THE EFFECT OF RUBBER COATING GLASS STRANDS IN FIBER REINFORCED POLYESTER COMPOSITES ON FRACTURE TOUGHNESS

by
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ABSTRACT

In this research, the effect of a rubber coating on strands in a glass fiber-reinforced polyester composite was studied. Glass strands were coated using a 2,4, and 6% ATBN rubber solution, then chopped into one inch lengths. These were arranged in a planar, random array polyester composite. Eight samples of uncoated, 2,4 and 6% coated strands were made into Double Edge Notch (DEN) test specimens and tested with the Instron 4505 machine. Using the maximum load from the load/displacement curve, fracture toughness values were calculated for each sample. The morphology of the damage zone was also studied to better understand the fracture mechanics of the composite. The fiber content of each sample was determined by burn-off, and then used to normalize the fracture toughness values. An average fracture toughness for each coating thickness was calculated, to see the effect of the rubber coating thickness on fracture toughness. It was determined that the ATBN rubber coating on the strands had no measurable effect on fracture toughness.

Thesis Supervisor: Professor Frederick McGarry
Title: Professor of Polymer Engineering and Civil Engineering

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1. INTRODUCTION

Composite materials have many important uses in today's industry. Because composites have better properties and possible applications than metals, they are being used in an increasing amount of engineering applications. A composite is defined as a material that combines two or more components, a filler or reinforcing agent and a compatible matrix resin, in order to obtain tailor made characteristics and properties. The reinforcing agents can be in either particle or fibrous form.

The advantages of using composite materials are numerous. By controlling the fiber content, fiber direction, and the difference of moduli and thermal properties between the reinforcement and the matrix, it is possible to tailor the properties of a composite for a particular application. Composites also have a high strength and modulus to weight ratios as compared to metals, leading to lighter materials. Composites also have more fracture toughness in some fracturing directions. A component of the fracture toughness comes from the work used to break the interface between the matrix and the reinforcing materials. [1] The reinforcing material provides more interfacial area to break for fracture, therefore requiring more energy to produce fracture. Higher fracture toughness in a material means the material is more resistant to cracking under a given load, thus it is an important parameter to maximize in materials design.

The most common reinforcing materials are fibers. Advances in the last fifteen years in fiber technology have resulted in man-made fibers which have high strength, low weight, and high heat and chemical resistance. These properties give them an competitive advantage over existing metals. For example, the weight of an aircraft determines how much payload it can carry in flight. By using a fiber-reinforced composite instead of metal for the fuselage, a significant reduction in weight is obtained, which leads to higher payloads and less fuel consumption. The properties of high heat and chemical resistance allow the use of composite materials in environments which metals cannot withstand. Another important feature of fibrous composites is the ability to control directional properties of the material; this allows a designer the flexibility of control of material properties.

One of most important factors in determining the material properties of any composite material is the interface between the reinforcement and the matrix. The interface provides the structural integrity of the whole composite. [2] The elastic properties of the composite are determined by the strength of the interface; it also affects the fracture toughness of the material. The importance of interfacial bond strength can be seen in the fracture surface morphology of a failed composite. Figure A1 shows the change in surface morphology with increasing interfacial bond strength. A strong bond produces a smooth fracture surface, an intermediate bond gives a irregular fracture pattern with some fiber pull-out, and a weak interfacial bond results in large amounts of fiber pull-out and a very irregular fracture surface. To maximize fracture toughness while maintaining strength, it is desirable to have an interface that is strong enough to use the strength of the reinforcing material but weak enough to allow a crack to propagate along the interface to give higher energy consumption.

One type of composite that is being used in a wide range of engineering applications is the short-fiber reinforced material. These have chopped fibers arranged randomly in the matrix. One of the most attractive of these is sheet molding compound (SMC) which is a modified polyester matrix with glass fibers as reinforcement. SMC has the advantages of high-volume processability, good mechanical properties and low cost. [3] It is used in the automotive industry to make auto body parts. Although SMC is being used in many applications, its fracture toughness properties have not been studied extensively. It was the objective of this study to try to improve the fracture toughness of SMC, to expand its possible engineering value. It is believed that the use of a rubber coating on the fibers will reduce stress concentrations at fiber ends and lead to a higher fracture toughness. In this research the amount of rubber coating on glass fiber strands in a polyester matrix was varied to determine the influence the coating had on the overall composite fracture toughness.

