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Free-Form Laser Consolidation for Manufacturing Rotary Cutting Dies

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Free-form laser consolidation is a novel process that produces a functional part layer by layer directly from a CAD model. A laser beam is used to melt a controlled amount of injected powder on a base plate to deposit the first layer and on previous passes for the subsequent layers. As opposed to conventional machining processes, this computer-aided manufacturing (CAM) technology builds complete functional parts or features on an existing component by adding instead of removing material. In this paper, laser consolidation of CPM-9V tool steel will be described to produce cutting blades on low alloy steel base to manufacture rotary cutting dies. The laser consolidated (LC) CPM-9V cutting blades as well as the bond between the LC blades and the base are metallurgically sound, free of cracks or porosity. Experimental results show that the LC CPM-9V has excellent mechanical properties. Its average tensile and yield strengths are about 1315 MPa and 821 MPa, respectively. Pin-on-disk wear tests demonstrate that the wear loss of the LC CPM-9V material is only about 1/3 compared to that of the heat treated D2 tool steel currently being used for making rotary cutting dies. In production test, the LC CPM-9V die has successfully cut more than 180,000 m of labels without the need of re-sharpening so far.

***Keywords:** laser consolidation, tool steel, CPM-9V, rotary cutting die, wear, strength*

1. Introduction

Rotary die cutters are high-volume, high-speed cutting facilities used for cutting a wide range of materials, such as label, sand paper, carpet and fabric, from roll stocks, or directly in-line with printing and processing equipment. In production lines, this type of advanced die cutting system has resulted in dramatic increase in productivity and cost savings[1]. The dies used for the rotary cutters are usually manufactured by a series of machining and heat treatment procedures. The manufacture of a rotary cutting die starts from an oversize bar stock, which is turned to the required bearer diameter on a lathe, leaving the central area for the CNC milling operation to form cutting blades. After the initial machining, the die is sent out for heat treatment. The dies are usually distorted after the heat treatment and are then re-centered and ground. Finally, the cutting edges are sharpened manually. Depending on the complexity of the cutting pattern and the height of the cutting blades, the whole manufacturing operation may take from several days to weeks.

The Integrated Manufacturing Technologies Institute (IMTI) is currently developing a novel process called "Free-Form Laser Consolidation" to build functional net-shape parts directly from alloy powder in one step[2-4]. IMTI has patented the process for making cutting dies[5]. Several other patents are pending on various aspects and applications of the process. The laser consolidation technology manufactures the rotary dies by building up cutting blades instead of machining. With this process, more wear resistant materials can be used to build up the cutting blades on a low-alloy steel blank and the need of hardening operation can be eliminated. Thus, the consolidation process could significantly reduce the lead-time in the manufacturing of cutting die along with an improvement in its life. In addition, with this process worn cutting blades could be repaired or the same blank could be used for building a new cutting pattern after machining out the old pattern.

This paper summarizes the preliminary investigation on the laser consolidation for manufacturing rotary cutting dies, including process development, evaluation of the microstructure and mechanical properties, wear test results, and the preparation of trial cutting dies for production test.

2. Experimental Details

The powder-injection laser consolidation technique was used in this study. A pulsed Nd:YAG laser, equipped with an optical fiber-coupled processing head, was used along with a precision powder feeder to simultaneously deliver powder through a nozzle into the molten pool. The laser consolidation was conducted in an enclosure filled with protective Ar gas. An average laser power ranging from 10 to 300 W and a powder feed rate ranging from 2 to 20 g/min were used to build cutting edges.

A commercially available high-vanadium tool steel, CPM-9V powder was used for laser consolidation in this study. The gas-atomised powder is spherical in shape with a size of around –45 μm. Chemical composition of the CPM-9V powder from the manufacturer certificate is listed in the Table 1.

Table 1: Chemical composition of CPM-9V powder

Element	Carbon	Chromium	Vanadium	Molybdenum	Manganese	Silicon	Iron
Wt. %	1.80	5.35	9.26	1.24	0.50	0.91	Bal.

