

# Comparison of Properties of Laser Deposited Co-Cr-Mo and Co-Cr-W Alloys

K L Narayana<sup>a\*</sup>, M Kedar Mallik<sup>b</sup>

**Abstract - Co-Cr-Mo and Co-Cr-W alloys, developed during the Second World War, are the best bio-compatible material with high strength so far known. Both the materials are deposited using the Laser Engineered Net Shaping, an additive manufacturing technology, as samples of standard sizes. The deposition was carried out by varying process parameters like Laser power, powder feed rate and laser scan speed. The deposited samples are tested for their microstructure, hardness and wear resistance. The results are compared and analyzed.**

**Key words: Co-Cr-Mo alloy; Co-Cr-W alloy; Laser Engineered Net Shaping; Microstructure; Hardness; wear resistance; corrosion resistance;**

## I. INTRODUCTION

Invented by Elwood Hynes in early 20<sup>th</sup> century cobalt chrome alloys have attracted the attention of manufacturers during Second World War because of their high hardness and resistance to wear and corrosion which includes molybdenum or Tungsten as the third element. Later these alloys are identified to be bio compatible and extensively used in the medical field [1]. After 1986 bio medical grade Co-Cr-Mo and Co-Cr-W alloys were developed with low nickel and carbon content [2]. In the Co-Cr-Mo and Co-Cr-W alloys, the face-centered cubic (FCC) and the hexagonal closed packed (HCP) crystalline structures co-exist. Typically, the FCC phase is predominant at room temperature, but the FCC to HCP transformation could be isothermal or strain- induced [3].

The investigation on as-cast Co-Cr-Mo revealed that although sigma and M<sub>23</sub>C<sub>6</sub> carbides were the only secondary phases formed in the face centered cubic cobalt-base alpha matrix (Co- $\alpha$ ), as identified by X-ray diffraction where M can be cobalt, chromium or Molybdenum [4].

The tensile properties of the laser deposited Co-Cr-Mo alloys are compatible with or superior than the as cast samples of Co-Cr-Mo alloys. The ductility of the Co-Cr-Mo alloy samples is observed to be more due to the fine grain size of LENS deposited samples [5].

The effect of heat treatment on hardness and wear behavior of the weld deposited Co-Cr-Mo has been evaluated and identified that high solution times are required for the best performance of the samples. The ageing treatment does not show much effect on the hardness and wear resistance of weld deposited Co-Cr-Mo samples [6].

The Co-Cr-W alloy has been deposited by the method of selective laser melting and the correlation between microstructure and mechanical anisotropy was studied and identified that the deposited samples contain only  $\gamma$ -FCC phase and does not have any  $\epsilon$ -HCP. Also the samples were evaluated for the hardness, elastic modulus and fatigue crack growth [7]. The Co-Cr-W alloys have exhibited high corrosion resistance when deposited with selective laser melting process followed by heat treatment at 1150°C and quenching when compared with furnace cooling [8].

Keeping the identifications of different researchers in view, experiments have been conducted on LENS deposited Co-Cr-Mo and Co-Cr-W alloys and in the current paper the properties like hardness, wear resistance and microstructure, evaluated from the experiments are compared

## II. EXPERIMENTATION

Commercially available Co-Cr-Mo and Co-Cr-W powders (Kennametal Stellite, Bengaluru, India – Stellite 21 and Stellite 6 respectively) of size 50 to 150 $\mu$ m have been used for experimentation.

TABLE I  
L9 ORTHOGONAL ARRAY OF TAGUCHI METHOD USED FOR  
FABRICATION OF SAMPLES

Sample No. Co-Cr-Mo	Sample No. Co-Cr-W	Laser power (W)	Powder feed rate (g/min)	Scan speed (mm/s)
S1	T1	200	5	10
S2	T2	200	10	15
S3	T3	200	7.5	20
S4	T4	275	5	15
S5	T5	275	10	20
S6	T6	275	7.5	10
S7	T7	350	5	20
S8	T8	350	10	10
S9	T9	350	7.5	15

The deposition took place on LENS<sup>TM</sup> (Optomec, Albuquerque, USA) machine with the process parameters, laser power; powder feed rate and laser scan speed, following the orthogonal array of Taguchi method as shown in table 1.