2. LITERATURE SURVEY

2.1 COMPOSITE STRUCTURE

In order to understand the fracture behavior of a composite it is necessary to study the details of the composite structure. For the case of glass-reinforced polyester (GRP), the alignment and packing arrangement of the fiber strands play an important role in determining many properties of the composite. Continuous fiber strands provide the highest strength and stiffness, but because of processing limitations, often it is advantageous to use discontinuous fibers. [4] With discontinuous fibers, the ends play an important role because they are sites of high stress concentration. These result from the fact that negligible stress is transferred to the fibers across their end faces. [4] The stress distribution along a fiber is seen in Figure A2, where both fiber tensile stress and interfacial shear stress are plotted along the fiber length. The interfacial stress is concentrated at the fiber ends. As the composite strain is increased, the interface at the fiber ends is first to fail, and either the fibers debond or shear failure of the matrix occurs. This begins when the interfacial stress reaches the interfacial strength or the shear strength of the matrix. [4] As the strain continues to increase, the debonding area increases along the fiber. The fiber will break if it reaches the critical stress required for fracture. This can occur only if the fiber is long enough for the stress to reach the critical limit. If the fibers are below the critical length, failure occurs when the debonding region extends along the entire length of the fiber, resulting in the fiber slipping within its hole in the matrix. Failure of the entire composite in this fashion results in lower strength and lower fracture toughness. Thus discontinuous fibers involve a reduction in strength and a greater probability of matrix-controlled failure. In this study, chopped, one inch long, glass fiber strands were arranged in an random, planar array. To increase the strength and fracture toughness of the composite it was important to reduce the stress concentrations at the strand ends. This was sought from a rubber coating on the fiber strand surface. If the coating was effective, it would reduce the end stress concentrations, inhibit interfacial fracture, reduce fiber pullout, and produce the desired improvements.

2.2 FRACTURE TOUGHNESS

The basic understanding of brittle crack propagation was established by Griffith who studied a thin, through-thickness crack of length 2a, in a thin, wide sheet subject to tensile stress. He recognized an exchange between the elastic strain energy released and the amount of work required to create new surfaces. As the crack propagates, the region behind the crack tip is no longer stressed, and this energy is released. If the stresses around the crack are examined , the strain energy released can be calculated:

$$\text{Energy} = \sigma^2 \Pi a^2 B/E \qquad (1)$$

where σ is the applied stress, a is the half crack length, B is the sample thickness, and E is Young's modulus [4].

Opposing the crack propagation is the work required to form the two new surfaces created by the crack. The total work of this crack formation is equal to the surface area of the crack times the surface energy of the material:

$$\text{Work} = 2aBG_c \qquad (2)$$

where a is again the half crack length, B the thickness, and Gc is equal to twice the surface energy of the material (twice since two surfaces are formed). [4]

The two equations (1) and (2) characterize the energy of the system. Unstable crack growth occurs when the derivatives of the two become equal: the elastic energy released equals the surface energy needed, per unit advance of the crack. Thus:

$$\sigma_F = (EG_c/\Pi a)^{0.5} \qquad (3)$$

G_c is the fracture energy of the material, but a more useful parameter is the plane-strain critical stress intensity factor K_c, which is defined as:

$$K_c = Y\sigma_F\,(\Pi a)^{0.5} \qquad (4)$$

where Y is a geometrical factor that depends on the sample geometry. K_c is used to compare the fracture toughness of materials. Assuming the largest crack size is known, a designer can determine if a material will fracture under a given stress; if $K < K_c$, the crack will not propagate. Obviously, the K_c value of a composite is extremely important to a designer to insure that the material will not fracture under normal loading.

2.3 DOUBLE EDGE NOTCH (DEN) TEST

The double edge notch tensile sample testing method is used to determine a material's fracture toughness (K_{Ic}). (The subscript "I" refers to Mode-1 loading) The sample geometry is shown in Figure A3. By measuring the tensile stress applied to the sample, it is possible to determine the critical stress needed to cause failure: σ_F. To determine K_{Ic}, the geometrical factor Y must be calculated for the sample. For DEN samples, Y is defined by the equation:

$$Y(\Pi)^{0.5} = 1.99 + 0.76(a/W) - 8.48(a/W)^2 + 27.36\,(a/W)^3 \quad (5)$$

where W is the width of the sample. [8] These values can be then put into equation (4), and solved for fracture toughness.

