in the stream of the deposited material efficiency of laser radiation drops sharply at a single passage of radiation through the stream. For maximum use of radiation multi pass scheme is offered Chivel, 2010 using a cylindrical mirrors 11, 12 (fig. 2). First, the stream heating increases and secondly, the laser radiation absorption increases up to the full absorption when returning the coherent part of the laser radiation to laser resonator by mirror 12 Chivel, 2016.

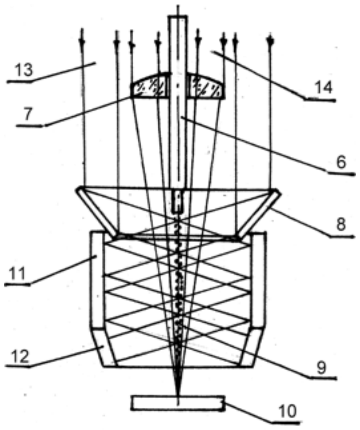

Fig. 2. Multi pass optical scheme of the laser cladding device .

Optimal regimes of cladding using multi-passage scheme were determined. The calculations were carried out for the case of a thin 2 mm in diameter stream of steel 30 µm powder and a thick stream -2 cm in diameter. Calculations on the Mie theory showed that the attenuation factor of an individual steel particle with 30 µm in diameter is equal Qi ≅ 2 and at a concentration of particles in a stream of 10^4 - 10^5 cm^{-3} are optimal for stream diameters of 20mm and 2mm, respectively. Under these conditions, the transmission of powder stream of 10 % is achieved in 10 passes of laser radiation.

4. Laser cladding with wire

While there are many processes you can utilize for cladding not all are ideal for the deposition of large amounts of material where minimal heat and dilution are needed. Laser cladding with powder has lower deposition rates and high "overspray" (material that does not stick to the clad).

Laser wire cladding is a process that combines a wire with a laser beam, and offers many benefits over traditional clad processes. It's ideal for corrosion and wear resistance, when you have a very detailed part or when exact chemistry specifications need to be met.

The new approach in wire laser cladding process has been elaborated. Using two conical beams (fig.3a) optimal heating of wire and substrate has been achieved.

Surface heating under surface absorption of radiation is described by equation Steen, 2004:

$$\nabla^2 T = (dT/dt)/a \qquad (8)$$

where T – temperature of the surface, a – thermal diffusivity.

In the one-dimensional approximation for a continuous source. we have a solution Libenson et al,2014:

$$T(x,t) = 2q/k\ [(at)^{1/2}\ \mathrm{ierfc}\ (x/2(at)^{1/2}\ ] \qquad (9)$$

For moving source the temperature distribution over the surface (z = 0) in moving coordinate system XY has the form:

$$T\ (x,y) = [Aqr^2/\ 2\pi k(x^2 + y^2)]\ \ \exp\{\ [-V(x + (x^2 + y^2)^{1/2}]/2a\} \qquad (10)$$

where V – velocity , r – radius of focal spot, q – power density,
A- absorptivity.

There are simple solutions for fast and slow motion of the heating spot. The criterion for choosing a solution is the ratio of the exposure time t_e and the thermal conductivity time t_c:

$$t_e = 2r/V\ ,\quad t_c = r^2/a \qquad (11)$$

If $t_c < t_e$, $V < 2a/r$ - slow motion .

And in this case, the temperature distribution over the surface (z = 0) in moving coordinate system has the form:

$$T = Aqr\ /k + T_0 \qquad (12)$$

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If V> 2a/r regime of fast motion is realized and temperature distribution has the form :

$$T(0)= 2Aq(2\cdot a\cdot r)^{1/2}/ \pi^{3/2}kV^{1/2} \qquad (13)$$

The calculations of the process of cladding a steel wire with diameter of 100 μm on a steel substrate are carried out. The diameter of the focusing spot on the substrate is 200 μm and on the wire - 80 μm (fig.3a). The scanning and wire feeding speed is assumed to be 200 mm/s. Calculations were carried out for the regime of fast heating. The results are shown in Fig. 3b. In particular, for a speed of 200 mm / s, the required power for melting the wire is 200 watts and heating the surface to the melting required 580 watts.