The base material used for the process development was low alloy steel plates with a thickness of around 10 mm. The surface of the base material was ground before laser consolidation to maintain a consistent surface finish. After laser consolidation, samples were examined metallurgically with an optical microscope. The microstructure of the laser consolidated (LC) CPM-9V sample was revealed with a chemical etchant of 10% Picral (10 g picric acid + 100 ml ethanol).

A simple electrochemical method was used to extract carbides from the LC material for further analysis. The LC CPM-9V sample was treated with anodic dissolution at room temperature in a 600 ml beaker containing a distilled water base electrolyte (60 g/l of ammonium chloride + 160 g/l of citric acid). The sample was thus suspended with a tightly wound platinum wire, which also served as the electrical connection for the circuit. A stainless steel cathode strip was placed around the periphery of the beaker, and a small 50 ml beaker was positioned below the sample to collect the residue. The applied current density was 0.06 mA/cm^2. After anodic separation, the collected residue as well as the spent sample were ultrasonically cleaned and centrifuged multiple times to separate and collect as much of the residue as possible. Remnant matrix material was separated from the carbide residue using a very strong magnet.

A Philips X'Pert X-ray Diffraction System with Cu tube was used to identify the phases of the LC samples as well as extracted carbides. A Hitachi S-4500 Field Emission Scanning Electron Microscope was used to study the microstructure at high magnification.

The tensile strength was measured by using a 100 kN Instron Mechanical Testing System. Hollow rectangular LC CPM-9V tubes were built vertically on the base and machined into flat tensile specimens having 25-mm gauge length (Fig.1). The specimen surfaces in the gauge length area were manually polished down to 600 grit for consistent surface finish.

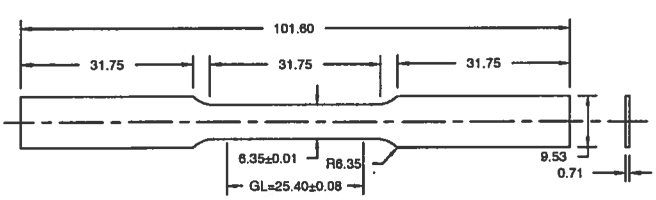
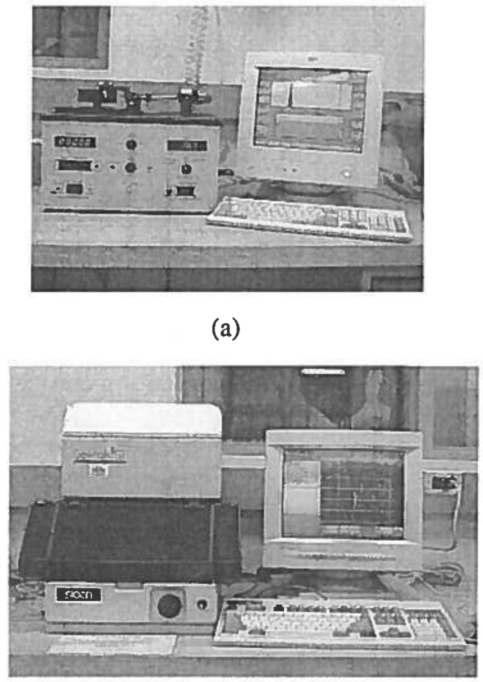


Fig. 1 Tensile specimen geometry (mm).

The wear resistance of LC CPM-9V was evaluated with a Falex ISC-200PC Pin-on-Disk System (Fig.2a) as per ASTM Standard G99. The pin consisted of a ¼" diameter WC sphere adhered to a cylindrical holder. The sphere had a composition of 94 wt% WC plus 6 wt% Co and the hardness of the sphere was Ra 92[6]. The disk consisted of a flat specimen mounted perpendicularly to the pin. The pin was pressed against the disk at a load of 500 g applied by a lever arm and a hanging weight. During the test, the pin remained stationary while the disk was rotated at a linear speed of 0.28 m/s running for the total distance of 8000 m.



(a)

(b)

Fig. 2 Wear test instruments: (a) Falex pin-on-disk wear tester, (b) Dektak surface profiler.