Dr. K. L. Narayana, (Corresponding author) Professor, Koneru Lakshmaiah Education Foundation (Deemed University), Guntur, Andhra Pradesh, India +91 98493 47580, drkln@kluniversity.in

Dr. M. Kedar Mallik, Associate Professor, Vasireddy Venkatadri Institute of Technology, Guntur, India. +91 92464 00126, mallikkedar@yahoo.co.in

The reason for selection of the above process parameters is that they are being the most influencing and the remaining process parameters are kept constant during deposition. In order to avoid oxidation of the deposited samples, the deposition chamber is maintained at less than 10ppm of oxygen level by the circulation of Argon gas continuously. Five layers of samples are deposited with 15 X 15mm size on the substrate of the same material for each sample.

After separating the samples from the substrate, one set of the deposited samples are cut across the layers, using abrasive cutter, to study the microstructure of the material and all the samples are polished with 200 to 1200 grit emery papers followed by polishing with alumina on single disk polishing machine to obtain smooth surface. The cut samples, which are meant for microstructure analysis, are etched across the layers, using electrochemical etching in 5% aqua solution of HCl by the supply of 5V electricity.

The microstructure images are collected on Scanning Electron Microscopy (SEM), hardness by Micro hardness tester ASTM E384-10 and wear resistance by pin on disk tribometer ASTM G99 – 95a (Reapproved 2000). Steel tubes of 6mm inner diameter are prepared to hold the samples firmly in the holders of the tribometer. The counterpart of the wear test i.e. the disc is hardened steel (EN31) whose hardness is above 650Hv. the samples are run for one km with 10N and 20N loads on the samples. The results obtained from microstructure analysis, hardness and wear resistance test are tabulated and analyzed. All the results are the average of at least five readings.

### III. RESULTS AND DISCUSSION

As mentioned earlier, the samples are tested for their hardness, wear resistance and microstructure analysis and are analyzed as follows.

#### A. Hardness

The Vicker's micro hardness test results are presented in the table 2.

TABLE II  
MICRO HARDNESS RESULTS OF LENS DEPOSITED Co-Cr-Mo AND Co-Cr-W ALLOY SAMPLES

Sample No.	Hardness (Hv)	Sample No.	Hardness (Hv)
S1	491 ± 50	T1	528±49
S2	382 ± 25	T2	545±17
S3	378 ± 10	T3	562±20
S4	372 ± 43	T4	491±42
S5	386 ± 25	T5	543±46
S6	512 ± 57	T6	528±48
S7	478 ± 80	T7	529±18
S8	484 ± 37	T8	511±58
S9	380 ± 35	T9	473±55

Sample S6 (Medium laser power, medium powder feed rate and low scan speed) among the Co-Cr-Mo alloy samples tested and Sample T3 (Low laser power, medium powder feed rate and high scan speed) among the Co-Cr-W samples tested have exhibited high hardness.

Evidently all the Co-Cr-W samples have exhibited high hardness values than the Co-Cr-Mo alloy samples. The content of tungsten in Co-Cr-W alloy could be the reason for exhibiting the high hardness. The large variation in the hardness values of the samples indicate that the process parameters have high influence on the samples deposited.