2.4 IMPORTANCE OF INTERFACE

One of the important factors in determining the fracture toughness of a composite material is the interface between the fibers and the matrix. [5] The stresses acting on the matrix must be transmitted to the fiber across the interface. [6] The strength of the interface bond determines the fracture surface morphology. (Figure A1) A strong interface bond gives the composite a higher stiffness and strength, but it is more brittle and notch-sensitive. [5] A strong interface bond causes breaking of the fiber instead of the interface, which takes advantage of the fiber's high tensile strength. However, it does not create much new surface area compared to breaking the interface and going partially around the fiber instead. With a strong interfacial bond, the fracture toughness is reduced. Ideally, the interface should be strong enough to exploit the tensile strength of the fiber, but it should also allow some crack growth along the fiber before the fiber fails. The fiber ends should remain bonded or anchored in the matrix, while much of the length of the fiber between the ends should debond from the matrix.

2.5 THEORY OF RUBBER COATING

To increase the fracture toughness of the composite, it is important to reduce the stress concentrations at the fiber ends. It is these concentrations which cause a crack to release the ends of the fibers from the matrix: fiber pullout. If the concentrations are reduced, the crack may still partially debond the fibers but the ends will remain anchored in the resin.

One method to reduce the stress concentrations is to coat the fiber strands with a thin layer of rubber before embedding them in the matrix material. This coating provides a compliant region at the interface, which can deform slightly to relieve the stress concentrations. If the rubber deforms enough it will require more energy for a crack to grow. This will produce an increase in fracture toughness. This was the purpose of the rubber coating: anchored fiber ends and appreciable intermediate debonding. Such a situation would produce the strongest, toughest composite. This study of the effect of rubber coating thickness on fracture toughness was undertaken to explore this general concept.

3. OUTLINE AND PLAN OF WORK

In order to study the effect of rubber coating thickness on fracture toughness in the polyester/glass fiber composite, it was necessary to develop several new processes. A consistent method of coating the strands with various thicknesses of rubber was needed, as was a method for producing the composites themselves. In order to coat the strands, an existing coating machine was modified to produce large quantities of strand with controlled amounts of rubber. It was necessary to relate the percentage of rubber in a toluene solution to the weight percent of the rubber coating deposited on the strand. Coatings were made with two, four, and six percent solutions of ATBN rubber.

Once the strands were coated, a method of cutting them into regular one inch pieces was needed. A chopping gun was used;

adjusting the blades until one inch segments were produced. In order to insure consistent size, the coated strands were separated into groups of 10-15 before cutting. If any more than 15 strands were cut at a time, many of the strands were not completely cut, resulting in a wide distribution of strand lengths. Once the strands were cut, they were ready to be added to the polyester.

The most important and most difficult step was producing the completed composite. Several methods of forming were attempted, varying the amount of pressure applied, curing time, vacuuming, and molding techniques. By using the hot press, along with a vacuum bag, it was possible to obtain samples with a high fiber content, low void content, and a consistent one eighth inch sample thickness. The samples were ready for the next step; cutting.

The cutting of the samples required study of the proper geometry for fracture toughness tests. It was decided that the double-edge notch test was the best geometry to use. ASTM standards were used to determine the exact specimen dimensions. Two inch wide samples were used in order to maximize the number of specimens per molding. This allowed four specimens per molding. A large number of samples was desirable because of the expected scatter of results, due to uncontrolled variables in the production of the composite.

Once all these processes were perfected, eight samples each of 0,2,4, and 6% rubber coatings were made and tested with the Instron machine. Using the maximum load value from the load/displacement curve, fracture toughness values were calculated for each sample. An average fracture toughness for each coating thickness was calculated, and then compared to see the effect of the rubber coating thickness on fracture toughness.

4. PROCEDURE

4.1 COATING OF STRANDS

The coating of the strands with ATBN rubber was accomplished by using a fiber coating machine. Figure A4 show the coating machine set-up. The fibers used in this study were supplied by Gencorp in a tow made up of about fifty strands of fiber. Each strand was composed of about 200 E-glass fibers tightly bound together with an insoluble proprietary coating. The tow of strands was fed into the coating machine off the first reel. The strands were then spread out with a blower to enable each strand to be coated. The strands were then run through a bath of ATBN rubber and toluene, which coated them with a thin coating of rubber. The ATBN rubber was mixed with EPON 828 epoxy in a 4.75:1 weight ratio. This composition has a modulus of elasticity of approximately 100 psi. The amount of rubber coating applied was controlled by controlling the percentage of ATBN rubber in the bath. By increasing the ATBN rubber concentration, the viscosity of the solution was increased, resulting in thicker coatings of rubber on the strands as they passed through the solution. Figure A5 shows the weight percent of rubber coated on the strands versus the weight percent of rubber in the coating solution. These results were collected by M. Groleau by burning off the rubber coating on the strands and measuring the weight loss. (Because of the insoluble coating on the strands, it is believed that the rubber only coats the outside surface of the strand and does not penetrate into the strand.) Once the strands were coated, they were wound through a number of reels, and then were dried by the heater at 80 ^{o}C. The finished strands were then rewound onto the take-up reel. The coated strands were then placed in an oven at 120 ^{o}C for two hours to complete the cure of the rubber. The strands were then ready for cutting.