The wear resistance of the LC CPM-9V tool steel disk specimens (Rc. 49-50) was evaluated and compared with that of normalized 4340 high strength steel (Rc. 35-36) and hardened D2 tool steel (Rc. 62-63). The amount of disk wear was determined by using a Dektak Surface Profiler (Fig.2b) to measure the depth profile of the wear scar and to calculate the area of wear loss from the profile. For each specimen, eight measurements were made along the whole wear scar and the average value of the wear loss area was then multiplied by the circumference of the wear scar to determine the volume loss of the disk. The amount of pin wear was determined by measuring the diameter of the circular wear scar on the ball to calculate the volume loss.

The impact resistance of cutting blade plays an important role in its performance. However, no standard method is available for this type of testing. A simple impact testing apparatus was designed and manufactured to address the specific need (Fig.3). During the test, a cutting blade sample was fixed horizontally in the cavity of the apparatus and a drop weight following a guide rod was allowed to fall down freely to impact the shearing hammer vertically, which transferred the impact perpendicularly and uniformly to the cutting blade. The impact energy of the testing was calculated by multiplying the drop distance with the mass of the drop weight and then divided by the cross-section of the blade.

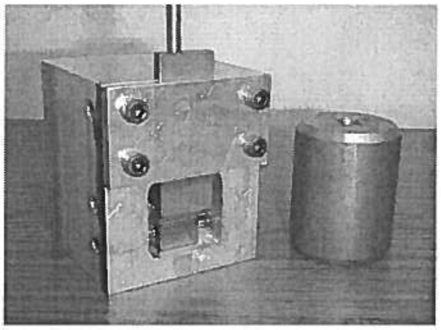


Fig.3 Impact test apparatus for cutting blade.

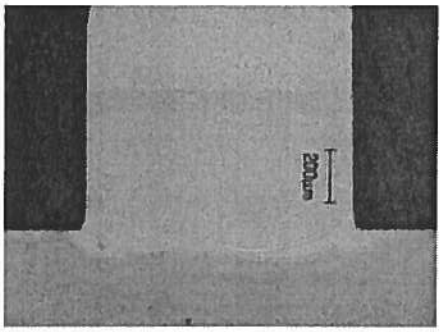
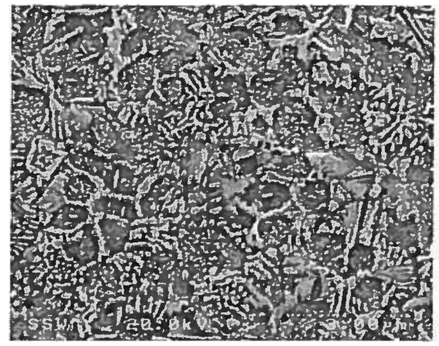
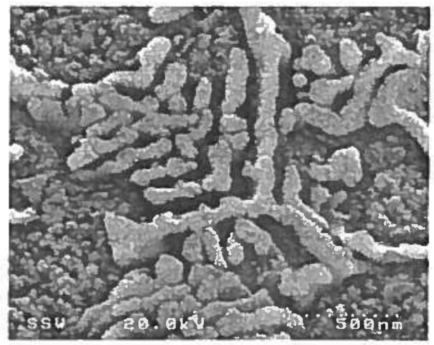


Fig.4 Cross-sectional view of LC CPM-9V cutting blade.



(a)



(b)

Fig.5 Microstructure of as-consolidated CPM-9V by high resolution SEM, (a) × 6,500, and (b) × 40,000.

Table 2 Comparison of chemical compositions of two phases in LC CPM-9V by EDS analysis.

Location		V	Cr	Mn	Si	Fe
Light Area	Area #1	11.70	6.03	1.42	1.55	79.31
	Area #2	14.74	6.64	1.69	1.67	75.26
	Area #3	13.63	6.41	1.90	1.23	76.83
	Average	13.36	6.36	1.67	1.48	77.13
Dark Area	Area #1	9.88	5.78	1.86	1.68	80.80
	Area #2	8.57	5.74	1.97	1.79	81.93
	Average	9.23	5.76	1.92	1.74	81.37
Overall Average		10.61	6.14	1.74	1.53	80.07

3. Results and Discussion

3.1 Process Development

The laser consolidation was concentrated on the development of processing parameters to build CPM-9V cutting blades steadily and uniformly without inducing cracking. With the optimised parameters, the free-form laser consolidation process can build metallurgically sound CPM-9V cutting blades on the low alloy steel base (Fig.4). Optical microscope and scanning electron microscope (SEM) examinations show that the LC CPM-9V samples are fully dense, free of cracks and porosity.