Fig. 1: Wear resistance test on Pin on Disc Tribometer

TABLE III  
WEAR RESISTANCE TEST RESULTS OF LENS DEPOSITED Co-Cr-Mo AND Co-Cr-W ALLOY SAMPLES

Sample No.	Wear rate (g/Nm)	Sample No.	Wear rate (g/Nm)
S1	2.87e-7	T1	2.67e-7
S2	2.36e-7	T2	5.00e-7
S3	2.37e-7	T3	4.00e-7
S4	1.92e-7	T4	1.50e-7
S5	2.34e-7	T5	3.00e-7
S6	2.17e-7	T6	2.83e-7
S7	1.91e-7	T7	2.40e-7
S8	1.95e-7	T8	3.00e-7
S9	1.81e-7	T9	2.78e-7



Fig. 2: Wear track of Co-Cr-Mo alloy samples

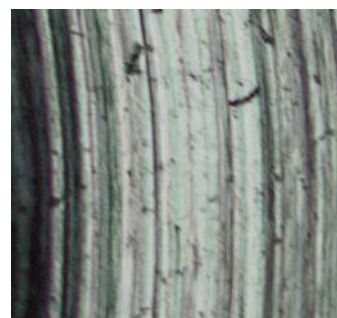


Fig. 3: Co-Cr-W alloy sample wear track

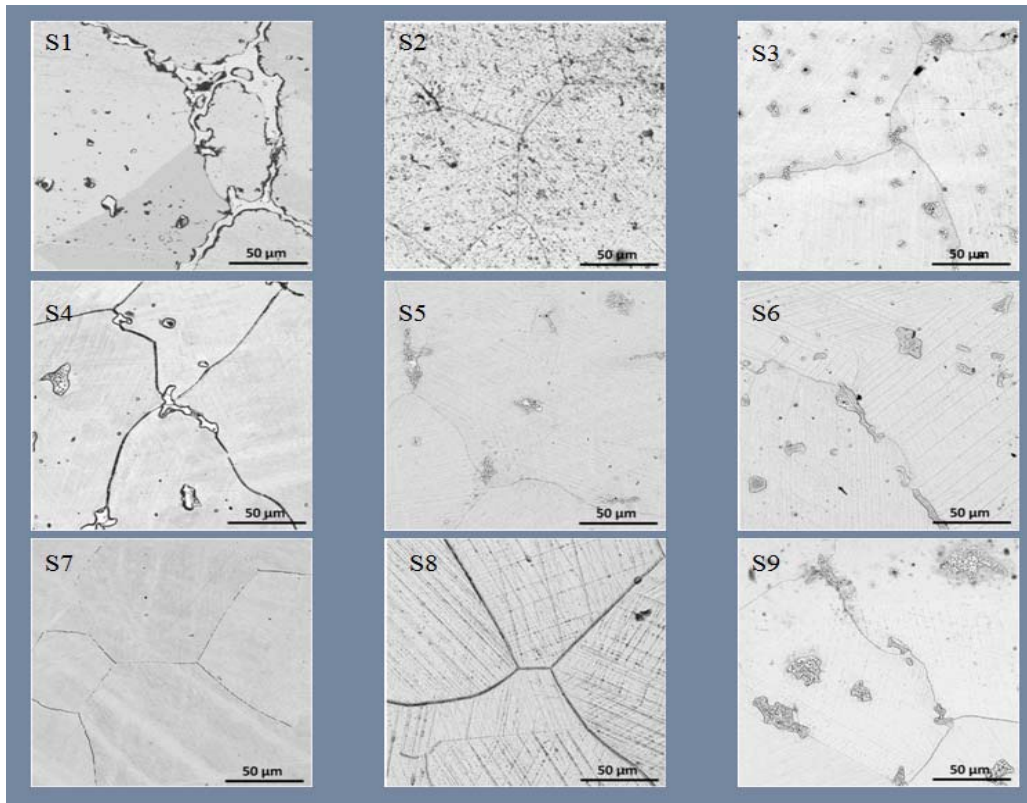


Fig. 4: Microstructure of the Co-Cr-Mo samples from S1 to S9

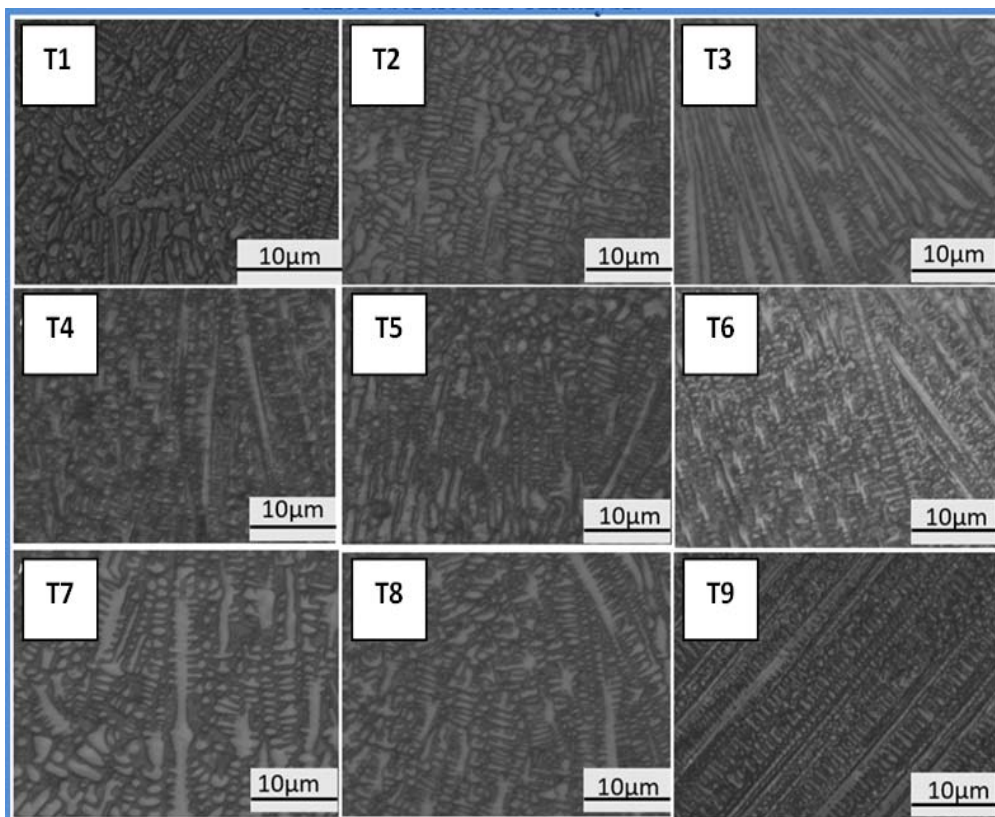


Fig. 5: Microstructure of the Co-Cr-W samples T1 to T9

### B. Wear Resistance

The results of wear resistance test on Pin on Disk machine are shown in table 3, in the form of wear rate. Samples S9 and T4 have shown high wear resistance. Enthusiastically almost all the Co-Cr-Mo alloy samples have exhibited high resistance to wear than the Co-Cr-W alloy samples. The results reveal that the influence of process parameters on the wear resistance is also very high in Co-Cr-W alloy samples but a little low in Co-Cr-Mo alloys as the variation among the samples is less. In all the samples the wear type is observed to be the abrasive and a couple of wear tracks obtained from the Co-Cr-Mo and Co-Cr-W alloys samples are shown in Fig. 1. Tiny pullouts on the wear track are the evidences of the same.

### C. Microstructure

The microstructure images of samples S1 to S9 and T1 to T9, obtained from SEM are presented in Fig. 2 and Fig. 3. It is observed that the both primary and secondary dendrites are formed in all the samples. In Co-Cr-W alloy samples, primary dendrites are very long with 30-40 $\mu$ m along with the secondary dendrite arms of length 3-5 $\mu$ m projecting out of the arms. In Co-Cr-Mo alloy samples, the images revealed that the microstructure of each sample is uniform throughout the deposition. But the scale of solidification (microstructure) is different in the deposits fabricated with different LENS process parameters.

