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Review
Laser surface alloying: a bibliography

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Laser alloying is a material processing method which utilizes the high power density available from focused laser sources to melt metal coatings and a portion of the underlying substrate. Since the melting occurs in a very short time and only at the surface, the bulk of the material remains cool, thus serving as an intimate heat sink. Large temperature gradients exists across the boundary between the melted surface region and the underlying solid substrate. The result is rapid self-quenching and resolidification. Quench rates as great as 10^{11} K sec^{-1} and concomitant resolidification velocities of 20 m sec^{-1} have already been realized. What makes laser surface alloying both attractive and interesting is the wide variety of chemical and microstructural states that can be retained because of the rapid quench from the liquid phase. These include chemical profiles where the "alloyed" element is highly concentrated near the atomic surface and decreases in concentration over shallow depths (hundreds of nanometers), and uniform profiles where the concentration is the same throughout the entire melted region. The types of microstructures observed include extended solid solutions, metastable crystalline phases, and metallic glasses. This bibliography is a compilation of published work in this area.

1. Introduction

The use of laser sources to produce metal surface alloys has become a materials processing application receiving considerable attention. The concept of laser surface alloying (LSA) is schematically pictured in the sequential cross-section views in Fig. 1. In Fig. 1a the metal substrate (B) coated with a thin metal film (A) is irradiated with a laser pulse. A fraction of the incident laser light is absorbed by free carriers within the electromagnetic skin depth (10^{-6} to 10^{-5} cm). For metal surfaces and most laser wavelengths a significant fraction of the incident light will be specularly or diffusely scattered away (the reflectance process is not shown in the illustration). The absorbed energy is "instantaneously" (10^{-12} sec) transferred to the lattice. The near surface region very rapidly reaches the melting point and a liquid/solid interface starts to move (solid arrows) through the film as shown in Fig. 1b. In Fig. 1c the liquid/solid interface has swept through the original thin film/substrate interface. Interdiffusion of the film (solid circles) and substrate (open circles) elements starts. The laser pulse is nearly terminated and the surface has remained below the vapourization temperature. In Fig. 1d the maximum melt depth has been reached. Interdiffusion continues. The resolidification interface velocity is momentarily zero and then rapidly increases. The resolidification interface then moves approximately half way back to the surface from the melt depth (Fig. 1e). Interdiffusion in the liquid continues but the resolidified metal behind the liquid/solid interface cools so rapidly that solid state diffusion may be neglected. In Fig. 1f the material is completely resolidified and a "surface alloy" of A in B has been produced. What makes laser surface alloying both attractive and interesting is the wide variety of chemical and microstructural states that can be retained because of the rapid quench from the liquid phase.

Fig. 2 is a bar graph of laser surface alloying (LSA) publications as a function of time. Much of the interest is rationalized from the standpoint of strategic element shortages and precious metal costs. All directed energy (laser, electron, and ion

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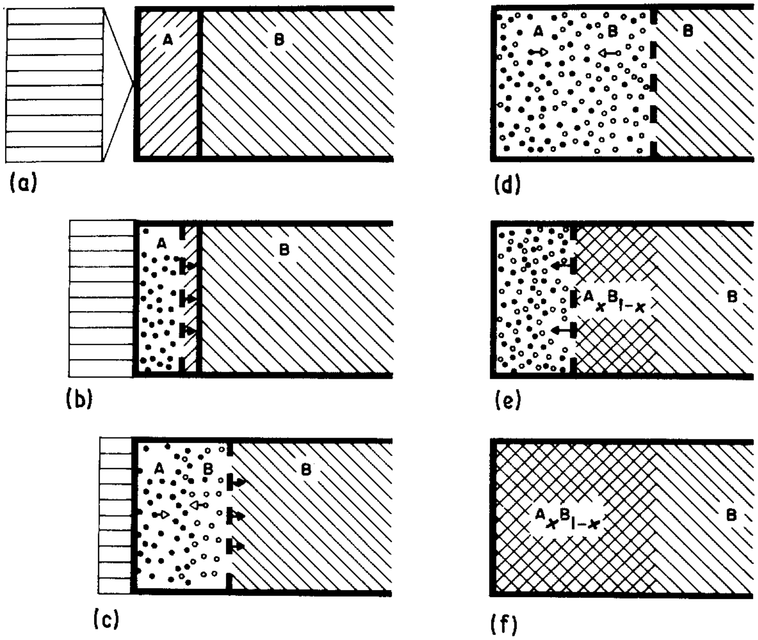

Figure 1 Sequential cross-section schematic illustration of mechanism of laser surface alloying from arrival of laser pulse to complete resolidification.

beam) methods of modifying surface composition are by their very nature materials conservation oriented. When an element is incorporated in a bulk alloy solely for the purpose of affecting the alloys response to its interface environment, surface rather than bulk alloying is attractive.

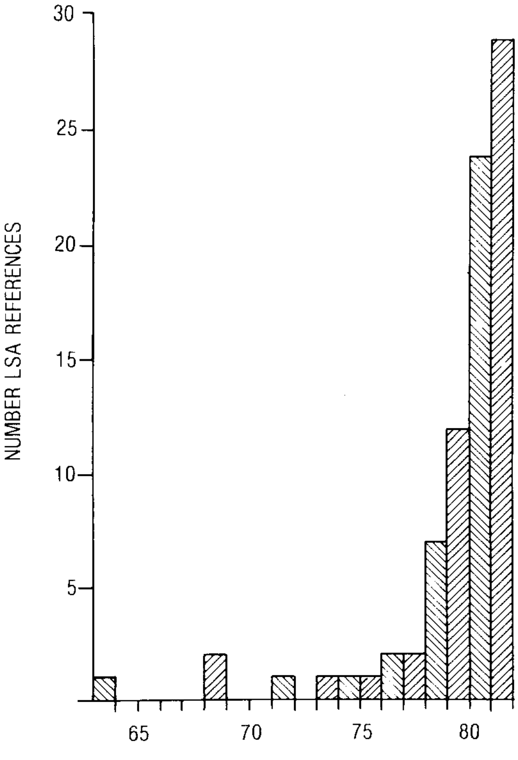

Figure 2 Growth in the LSA literature over the last 20 years.