3.2 Microstructure of LC CPM-9V Material

LC CPM-9V has extremely fine microstructure and was very hard to identify by an optical microscope. A high resolution SEM photo (Fig.5a) shows that as-consolidated CPM-9V has two-phase microstructure: a light, very fine and snowflake-like phase precipitated on the dark matrix. The thickness of the light snowflake-like phase is only about 100 nm (Fig.5b). EDS analysis (Table 2) indicates that the light phase contains higher percentage of Vanadium (about 12 – 14 wt%) and Chromium (about 6 – 6.6 wt%) compared to the dark matrix (about 9 wt% V and 5.7 wt% Cr).

Phase identification of LC CPM-9V material was performed by X-ray diffraction (XRD) technique. Fig.6 shows that CPM-9V powders used for the laser consolidation consist of a majority of α phase plus small amount of γ phase. After laser consolidation, the γ phase almost disappeared. Due to very weak peak intensity, the carbide phases could not be identified directly from the XRD patterns for both powder and laser consolidated CPM-9V materials.

An electrochemical method was used to extract carbides from the laser-consolidated material. X-ray

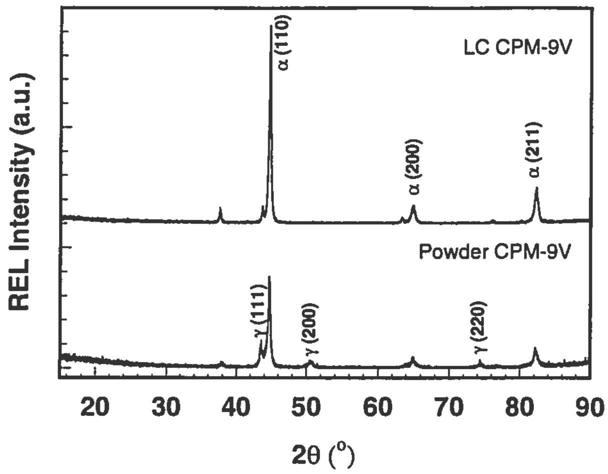


Fig.6 X-ray diffraction patterns of powder and LC CPM-9V.

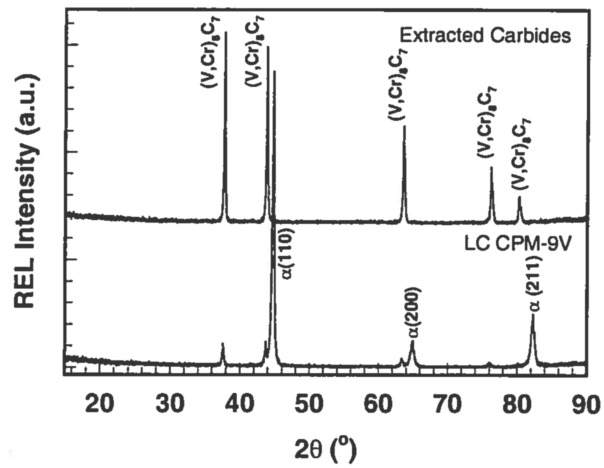


Fig.7 Comparison of X-ray diffraction patterns of extracted carbides with LC CPM-9V material.

diffraction peaks of the extracted carbides are very strong and clear, all of them can find the matching small peaks in the XRD pattern of LC CPM-9V material (Fig.7). The XRD analysis indicates that the carbides in the LC CPM-9V matrix are of $(V,Cr)_8C_7$ type.

Based on the analysis of EDS and XRD results, it may be reasonable to conclude that during the laser consolidation, eutectic $(V,Cr)_8C_7$ carbides (the light, very fine and snowflake-like phase observed in high resolution SEM photos) first precipitated from liquid phase. Because of the high cooling rate inherent to the consolidation process, the precipitated eutectic carbides had very fine spacing (around 100 nm). Also due to the high cooling rate, the rest of liquid phase solidified rapidly and transformed almost instantaneously to Martensite (dark matrix in high resolution SEM photos). The observation of particles in the matrix (Fig.5b) also indicates that other type of carbides might also be present. More detailed investigations, such as TEM analysis will be required to reveal the details.