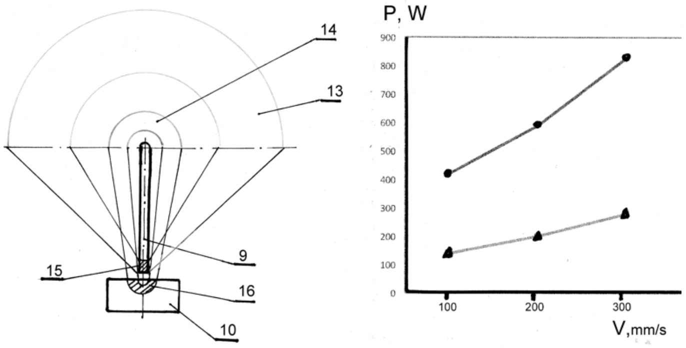

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Fig.3. (a) Scheme of laser wire cladding. (b) Laser power versus scan velocity.

These powers are much lower than when using a single laser beam.

Because of these characteristics, coaxial laser wire cladding with conical beams has a lower dilution rate compared to other cladding processes with high travel speed and minimal heat input, maximizing the temperature of the wire, which is quickly melted off in the puddle.

The result is that the process can be operated at higher speeds resulting in thinner layers, with less heat input, and therefore, less impact dimensionally or metallurgically to a part.

5. Experimental

Experimental laser cladding system has been elaborated and produced (Fig.4b). The main optical scheme (Fig.4a) has been used.

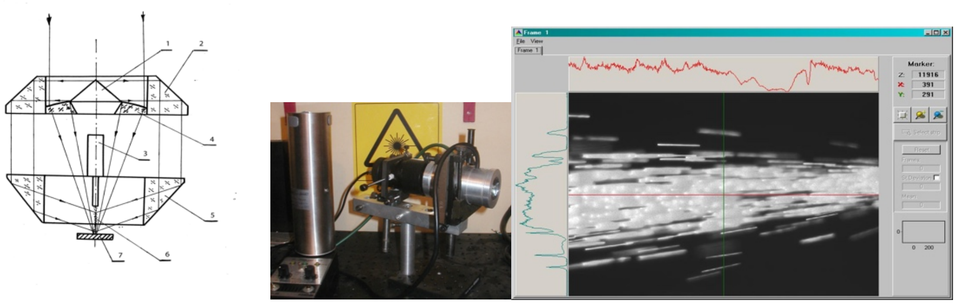

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Fig. 4. (a) The optical scheme of the laser cladding system .1 – conical mirror, 2,5 – totally reflecting conical prism, 4 – lens, 6 – focusing region in powder stream, 7- workpiece; (b) photo of laser cladding system; (c) powder stream image under laser heating. Input diameter of stream – 0.5 mm.

The process of heating of dense powder stream was worked out. CW diode laser with power 200W was optically connected with adjustable beam expander.

Spherical INOX powder +15-30 µm in size was fed to focal region of conical beam 8 mm in length through tube 0.8 mm in diameter by the use of the powder feeder at the rate ~2 m/s. According the calculation particle density in focal region was about $10^5 cm^{-3}$.

At Fig.4c powder stream under action registered by CMOS camera are presented.
Dense powder stream is almost completely warmed up to the full depth.

Conclusions

For separated heating of the deposited material and surface the new system of laser cladding using conical laser beams has been elaborated. Space-independent and separated heating of workpiece and stream of deposited material provides optimum thermal process conditions, can significantly reduce energy costs and increase cladding accuracy.

The calculations and modelling demonstrate that the new method of the independent energy input to powder stream and surface using conical laser beams is more efficient because heating of small particles at stationary mode of operation and a total uniform absorption of laser beam energy is possible in the dense powder stream.

By this means the harnessing of the conical beams allows to carry out a laser power delivery to powder stream uniformly across the surface of stream, resulting in gain in productivity and accuracy. The laser radiation distribution within the dense streams is sufficiently uniform, excluding a small region near the axis of stream. The optimum heating of powder particles may be achieved with high efficiency. The optimal regimes of laser cladding can be achieved using multi pass optical scheme and conical beams with different wavelengths. New method also allows significantly raise parameters of the laser wire cladding and efficiency of this process. Coaxial laser wire cladding with conical beams has a lower dilution rate compared to other cladding processes with high travel speed and minimal heat input.

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