Much of the more recent work explores the use of Q-switched laser sources to achieve high velocity regrowth ($10\,\mathrm{m\,sec^{-1}}$) of the molten metal interface. Extended solid solutions, metastable crystalline and amorphous surface alloys have all been formed by LSA processing. Other reasons for the growing interest are the wider availability of laser sources capable of energy fluences sufficient to melt metal surfaces and some spin-off from the immense push into semiconductor laser annealing.

Whatever the reason, it appears that there will continue to be significant growth in the literature on LSA, and that a timely updated bibliography [108] will aid interested parties in keeping abreast of current research activity.

In assembling Tables I and II, we have attempted to include all scientific literature that falls within the scope of laser surface alloying. Search methods included computer keyword and author searches of chemical, physics, metals, and laser abstracts. Written correspondence and telephone conversations with other active researchers in this field have been very helpful.

Table I is a chronological list of the laser surface alloying literature. No attempts have been made to order the literature on a finer scale than the year of publication. Table headings include the reference year, type of laser sources, alloying specie/host substrate, post-irradation analysis of

TABLE I

Year	Laser	Alloying specie/substrate	Analysis	Reference
1964	P-Ruby	C, W, TiC, WC/St	COMP:EPM SSB:MH	[1]
1969	P-NdG	C/Fe	STRT:XRD SSB:MH	[2]
1969	P-Ruby	WC/St	STRT:OM COMP:EPM SSB:WR	[3]
1972	P-Ruby	C, WC/St	STRT:XRD SSB:MH	[4]
1974	P-NdG	C, W/Fe; Co/W; Al/Nb	STRT:OM, XRD	[5]
1975	CW-CO_2	Cr, Ni, W, V, Mn, C/St	COMP:ANG SSB:MH	[6]
1976	P-NdG	Ni, Mo, Ti, Ta, Nb, V/Fe, St	SSB:MH	[7]
1977	P-NdG	Mo, Nb/Fe	COMP:ANG	[8]
1977	P-NdG	Mo/Fe	STRT:OM, XRD COMP:XRD SSB:MH	[9]
1978	P-NdG	V/Fe	STRT:OM, XRD COMP:XRD SSB:MH	[10]
1978	CW-CO_2	CrC, WC/St	STRT:OM COMP:ANG SSB:MH	[11]
1979	CW-CO_2	Cu/Ag–7 Cu	STRT:OM, SEM	[12]
1979	Q-Ruby	Cu/Al	STRT:CHN COMP:RBS	[13]
1979	CW-CO_2	Cr, Ni/St	STRT: OM COMP:EPM, EDX	[14, 15]
1979	CW-CO_2	Cr–C–Mn–Al/St	STRT:OM COMP:EPM SSB:MH	[16, 20]
1979	P-NdG	Fe/Nb	STRT:MOSB, XRD	[17]
1979	CW-CO_2	Mo–Ni–Si–Cr–C/St	STRT:OM, XRD COMP:EDX, ANG SSB:MH, HTS, WR	[18]
1979	CW-CO_2	Cr/St	STRT:OM, SEM COMP:EPM, EDX, AES	[19]
1980	CW-CO_2, Q-NdY	Au, Ag, Pg, Sn, Ta/Ti	STRT:OM, SEM, CHN COMP:RBS, EDX, AES, ESCA SSB:MH, COR	[21]
1980	CW-CO_2	TiC, WC/Ti–6Al–4V, Inconel	STRT:OM, SEM	[22]
1980	Q-NdG	Sb/Al	STRT:OM, XRD COMP:RBS	[23]
1980	Q-Ruby	Ni/Fe/SiO_2	STRT:TEM SSB:MAG, OPT	[24]
1980	CW-CO_2	TiC, WC/St, Ti–6Al–4V, Inconel, 5052Al	STRT:OM SSB:MH	[25]
1980	P-NdY	Re/Fe–50 Ni	STRT:OM, SEM COMP:EPM	[26]
1980	Q-NdY	Au, Ag, Ta/Ni	STRT:OM, CHN COMP:RBS	[27]
1980	Q-dNdY	Pb/Cu	STRT:CHN COMP:RBS	[28]
1980	CW-CO_2	TiC/304 St	STRT:SEM SSB:MH	[29]
1980	Q-Ruby	Cu, Pb/Al	COMP:RBS	[30]
1980	CW-CO_2	B, FeB/St	STRT:OM, SEM, TEM SSB:MH, HTS	[31]