The average hardness of as-consolidated CPM-9V material is around HV_{200} 570, which is the overall contribution of both snowflake-like $(V,Cr)_8C_7$ carbides and the martensite matrix. Because the thickness of these carbides is only around 100 nm, the conventional microhardness tester can not be used to measure the hardness of these carbides.

3.3 Tensile Properties of LC CPM-9V Material

As-consolidated CPM-9V material shows very good tensile properties (Table 3). Along the vertical direction (the build direction), the as-consolidated CPM-9V has an average yield strength of 821 MPa and tensile strength of 1315 MPa. The Elastic modulus of the consolidated CPM-9V is about 234 GPa. The elongation of the as-consolidated CPM-9V is between 2.2% and 3.1%. It should be noted that all tensile test data are very consistent and the scatter ranges are small, which indicates that the laser consolidation process has an excellent reproducibility.

As the tensile specimens were machined from vertically grown coupons, all the tensile properties are evaluated along the vertical direction (the build direction). Based on the metallurgical observation, there is no anisotropic indication in microstructure. It may be reasonable to expect that the tensile properties along the horizontal direction (perpendicular to build direction) will be very similar to those along the build direction.

Table 3: Tensile properties of the laser consolidated CPM-9V tool steel

Sample No.	Vertical Direction (As Consolidated)			
	σ_{UTS} (MPa)	σ_y (MPa)	Elongation (%)	E (GPa)
#1	1358.9	883.8	2.3	229.6
#2	1295.0	787.0	2.8	230.6
#3	1303.8	835.9	2.2	244.5
#4	1303.8	778.1	3.1	232.7
Average	1315±29	821±49	2.6±0.4	234±7

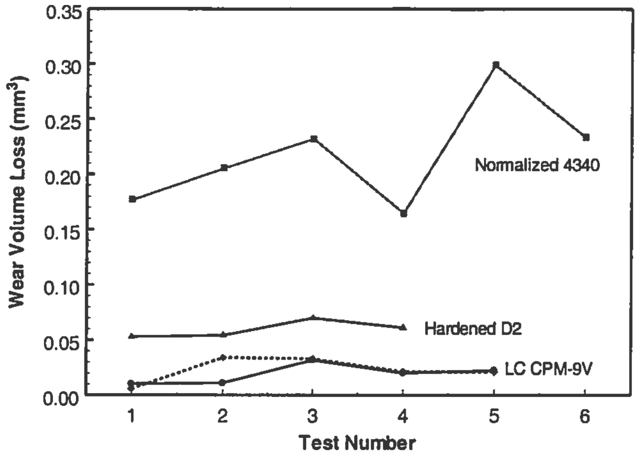


Fig.8 Pin-on-disk wear test results: disk volume loss.

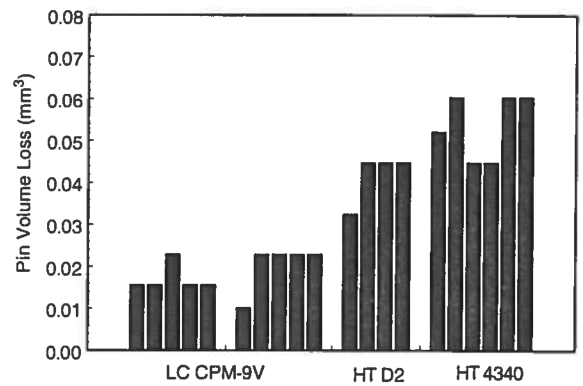


Fig.9 Pin-on-disk wear test results: pin volume loss.