Due to the faster cooler rates in the samples with low energy input, result in finer microstructure and vice a versa. Further Formation of carbide network along the grain boundaries or at inter-dendritic regions clearly suggests that they are formed at the later stages of solidification. Note worthy that the heat affected zone in the laser deposited is thin, and the layers are subjected to repeated melting and cooling. Rapid solidification and thermal cycling effects inherent to the additive manufacturing process would lead to the formation of variegated microstructures, multiple phases and residual stresses at small length scales, which significantly contribute to the hardening behavior of samples.

## IV. CONCLUSIONS

The conclusions drawn from the comparison of the LENS deposited Co-Cr-Mo and Co-Cr-W alloys for their hardness; wear resistance and microstructure are as follows.

- The hardness of Co-Cr-W alloys is higher than Co-Cr-Mo alloys
- The wear resistance of the Co-Cr-Mo alloys is significantly more than the Co-Cr-W alloys.
- The primary and secondary dendrites are formed as lamellar in Co-Cr-W alloys whereas the samples with low energy input have exhibited finer microstructure in Co-Cr-Mo alloys
- The process parameters laser power, powder feed rate and laser scan speed have extensive influence on the properties of the LENS deposited Co-Cr-Mo and Co-Cr-W alloys.

## REFERENCES

- [1] G. D. Janaki Ram, C. K. Esplin and B. E. Stucker "Microstructure and wear properties of LENS deposited medical grade CoCrMo" *Journal of Material Science*, Vol. 19, 2008; pp 2105–2111.
- [2] C. Valero-Vidal, L. Casabán-Julían, I. Herraiz-Cardona, and A. Igual-Muñoz, "Influence of carbides and microstructure of CoCrMo alloys on their metallic dissolution resistance", *Materials Science and Engineering C*, Vol.33, Issue 8, pp 4667 - 4676
- [3] C. Balagna, S. Spriano and M.G. Faga, "Characterization of Co-Cr-Mo alloys after a thermal treatment for high wear resistance" *Materials Science and Engineering: C*, Vol. 32, No. 7, 2012, pp. 1868-1877
- [4] R. Rosenthal, B. R. Cardoso, I. S. Bott, R. P. R. Paranhos and E. A. Carvalho, "Phase characterization in as-cast F-75 Co-Cr-Mo-C alloy", *J Mater Science*, Vol. 45, 2010, pp 4021–4028
- [5] Mantrala, K.M., Rao, C.S., Rao, V.V.S.K. and Abdul Munaf, S. (2018) 'Effect of process parameters on the tensile properties of LENS deposited Co-Cr-Mo alloy', *Int. J. Manufacturing Technology and Management*, Vol. 32, No. 6, pp.509–516.
- [6] Mantrala Kedar Mallik, Chalamalasetty Srinivasa Rao and Vaddi Venkata Sundara Kesava Rao, "Effect of heat treatment on hardness and wear behavior of weld deposited Co-Cr-Mo alloy" *Revista Materia*, Vol.20, No.2, 2015, pp.544-549,
- [7] Ho Won Lee, Kyung-Hwan Jung, Sun-Kwang Hwang, Seong-Hoon Kanga, Dong-Kyu Kim, "Microstructure and mechanical anisotropy of CoCrW alloy processed by selective laser melting", *Materials Science and Engineering: A*, Volume 749, 11 March 2019, Pages 65-73
- [8] Yanjin Lu, Sai Guo, Yang Yang, Yujing Liu, Yu Zhou, Songquan Wu, Chaoqian Zhao, and Jinxin Lin "Effect of thermal treatment and fluoride ions on the electrochemical corrosion behavior of selective laser melted CoCrW alloy" *Journal of Alloys and Compounds*, Volume 730, 5 January 2018, Pages 552-562