TABLE I Continued

Year	Laser	Alloying specie/substrate	Analysis	Reference
1980	CW-CO$_2$	Cr/4815 St; Ni, Cr, Si/Al VC, WC/St; TiC/Ti; Ni–CrAl/St	STRT:OM COMP:ANG	[32]
1981	Q-Ruby	Zn, Sb/Al	STRT:TEM, CHN COMP:RBS	[33]
1981	Q-NdY	Au, Ag, Pd, Ta, Sn/Ni	STRT:TEM, CHN COMP:RBS	[34]
1981	Q-Ruby	Ni/Au/Ni	STRT:TEM COMP:RBS	[35]
1981	Q-Ruby	Mo, Cd/Al	STRT:CHN COMP:RBS	[36]
1981	Q-NdY	Hf/Ni	STRT:CHN, PAC COMP:RBS, AES	[37]
1981	Q-NdY	Pd/Ti	COMP:RBS SSB:COR	[38]
1981	CW-CO$_2$	TiC, WC, WC–Co/St	COMP:EDAX STRT:SEM SSB:MH	[39]
1981	CW-CO$_2$	Cr, Cr–Co/St	STRT:OM SSB:MH	[40]
1981	CW-CO$_2$, Q-NdY, Q-dNdY, Q-Ruby	Au/Ni	STRT:CHN COMP:RBS	[41]
1981	CW-CO$_2$, Q-NdY, Q-dNdY	Au/Ni	STRT:CHN COMP:RBS	[42]
1981	Q-Ruby	Cr, Sb/Al	THRY:HF, MT	[43]
1981	Q-dNdY	Ag/Ni	STRT:CHN COMP:RBS	[44]
1981	CW-CO$_2$	TiC/Ti–6Al–4V, 304 St, 4340 St, 5052 Al, Al-bronze	STRT:OM, SEM	[45]
1981	CW-CO$_2$	Si, TiC/5052 Al	STRT:OM, SEM	[46]
1981	CW-CO$_2$	Fe–B/Fe–12Cr–2C, Ni$_{60}$Nb$_{40}$/Nb	STRT:TEM, OM SSB:MH, HTS	[47]
1981	CW-CO$_2$	Cr/St	SSB:COR	[48]
1981	Q-NdG	Cr/Al	COMP:RBS, SEM	[49]
1981	CW-CO$_2$	Cr, Cr–Ni/St Cr–W–TiC/St	COMP:ANG SSB:MH	[50]
1981	CW-CO$_2$	TiC, WC/Ti–6Al–4V, 304 St, 5052 Al	STRT:SEM SSB:MH, WR	[51]
1981	Q-Ruby	In/Al	STRT:PAC	[52]
1981	CW-CO$_2$	Cr/Fe	COMP:EPM STRT:OM	[53]
1981	Q-NdG	Sb/Al	COMP:RBS, SEM	[54, 55]
1982	Q-Ruby	Zn/Al, Au/Ni	THRY:MT	[56]
1982	Q-NdG	Pb/Al	COMP:RBS, SEM	[57]
1982	Q-Ruby	Cu/Al	Soret coeff.	[58]
1982	Q-Ruby	V–Si/sapphire	COMP:RBS STRT:XRD SSB:SC	[59]
1982	Q-Ruby	Cr/Al	COMP:RBS STRT:CHN, SEM	[60]
1982	Q-Ruby	Cr, Mo/Al	COMP:RBS STRT:CHN SSB:HTS	[61]
1982	Q-Ruby	Eu, Ni/Ni	COMP:RBS STRT:CHN, SEM	[62]
1982	Q-Ruby	Sb/Al	STRT:CHN, TEM	[63]
1982	Q-dNdY	Cr, Ni/Cu	COMP:RBS, AES STRT:CHN, TEM, XRD SSB:COR	[64]
1982	Q-dNdY	Zr/Ni, Al, Fe, Ti, V Cu/Zr	COMP:RBS STRT:TEM, CHN, XRD	[65]

TABLE I Continued

Year	Laser	Alloying specie/substrate	Analysis	Reference
1982	Q-Ruby	Cu, Zn/Al Au/Ni	THRY:MT	[66]
1982	CW-CO$_2$	WC–Co, WC–Co–Mo, WC–Ni–Cr–B–Si/St	COMP: ANG STRT:OM, SEM SSB:MH	[67]
1982	CW-CO$_2$	Fe–B/St	STRT:XRD, TEM	[68]
1982	CW-CO$_2$	Cr/Fe–0.2C	COMP:EDAX STRT:OM, TEM	[69]
1982	CW-CO$_2$	FeTi, FeCr, FeCb, FeV, FeSi/St	STRT:OM, SEM	[70]
1982	CW-CO$_2$	8Al–12Mo–3Ta–Ni 12Al–15Mo–Ni	COMP: ANG STRT:TEM SSB:TNS	[71]
1982	CW-CO$_2$	Mo/St	COMP:EDAX STRT:SEM SSB:MH	[72]
1982	CW-CO$_2$	Ni/Fe	COMP:EPM THRY:MT	[73]
1982	Q-NdG	Sn/Al, W/V, Pb/Fe, W/Cr	COMP:RBS STRT:CHN	[74]
1982	CW-CO$_2$	Cr/Fe	COMP:EPM STRT:SEM	[75]
1982	Q-NdG	Pb/Al	COMP:RBS STRT:SEM	[76]
1982	ML-NdY	Fe$_3$B/Fe	STRT:TEM	[77]
1982	CW-CO$_2$	Al, Cr, Ni/Fe	COMP:EPM THRY:MT	[78]
1982	CW-CO$_2$	Ni/Fe	COMP:EDAX STRT:TEM, OM	[79]
1982	CW-CO$_2$	Cr/St	COMP:EDAX STRT:TEM, SEM SSB:MH	[80]
1982	CW-CO$_2$	Cr–Ni/4140 St	COMP:EPM SSB:COR	[81]
1983	Q-Ruby	Cu/Au/Co Cu/W/Cu	COMP:RBS	[82]
1983	Q-NdY	Hf/Ni	COMP:RBS STRT:PAC, CHN	[83]
1983	CW-CO$_2$	Mo/6150 St	COMP:EDAX STRT:SEM, TEM SSB:MH	[84]
1983	CW-CO$_2$	Ni/1020 St Cr/1018 St	THRY:MT COMP:EPM	[85, 88]
1983	CW-CO$_2$	Cr, Ni/Fe; Cr/Ni/Fe	COMP:EDAX STRT:OM, SEM, TEM	[86]
1983	CW-CO$_2$	Cr/Fe	COMP:EDAX STRT:OM, SEM, TEM SSB:MH	[87]
1983	ML-NdY	Fe$_3$B/Fe	STRT:TEM	[89]
1983	P-CO$_2$	Ar, N$_2$, CO$_2$, C$_2$H$_4$/St	STRT:OM SSB:MH	[90]
1983	Q-Ruby	N, C/Mo	COMP:RBS SSB:SC	[91]
1983	Q-NdG	Ni^{62}/Ni, Fe^{55}–Fe^{59}/Fe	COMP:RI THRY:MT	[92]
1983	CW-CO$_2$	Cr/St	STRT:OM, SEM, TEM SSB:MH	[93]
1983	CW-CO$_2$	Cr, WC-10Co/St	STRT:OM SSB:MH	[94]
1983	CW-CO$_2$	TiC/6061 Al	STRT:SEM SSB:WR	[95]