3.4 Wear Test Results

Pin-on-disk wear test results (Fig.8) indicate that, under the given test conditions, LC CPM-9V specimens (Rc.50-55) showed significantly better wear resistance compared to hardened D2 (Rc. 62-63) and normalised 4340 (Rc.35-36) materials. The average volume loss of the LC CPM-9V specimens was about 0.0211 mm^3, which was only about the 1/3 of the volume loss of D2 specimens (0.0595 mm^3) and about one order of magnitude lower compared to the 4340 specimens (0.2185 mm^3). In addition, the wear loss of WC balls against the LC CPM-9V material was also significantly lower than that of the same balls against the D2 and 4340 steel (Fig.9). The average wear volume loss of the WC balls against the LC CPM-9V was about 0.01855 mm^3, while the ball volume loss against the D2 and 4340 steel was 0.0417 mm^3 and 0.0538 mm^3 respectively.

It is interesting to notice that although the hardness of the LC CPM-9V material is only around Rc.50-55, but its wear resistance is clearly superior to the hardened D2 steel with a hardness of around Rc. 62-63, which is consistent with the observation on powder metallurgy (P/M) CPM-9V material[7]. The excellent wear resistance of the LC CPM-9V may be attributed to the precipitation of $(V,Cr)_8C_7$ carbides due to the high vanadium contents in the alloy.

3.5 Impact Test Results

Table 4 lists the impact test results produced by the non-standard apparatus to give a rough comparison of the impact resistance between the annealed LC CPM-9V and heat-treated D2 materials. The results indicate that the heat-treated D2 cutting blades remained unbroken when the impact energy was lower than 12.29 J/cm^2, while three out of four D2 blades were completely fractured when the energy exceeded 13.28 J/cm^2. The impact resistance of the HT D2 blades could be estimated roughly around 13 J/cm^2. After stress relief, the laser consolidated CPM-9V cutting blades had no fracture when the impact energy was lower than 6.93 J/cm^2, but all blades were completely broken when the energy was higher than 7.6 J/cm^2. The impact resistance of the LC CPM-9V was in the range of 7 – 7.5 J/cm^2.

Table 4: Impact test results

Mat.	Spe. No.	Sample Dimension	Test Condition		Impact Energy (J/cm^2)	Observation
		Length × Thickness (cm × cm)	Mass (kg)	Drop Height (cm)		
D2 (HT)	B01	1.946 × 0.102	0.5	20	4.94	No fracture
	B02	1.994 × 0.097	0.5	40	10.14	No fracture
	B04	1.956 × 0.102	1.0	25	12.29	No fracture
	B06	1.862 × 0.102	1.0	26	13.42	No fracture
	B07	1.918 × 0.104	1.0	27	13.28	Complete shear
	B08	1.869 × 0.102	1.0	26	13.38	Complete shear
	B05	1.880 × 0.104	1.0	27	13.55	Complete shear
	B02	1.971 × 0.102	1.0	30	14.63	Complete shear
LC CPM-9V (Annealed)	D02	1.994 × 0.099	1.0	12	5.96	No fracture
	D03	2.022 × 0.091	1.0	13	6.90	No fracture
	E02	2.012 × 0.091	1.0	13	6.93	No fracture
	E01	1.976 × 0.091	1.0	14	7.6	Complete shear
	E03	1.935 × 0.089	1.0	14	7.98	Complete shear
	D01	1.981 × 0.091	1.0	15	8.12	Complete shear
	D04	2.032 × 0.089	1.0	15	8.14	Complete shear

The impact test results indicate that the laser consolidated CPM-9V cutting blades have a relatively inferior impact resistance compared to the heat-treated D2 blades.

3.6 Dimensional Accuracy

A rectangular cutting pattern (Fig.10) was manufactured by the laser consolidation of CPM-9V material on a flat base for the dimensional accuracy measurement. The measurement was performed by using a Mitutoyo microscope equipped with an X-Y stage. Three points on each wall were selected to measure the wall thickness as well as the distance between the walls.

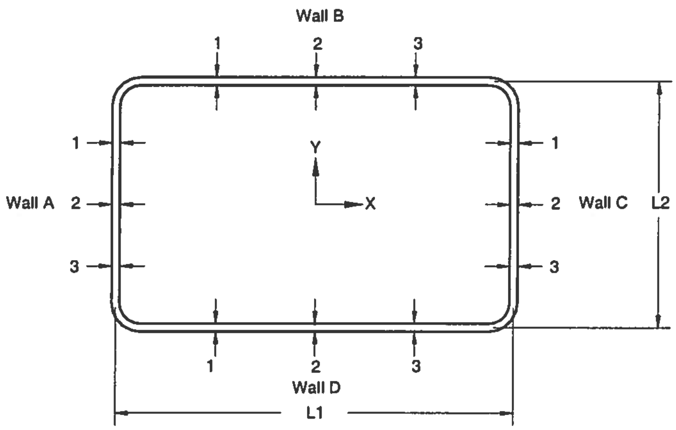


Fig.10 Details of dimensions taken for measurement on a laser consolidated rectangular cutting pattern.