TABLE I Continued

Year	Laser	Alloying specie/substrate	Analysis	Reference
1983	EB	Ag/Al, Mn/Al, As/Si	THRY:MT	[96]
1983	ML-NdY	Fe_3B/Fe	STRT:TEM	[97]
1984	ML-NdY	Fe_3B/Fe, Ni/Nb Mo/Ni, Mo/Co, Nb/Co	STRT:TEM	[98]
1984	CW-CO_2	Cr/St	COMP:EDAX STRT:SEM, TEM	[99]
1984	Q-Ruby	La, Eu/Ni	COMP:RBS STRT:CHN	[100]
1984	Q-Ruby	Pb/Ni	COMP:RBS STRT:SEM	[101]
1984	Q-Ruby	Au, Co, Cr, Zr/Ti	STRT:XRD	[102]
1984	Q-dNdY	Cu/Zr	STRT:XRD, TEM	[103]
1984	Q-dNdY	Ni–8V/Cr/Cu–2Sn	COMP:AES, RBS	[104]
1984	CW-CO_2	Cr/St	COMP:EDAX STRT:OM SSB:MH	[105]

structure, composition or modification of surface sensitive behaviour, and finally the numerical reference. Abbreviations used are explained in Table II. Take for example the 1978 Kovalenko work [10]; samples of iron coated with vanadium were alloyed with a pulsed neodymium:glass laser. Alloyed samples were analysed structurally using optical microscopy and X-ray diffraction. Compositions are given based on lattice parameter changes in the X-ray diffraction patterns. The microhardness of the irradiated sample is reported.

Table I does not provide insight into how the alloying elements were put down prior to laser irradiation. The methods used are numerous and include vacuum evaporation, electroplating, electroless plating, powder coatings, thin-foil application, and ion implantation. In some cases the element is injected into the melt region in the form of particles or wire. These last two methods of introducing the alloying specie are the most attractive from a commercial standpoint. When coupled with repetitive laser scanning it has been demonstrated that one can build up the surface alloyed region. This is the basis of the United Technologies effort in a commercial processing method called "layer glazing". A sizable body of that work has been summarized [112, 113].

There have been several short review type articles which may be useful to the reader interested

TABLE II Abbreviations used in Table I

Laser
P, pulsed
CW, continuous
Q, Q-switched
ML, mode locked
CO_2, carbon dioxide
NdY, neodymium yttrium aluminium garnet
NdG, neodymium glass
dNdY, frequency doubled NdY
Ruby, chromium doped aluminium oxide
EM, electron beam
EX, excimer

Alloying specie/substrate – elemental symbols
St, steel, cast irons, general designation for Fe alloy substrates
Commas (,), denote individual experiments
Dashes (–), denote a mixture of elements
Semicolon (,), denote individual experiments (added clarity)

For example, C, WC/St denotes carbon film and tungsten carbide film on a steel substrate
Re/Fe–50Ni denotes a rhenium film on an iron–50 wt% nickel alloy substrate

TABLE II Continued

Analysis
STRT, structure
SEM, scanning electron microscopy
TEM, transmission electron microscopy
OM, optical microscopy
XRD, X-ray diffraction
CHN, channelling
MOSB, Mössbauer spectroscopy
PAC, perturbed angle correlation

COMP, composition RBS, Rutherford backscattering spectroscopy
EPM, electron probe microanalysis
EDAX, energy or wavelength dispersive X-ray, elemental mapping
ESCA, electron spectroscopy for chemical analysis
AES, Auger electron spectroscopy
RI, radioactive isotope analysis

SSB, surface sensitive behaviour
MH, microhardness
COR, corrosion
WR, wear
TNS, tensile properties
HTS, high temperature stability
SC, superconductivity measurements
MAG, magnetic
OPT, optical

ANG, results quoted by analytical method not given

THRY, theory
MT, mass transport
HF, heat flow

in more details on the general topic, mechanisms and methodology of laser surface alloying. These are listed at the end of the Bibliography under [106–111].

We hope that this bibliography will serve several purposes. The first is to assemble in one place references of work in this area of research. The manner in which Table I has been constructed allows one to quickly extract the alloying elements, substrates, laser sources, and analyses performed for each reference. It is hoped that the authors will be made aware of both references missed and those forthcoming in order to be able to update the tabulated material presented here.

2. Bibliography 1964–1984

2.1. References

1. F. E. CUNNINGHAM, "The Use of Lasers for the Production of Surface Alloys", MS thesis, Massachusetts Institute of Technology (1964).
2. L. I. MIRKIN, "On the Possibility of Impregnating Iron with Carbon by the Action of a Laser Light Pulse", *Dokl. Akad. Nauk SSSR* **186** (1969) 305. [English reference *Sov. Phys. Dokl.* **14** (1969) 494.]
3. A. O. SCHMIDT, "Tool and Engineering Materials with Hard, Wear-Resistant Infusions", *J. Eng. Ind.* **91** (1969) 549.
4. A. I. BETANELI, L. I. DANILENKO, T. N. LOLADZE, E. F. SEMILETOVA, B. M. ZHRIYAKOV and A. K. FANNIBO, "Investigation of Possible Additional Surface Alloying of R18 Steel using a Laser Beam", *Fiz. I. Khim. Obrab. Mater.* (6) (1972) 22.
5. I. V. GAZUKO, L. L. KRAPIVIN and L. I. MIRKIN, "Use of Laser Beam Heating for the Sintering of Powders and Chemicothermal Treatment of Metal Surfaces", *Poroshk. Metall.* **133** (1) (1974) 27.
6. F. D. SEAMAN and D. S. GNANAMUTHA, "Using the Industrial Laser to Surface Harden and Alloy", *Met. Prog.* **108** (3) (1975) 67.
7. V. S. KOVALENKO and V. I. VOLGIN, "Laser Alloying of Structural Materials", *Tekhnol. Organ. Proizvod.* (7) (1976) 60.
8. V. S. KOVALENKO, V. I. VOLGIN and V. V. MIKHAILOV, "Electrophysical and Electrochemical Methods of Treating Parts, Improved Technology for Laser Alloying of the Surface of Structural Materials", *ibid.* (3) (1977) 50.
9. A. V. BELOTSKII, V. S. KOVALENKO, V. I. VOLGIN and V. I. PSHENICHNYI, "Study of the Possibility of Alloying an Iron Surface with Molyb-

denum under the Action of Laser Radiation", *Fiz. I. Khim. Obrab. Mater.* (3) (1977) 24.

10. V. S. KOVALENKO and V. I. VOLGIN, "Characteristics of Laser Alloying of an Iron Surface with Vanadium", *ibid.* (3) (1978) 28.
11. G. SEPOLD, Hardening and alloying of steel surfaces by high-power laser beams, in "Gas-Flow and Chemical Lasers", edited by J. F. Wendt (Hemisphere, Washington, 1978) pp. 561–9.
12. S. M. COPLEY, M. BASS, E. W. VAN STRYLAND, D. G. BECK and O. ESQUIVEL, Microstructures of surface alloyed Ag–Cu films produced by laser melt quenching, in "Rapidly Quenched Metals III", Vol. 1, edited by B. Cantor (The Metals Society, London, 1979) pp. 147–50.
13. G. DELLA MEA and P. MASSOLDI, Redistribution of Cu in polycrystalline and single crystal Al after laser irradiation, in "Laser–Solid Interactions and Laser Processing, Proceedings of the 1978 Materials Research Society", edited by S. D. Ferris, H. J. Leamy and J. M. Poate (AIP Conf. Proceed. No. 50, New York, 1979) pp. 212–13.
14. L. S. WEINMAN and J. N. DEVAULT, A microprobe study of rapidly solidified laser surface alloyed low carbon steel, *ibid.*, pp. 239–44.
15. L. S. WEINMAN, J. N. DEVAULT and P. MOORE, Properties of rapidly solidified, laser surface alloyed, low carbon steels, in "Applications of Lasers in Materials Processing", edited by E. A. Metzbower (American Society for Metals, Metals Park, 1979) pp. 245–58.
16. D. S. GNANAMUTHU, Laser surface treatment, *ibid.*, pp. 177–211.
17. I. YA. DEKHTYAR, M. M. NISHCHENKO, V. V. BUKHALENKO and S. YA. KHARITONSKII, "Mossbauer Effect in Nb–Fe System Synthesized by Laser Irradiation", *Fiz. Met. Metall.* **47** (1979) 887.
18. A. BELMONDO and M. CASTAGNA, "Wear Resistant Coatings by Laser Processing", *Thin Solid Films* **64** (1979) 249.
19. P. M. MOORE and L. S. WEINMAN, "Surface Alloying using High-Power Continuous Lasers", *SPIE* **198** (1979) 120.
20. D. S. GNANAMUTHU, "Laser surface treatment", *Opt. Eng.* **19** (1980) 783.
21. C. W. DRAPER, C. M. PREECE, L. BUENE, D. C. JACOBSON and J. M. POATE, Laser alloying of deposited metal films on nickel, in "Laser and Electron Beam Processing of Materials", Proceedings of the 1979 Materials Research Society, edited by C. W. White and P. S. Peercy (Academic Press, New York, 1980) pp. 721–7.
22. R. J. SCHAEFER, T. R. TUCKER and J. D. AYERS, Laser surface melting with carbide particle injection, *ibid.*, pp. 754–9.
23. A. K. JAIN, V. N. KULKARNI, D. K. SOOD, M. SUNDARARAMAN and R. D. S. YADAV, "Laser Induced Surface Alloy Formation and Diffusion of Antimony in Aluminium", *Nucl. Instrum. Methods* **168** (1980) 275.
24. A. I. USHAKOV, A. M. GOROVOY, V. G. KAZAKOV and A. G. IL'CHUK, "Alpha to Gamma Phase Transition Induced in Fe–Ni Films by Pulsed Laser Irradiation", *Fiz. Met. Metall.* **50** (1980) 440. [English reference *Phys. Met. Metall.* **50** (1980) 189].
25. J. D. AYERS, T. R. TUCKER and R. J. SCHAEFER, "Wear resistant surfaces by carbide particle injection", in Proceedings 2nd International Conference on Rapid Solidification Processing (Claitors, Baton Rouge, 1980) pp. 212–20.
26. K. TAKEI, S. FUJIMORI and K. NAGAI, "Rhenium Film Preparation by Laser Melting", *J. Appl. Phys.* **51** (1980) 2903.
27. L. BUENE, J. M. POATE, D. C. JACOBSON, C. W. DRAPER and J. K. HIRVONEN, "Laser Irradiation of Nickel Single Crystals", *Appl. Phys. Lett.* **37** (1980) 385.
28. E. RIMINI and J. E. E. BAGLIN, "Pulsed Laser Irradiation of Lead-Implanted Single-Crystal Copper Films", *ibid.* **37** (1980) 481.
29. J. D. AYERS and T. R. TUCKER, "Particulate-TiC-Hardened Steel Surfaces by Laser Melt Injection", *Thin Solid Films* **73** (1980) 201.
30. G. DELLA MEA, L. DONNA DALLE ROSE, P. MAZZOLDI and A. MIOTELLO, "Laser Irradiation Effects on High Dose Implanted Cu and Pb in Polycrystalline Aluminium", *Rad. Effect* **46** (1980) 133.
31. H. W. BERGMANN and B. L. MORDIKE, "Structure of Laser Melted Steel Surfaces", *Z. Metallk.* **71** (1980) 658.
32. P. G. CAPPELLI, "Laser Surface Alloying", in Advisory Group for Aerospace Research and Development, NATA, Lecture Series 106 (March 1980) pp. 6.1–6.13.
33. W. R. WAMPLER, D. M. FOLLSTAEDT and P. S. PEERCY, Pulsed laser annealing of aluminium, in "Laser and Electron-Beam Solid Interactions and Materials Processing", proceedings of the 1980 Materials Research Society, Vol. 1, edited by J. F. Gibbons, L. D. Hess and T. W. Sigmon (Elsevier, North-Holland, New York, 1981) pp. 567– 74.
34. L. BUENE, D. C. JACOBSON, S. NAKAHARA, J. M. POATE, C. W. DRAPER and J. K. HIVOVEN, Laser irradiation of nickel: defect structures and surface alloying, *ibid.*, pp. 583–90.
35. P. P. PRONKO, H. WIEDERSICH, K. SESHAN, A. L. HELLING, T. A. LOGRASSO and P. M. BALDO, Pulsed laser mixing of Ni–Au surface films on nickel substrates, *ibid.* pp. 599–606.
36. G. BATTAGLIN, A. CARNERA, G. DELLA MEA, P. MAZZOLDI, A. K. JAIN, V. N. KULKARNI and D. K. SOOD, High power laser effects on unimplanted and implanted aluminium single crystals, *ibid.* pp. 615–22.
37. L. BUENE, E. N. KAUFMANN, M. L. MCDONALD, J. KOTHAUS, R. VIANDEN, K. FREITAG and C. W. DRAPER, Laser-pulse melting of hafnium-implanted nickel studied with TDPAC and RBS/channeling techniques, in "Nuclear and Electron Resonance Spectroscopy", Proceedings of the 1980 Materials Research Society, Vol. 3, edited by E. N. Kaufmann and G. Schenoy (Elsevier, North-Holland, New York, 1981) pp. 391–6.
38. C. W. DRAPER, L. S. MEYER, D. C. JACOBSON,