The measurement results (Table 5) show that the distance between walls is very uniform. The standard deviation of the three measurements for distance L1 and L2 is only about 0.028 mm and 0.005 mm respectively, and the difference between the laser consolidated wall and the CAD design is only about 0.030 mm for both cases. Wall thickness is very uniform with a standard deviation only from 0 to 0.046 mm. However, there is slightly more thickness difference between walls. The thickness of thickest Wall D is about 1.153 mm, while the thinnest wall C is only about 0.927 mm, leaving the maximum thickness difference between walls to about 0.226 mm. Because all laser-consolidated walls will be finish machined, the thickness difference will not affect the sharpening of the cutting blades as long as the distance between walls and the wall thickness are within the acceptable range.

3.7 Manufacturing of Test Dies

Several trial rotary cutting dies have been manufactured by using the laser consolidation process. Fig.11 shows a laser consolidated rotary cutting die after final sharpening. Currently, two rotary cutting dies are undergoing production testing and the LC CPM-9V die has successfully cut more than 180,000 meters of labels without the need of re-sharpening. D2 dies usually need re-sharpening after running that long.

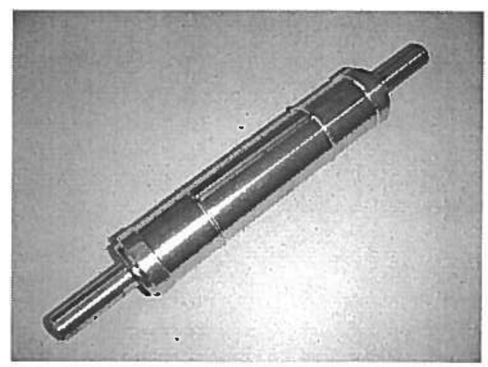


Fig.11 Laser consolidated CPM-9V rotary cutting die after final sharpening.

Table 5: Dimensional measurement results

Dimension	Measurements (mm)			Average (mm)	Std. Deviation (mm)	Nominal (mm)	Difference (mm)
	Position 1	Position 2	Position 3				
Wall Thickness Measurement							
Wall A	0.996	1.034	1.036	1.021	0.023	-	-
Wall B	1.143	1.143	1.143	1.143	0.000	-	-
Wall C	1.001	1.008	0.927	0.978	0.046	-	-
Wall D	1.153	1.146	1.153	1.151	0.005	-	-
Wall Distance Measurement							
L1	50.744	50.764	50.800	50.770	0.028	50.800	-0.030
L2	31.463	31.463	31.471	31.466	0.005	31.496	-0.030

4. Conclusions

1. The feasibility has been established for the laser consolidation of CPM-9V tool steel powder for the manufacturing rotary cutting dies.
2. The consolidated CPM-9V cutting blades as well as the bond between the consolidated blades and substrate are metallurgically sound, free of cracks and porosity.
3. Several trial rotary cutting dies with CPM-9V cutting blades have been successfully manufactured by laser consolidation method. On production testing, the LC CPM-9V die has successfully cut more than 180,000 meters of labels without the need of re-sharpening so far.
4. The LC CPM-9V shows two phase microstructure: very fine and snowflake-like eutectic $(V,Cr)_8C_7$ carbides precipitated on the dark martensitic matrix.
5. The LC CPM-9V has average yield strength of about 820 MPa and average tensile strength of about 1310 MPa.
6. The wear resistance of LC CPM-9V is almost triple compared to heat treated D2 and almost one order of magnitude better compared to normalize 4340 steel.
7. The impact resistance of the consolidated CPM-9V is within the range of 7 - 7.5 J/cm^2, which is lower than the heat-treated D2 material (about 13 J/cm^2).

Acknowledgements

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