L. BUENE and J. M. POATE, "Laser Surface Alloying for Passivation of Ti–Pd", *Thin Solid Films* **75** (1981) 237.

39. H. W. BERGMANN and B. L. MORDIKE, "Surface Alloying of Tool Steels with Carbides by Laser or Electron Beam Melting", *Z. Wekstofftech.* **12** (1981) 142.
40. V. P. GRECO, "Microstructural and Property Changes of Laser-Treated Electrodeposits", *Plating and Surface Finishing* **68** (3) (1981) 56.
41. D. C. JACOBSON, W. M. AUGUSTYNIAK, L. BUENE, J. M. POATE and C. W. DRAPER, "Analysis of Laser Alloyed Surfaces", *IEEE Trans. Nucl. Sci.* **28** (1981) 1828.
42. C. W. DRAPER, L. S. MEYER, L. BUENE, D. C. JACOBSON and J. M. POATE, "Laser Surface Alloying of Gold Films on Nickel", *Appl. Surf. Sci.* **7** (1981) 276.
43. A. K. JAIN, V. N. KULKARNI and D. K. SOOD, "Pulsed Laser Heating Calculations Incorporating Vaporization", *Appl. Phys.* **25** (1981) 127.
44. C. W. DRAPER, L. BUENE, J. M. POATE and D. C. JACOBSON, "Rutherford Backscattering and Marker Diffusion to Determine Melt Threshold in Laser Mirror Damage Studies", *Appl. Opt.* **20** (1981) 1730.
45. J. D. AYERS, in "Particulate Composite Surfaces by Laser Processing", edited by K. Mukherjee and J. Mazumder (TMS-AIME, Warrendale, 1981).
46. J. D. AYERS, "Modification of Metal Surfaces by the Laser Melt/Particle Injection Process", *Thin Solid Films* **84** (1981) 323.
47. H. W. BERGMANN and B. L. MORDIKE, "Laser and Electron-Beam Melted Amorphous Layers", *J. Mater. Sci.* **16** (1981) 863.
48. P. G. MOORE and E. MCCAFFERTY, "Passivation of Fe/Cr Alloys Prepared by Laser-Surface Alloying", *J. Electrochem. Soc.* **128** (1981) 1391.
49. A. K. JAIN, V. N. KULKARNI and D. K. SOOD, "Laser Treatment of Chromium Films on Aluminium at High Power Densities", *Thin Solid Films* **86** (1981) 1.
50. P. L. ANTONA and A. BERTANI, "Surface treatment of steel by alloying with a high power laser", in 9th Convegno Nazionale Trattamenti Termici, Assoc. Italiana di Metallurgia, Milano, Italy (1981) pp. 61–4.
51. J. D. AYERS, R. J. SCHAEFER and W. P. ROBEY, "A Laser Processing Technique for Improving the Wear Resistance of Metals", *J. Met.* **33** (1981) 19.
52. F. PLEITER and K. G. PRASAD, "Investigation of Laser Irradiated Poly- and Monocrystalline Aluminium by Perturbed Angular Correlation Measurements", *Phys. Lett.* **84A** (1981) 345.
53. G. SEPOLD, Surface Finishing with Laser Beams, in "Proceedings of the International Congress on Surface Technology 1981", edited by C. Rohrbach (VDI-Verlag GmbH, Dusseldorf, W. Germany, 1981) pp. 323–30.
54. A. K. JAIN, V. N. KULKARNI and D. K. SOOD, "A Nuclear Microprobe Analysis of Laser Treated Aluminium Implanted with Antimony", *Nucl. Instrum. Meth.* **191** (1981) 151.
55. A. K. JAIN, V. N. KULKARNI, K. B. NAMBIAR, D. K. SOOD, S. C. L. SHARMA and P. MAZZOLDI, "Pulsed Laser Treatment of Lead Films on Aluminium", *Rad. Effects* **63** (1982) 175.
56. A. MIOTELLO and L. F. DONA DALLE ROSE, "New Evidence for the Soret Effect in Pulsed Laser Experiments", *Phys. Lett.* **87A** (1982) 317.
57. A. K. JAIN, V. N. KULKARNI and D. K. SOOD, "Nonequilibrium Segregation During Pulsed Laser Treatment of Antimony Implanted Aluminium", *Rad. Effects* **63** (1982) 183.
58. A. MIOTELLO, L. F. DONA DALLE ROSE and A. DESALVO, "Role of Thermal Diffusion in the Redistribution of Cu During Pulsed Laser Irradiating of Cu-planted Al", *Appl. Phys. Lett.* **40** (1982) 135.
59. B. STRITZKER, B. R. APPLETON, C. W. WHITE and S. S. LAU, "Superconducting V_3Si Produced by Pulsed Laser Annealing", *Solid State Commun.* **41** (1982) 321.
60. G. BATTAGLIN, A. CARNERA, G. DELLA MEA, P. MAZZOLDI, E. JANNITTI, A. K. JAIN and D. K. SOOD, "Laser Treatment of a Nonsubstitutional Alloy Cr Implanted in Aluminium", *J. Appl. Phys.* **53** (1982) 3224.
61. *Idem*, Thermal stability of metastable phases produced by laser treatment of aluminium implanted with chromium and molybdenum, in "Metastable Materials Formation by Ion Implantation", Proceedings of the 1981 Materials Research Society, Vol. 7, edited by S. T. Picraux and W. J. Choyke (Elsevier North-Holland, New York, 1982) pp. 327–32.
62. *Idem*, Pulsed laser treatment of virgin, self and europium implanted nickel: evidence of defect impurity interaction, *ibid.*, pp. 333–8.
63. P. S. PEERCY, D. M. FOLLSTAEDT, S. T. PICRAUX and W. R. WAMPLER, Defects and AlSb precipitate nucleation in laser irradiated aluminium, in "Laser and Electron-Beam Interactions with Solids", Proceedings of the 1981 Materials Research Society, Vol. 4, edited by B. R. Appleton and G. K. Celler (Elsevier North-Holland, New York, 1982) pp. 401–6.
64. C. W. DRAPER, D. C. JACOBSON, J. M. GIBSON, J. M. POATE, J. M. VANDENBERG and A. G. CULLIS, Laser and ion beam mixing Cr and Ni+Cr films on Cu, *ibid.*, pp. 413–18.
65. C. W. DRAPER, F. J. A. DEN BROEDER, D. C. JACOBSON, E. N. KAUFMANN, M. L. MCDONALD and J. M. VANDENBERG, Studies of laser-alloyed Zr-containing surface layers, *ibid.*, pp. 419–24.
66. L. F. DONA DALLE ROSE and A. MIOTELLO, Interplay of Soret vs. normal impurity diffusion during laser or E-beam induced heat flow transients in metals, *ibid.*, pp. 425–30.
67. B. L. MORDIKE and H. W. BERGMANN, Surface alloying of iron alloys by laser beam melting, in "Rapidly Solidified Amorphous and Crystalline Alloys", Proceedings of the 1981 Materials Research Society, Vol. 8, edited by B. H. Kear, B. C. Giessen and M. Cohen (Elsevier North-Holland, New York,

1982) pp. 463–83.

68. H. W. BERGMANN and B. L. MORDIKE, Production and properties of amorphous layers on metal substrates by laser and electron beam melting, *ibid.*, pp. 497–503.
69. P. A. MOLIAN, P. J. WANG, K. H. KHAN and W. E. WOOD, Phase transformation studies of laser-processed Fe–0.2% C–Cr surface alloys, *ibid.*, pp. 511–15.
70. Y. NILSSON, Surface melting of cast iron with a high power laser beam, *ibid.*, pp. 517–21.
71. D. B. SNOW, Microstructure and mechanical properties of laser-processed Ni–Al–Mo based alloys, *ibid.*, pp. 523–7.
72. T. R. TUCKER, A. H. CLAUER, S. L. REAM and C. T. WALTERS, Rapidly solidified microstructure in surface layers of laser-alloyed Mo on Fe–C substrates, *ibid.*, pp. 541–5.
73. T. CHANDE and J. MAZUMDER, "Mass Transport in Laser Surface Alloying: Iron-Nickel System", *Appl. Phys. Lett.* **41** (1982) 42.
74. U. A. BYKOVSKII, V. S. KULIKAUSKAS, V. N. NEVOLIN and I. D. KHABELASHIVILI, "Obtaining Non-Equilibrium Alloys with the Aid of Monochromatic Radiation", *Zh. Tekh. Fiz.* **52** (1982) 61.
75. P. A. MOLIAN, "Effect of Fusion Zone Shape on the Composition Uniformity of Laser Surface Alloyed Iron", *Scripta Metall.* **16** (1982) 65.
76. A. K. JAIN, V. N. KULKARNI, K. B. NAMBIAR, D. K. SOOD, S. C. L. SHARMA and P. MAZZOLDI, "Pulsed Laser Treatment of Lead Films on Aluminium", *Rad. Effects* **63** (1982) 175.
77. C. J. LIN and F. SPAEPEN, "Fe–B Glasses Formed by Picosecond Pulsed Laser Quenching", *Appl. Phys. Lett.* **41** (1982) 721.
78. I. B. BOROVSKII, D. D. GORODSKII, I. M. SHARAFEEV and S. F. MORYASHCHEV, "Mass Transfer During Treatment of Metal Surfaces by Fusion Induced by Continuous Laser Radiation", *Sov. Phys. Dokl.* **27** (1982) 259.
79. P. A. MOLIAN and W. F. WOOD, "Martensitic Transformation of Laser Processed Fe–5% Ni Alloy", *Scripta Metall.* **16** (1982) 1301.
80. *Idem*, "Formation of Austenite in Laser-Processed Fe–0.2% C–20% Cr Alloy", *Mater. Sci. Eng.* **56** (1982) 271.
81. J. B. LUMSDEN, D. S. GNANAMUTHU and R. J. MOORES, Corrosion resistance of AISI 4140 steel laser surface alloyed with Cr and Ni, in "Corrosion of Metals Processed by Directed Energy Beams", edited by C. R. Clayton and C. M. Preece (TMS-AIME, New York, 1982) pp. 129–34.
82. Z. L. WANG, J. F. M. WESTENDORP and F. W. SARIS, "Laser and Ion-Beam Mixing of Cu–Au–Cu and Cu–W–Co Thin Films", *Nucl. Instrum. Meth.* **209/210** (1983) 115.
83. E. N. KAUFMANN, L. BUENE, M. L. MCDONALD, J. KOTTHAUS, K. FREITAG, R. VIANDEN and C. W. DRAPER, "Hf-Implanted Ni Studied with TDPAC and RBS/Channeling Before and After Laser Surface Melting and Thermal Annealing", *ibid.* **209/210** (1983) 427.
84. P. A. MOLIAN, "Structural Characterization of Laser-Processed Molybdenum Steel", *Mater. Sci. Eng.* **58** (1983) 175.
85. T. CHANDE and J. MAZUMDER, "Composition Control in Laser Surface Alloying", *Met. Trans.* **14B** (1983) 181.
86. P. A. MOLIAN and W. E. WOOD, "Transformation Behaviour of Laser Processed Fe–5% Cr, Fe–5% Ni and Fe–6% Cr–2% Ni Alloys", *J. Mater. Sci.* **18** (1983) 2555.
87. *Idem*, "Transformation Structures and Strengthening Mechanisms of Laser Processed Fe–Cr Alloys" *ibid.* **18** (1983) 2563.
88. T. CHANDE and J. MAZUMDER, "Dimensionless Parameters for Process Control in Laser Surface Alloying", *Opt. Eng.* **22** (1983) 362.
89. C. -J. LIN and F. SPAEPEN, Fe–B glasses formed by picosecond pulsed laser quenching, in "Chemistry and Physics of Rapidly Solidified Materials", edited by B. J. Berkowitz and R. O. Scattergood (TMS-AIME, New York, 1983) pp. 273–280.
90. B. L. MORDIKE, H. W. BERGMANN and N. GROB, "Gaseous Alloying with Laser Heating", *Z. Werkstofftech.* **14** (1983) 253.
91. S. T. SEKULA, J. R. THOMPSON, G. M. BEARDSLEY and D. H. LOWNDES, "Low Temperature Laser Quenching Studies of Superconducting Mo–N and Mo–C Alloys", *J. Appl. Phys.* **54** (1983) 6517.
92. M. E. GUREVICH, L. N. LARIKOV, V. G. NOVITSKII, A. E. POGORELOV and A. F. ZHURAVLEV, "Laser-Stimulated Mass Transfer in Metals", *Phys. Status Solidi* **76** (1983) 479.
93. P. A. MOLIAN, "Non-Equilibrium Phases in Laser-Processed Fe–0.2 wt % C–20 wt % Cr Alloys", *Mater. Sci. Eng.* **60** (1983) 241.
94. G. SEPOLD, "Hardening and Alloying of Steel Surfaces by High-Power Laser Beams", in Physical Processes in Laser/Materials Interactions, edited by M. Bertolotti (Plenum Press, New York, 1983) pp. 163–73.
95. R. BROWN and J. D. AYERS, "Solid Particle Erosion of Al 6061 with a Laser Melted and TiC Particle Injected Surface Layer", in Wear of Materials 1983, edited by K. C. Ludema (ASME, New York, 1983) pp. 325–32.
96. R. J. SCHAEFER and R. MEHRABIAN, "Processing/Microstructure Relationships in Surface Melting", in Laser-Solid Interactions and Transient Thermal Processing of Materials, edited by J. Narayan, W. L. Brown and R. A. Lemons (North-Holland, New York, 1983) pp. 733–44.
97. C. -J. LIN and F. SPAEPEN, "Solidification Morphology of Picosecond Pulsed Laser Quenched $Fe_{96}B_4$", *Scripta Metall.* 17 (1983) 1259.
98. C. -J. LIN, F. SPAEPEN and D. TURNBULL, "Picosecond Pulsed Laser-Induced Melting and Glass Formation in Metals", *J. Non-Cryst. Solids* **61–62** (1984) 767.
99. P. A. MOLIAN and W. E. WOOD, "Rapid Solidification of Laser-Processed Chromium Steels", *Mater. Sci. Eng.* **62** (1984) 271.
100. G. BATTAGLIN, A. CANERA, J. CHAUMONT, G. DELLA MEA, L. F. DONA DALLE ROSE, A. K.

JAIN, V. N. KULKARNI, P. MAZZOLDI, A. MIOTELLO and D. K. SOOD, "Pulsed laser treatment of Eu and La implanted in Ni: surface alloying, trapping and damage", in Proceedings of the 1983 European Materials Research Society, Strasbourg, BRD May 1983, to be published.

101. G. BATTAGLIN, A. CARNERA, G. DELLA MEA, L. F. DONA DALLE ROSE, V. N. KULKARNI, S. LO RUSSO and P. MAZZOLDI, "Mixing of Pb and Ni under ion bombardment and pulsed laser irradiation", in Proceedings of the NATO-ASI on Surface Engineering, Les Arcs, Fr. July 1983 to be published.
102. K. AFFOLTER and M. VON ALLMEN, "Glass Forming Ability of Laser Quenched Transition-Metal Alloys", *Appl. Phys. A*, in press.
103. F. J. A. DEN BROEDER, J. M. VANDENBERG and C. W. DRAPER, "Microstructures of Cu–Zr Phases Formed by Laser Surface Treatment", *Thin Solid Films* **111** (1984) 43.
104. I. SAWCHYN and C. W. DRAPER, "AES and RBS Analysis of Laser Mixed Cr and Ni Films on Cu Alloys", *Appl. Surf. Sci.* **18** (1984) 84.
105. R. BECKER, R. ROTHE and G. SEPOLD, "Surface alloying by means of laser beams", in 3rd International Colloquim on Welding and Melting by Electrons and Laser Beam, Lyon, Fr. September 1983, in press.

2.2. Review articles

106. C. W. DRAPER, Laser surface alloying: the state of the art, in "Lasers in Metallurgy", edited by K. Mukherjee and J. Mazumder (TMS-AIME, New York, 1981) pp. 67–92. [*J. Met.* **34** (6) (1982) 24].
107. D. K. SOOD, "Criteria for Formation of a Metastable Solid Solution by Rapid Melt Quenching During Pulsed Laser or Electron Beam Treatment", *Rad. Effects Lett.* **67** (1981) 13.
108. C. W. DRAPER, "Laser Surface Alloying: A Bibliography", *Appl. Opt.* **20** (1981) 3093.
109. D. M. FOLLSTAEDT, Metallurgy and microstructures of pulse melted alloys, in "Laser and Electron-Beam Interactions with Solids", Proceedings of the 1981 Materials Research Society, Vol. 4, edited by B. R. Appleton and G. K. Celler (Elsevier North-Holland, New York, 1982) pp. 377–88.
110. D. K. SOOD, "Metastable Surface Alloys Produced by Ion Implantation, Laser and Electron Beam Treatment", *Rad. Effects* **63** (1982) 141.
111. C. W. DRAPER and J. M. POATE, Laser surface alloying, in "Surface Modification and Alloying", edited by J. M. Poate, G. Foti and D. C. Jacobson (Plenum Press, New York, 1983) Ch. 13, pp. 385–404.
112. D. B. SNOW, E. M. BREINAN and B. H. KEAF, "Rapid solidification processing of superalloys using high power lasers", Superalloys 1980, in Proceedings of the Fourth International Symposium on Superalloys, edited by J. K. Tien, S. T. Wlodek, H. Morrow, M. Gell and G. E. Maurer (American Society for Metals, Metals Park, Ohio, 1980) pp. 189–203.
113. E. M. BREINAN, D. B. SNOW and C. O. BROWN, "Program to Investigate Advanced Laser Processing of Materials", Final Report to Office of Naval Research N00014-C-0387 (January 1981).

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