4.2 CUTTING OF STRANDS

A chopping gun was used to cut the strands into one inch pieces. The gun was used instead of cutting by hand because of the volume of fiber necessary to make each composite. The strands were first separated into groups of ten to fifteen and then run through the chopper. By limiting the number of strands cut at one time, it was possible to produce a large quantity of consistent one inch segments. Safety goggles and gloves were used in order to ensure protection and to prevent the strands from being damaged by handling. The cut strands were then ready to be impregnated with the polyester resin.

4.3 POLYESTER PREPARATION

A modified polyester resin was produced for use as the matrix material. The polyester was supplied by the Allied Chemical Company and is known as polyester 32-033. The exact chemical composition of this polyester was not given by the company. The polyester was mixed with Tert-Butyl Peroxybenzoate (TPBP, an initiator, $C_6H_5CO_2OC(CH_3)_3$) and a silica based thickening agent, Cabosil. Table B1 shows the relative amounts of each constituent used. Cabosil was used to increase the viscosity of the resin. This was necessary because without thickening, the pressure necessary to produce the pressed samples pushed strands through the resin and against the sides of the mold. This resulted in damage to the strands. The viscosity of the polyester prevented the strands from being pushed through to the surface. The polyester, TPBP, and Cabosil were mixed by hand until a uniform consistency was obtained. The polyester resin was now ready to be mixed with the strands.

4.4 MOLDING PROCEDURE

The most important and difficult step in the sample preparation was the molding of the composite. A steel mold was used which allowed only small amounts of resin to be pushed out the sides during pressing. The mold was sprayed with a mold-release agent to ease sample removal. In order to obtain a high percent of fibers in the finished sample and to insure the randomness of the fiber orientation, extreme care was used. First, a thin layer of polyester was poured into the mold and was spread out to completely cover the mold's bottom surface. Next, the chopped strands were hand-laid on top of the polyester, and lightly pushed into the resin to insure complete wetting of the strand. These steps were alternated until the amounts of resin and fiber needed to fill the mold were used. It was very important to make sure that all the strands were completely wetted by polyester, or voids and/or fiber damage would result. Once the mold was filled with polyester and fiber, the top lid was put in place, and the mold was ready for pressing.

Pressing the mold was accomplished using the PHI Company hot-press. Figure A6 is a diagram of the hot-press used. The mold was first placed in a vacuum bag, and then a vacuum was applied. The vacuum was used to reduce the number of air bubbles present in the sample. The vacuum bag containing the mold was then put into the hot-press and was pressed for 20 minutes at 120 ^{o}C. After the required time, the mold was removed and placed in the hood to cool, in order to prevent sample warping. Once the sample was cool, it was removed from the mold, and excess resin was cut away from the sample sides. Each molding resulted in a four by ten by one eighth inch sample, with approximately thirty weight percent of glass fiber. The sample was now ready to be cut into fracture toughness specimens.

4.5 CUTTING OF SAMPLES

The composite samples were cut into two by five inch, double edge notch specimens. The specimen dimensions can be seen in Figure A3. A diamond edged saw was used to cut the specimens to size. After testing, the saw was used to cut out the fracture zone of the specimen. These pieces were analyzed to determine the fiber content of that particular specimen. This was accomplished by weighing the sample before and after burning off the polyester resin, using an oven.

4.6 FRACTURE TOUGHNESS TESTING

Fracture toughness of each sample was determined by using the Instron 4505 machine. A strain rate of 0.2 inches per minute was used to test each DEN sample. The applied load versus grip displacement was plotted by the machine's computer. When the sample failed, the load carried by the sample dropped off. The maximum load applied was used as the critical load, and is then converted into the critical stress at failure (σ_F). Equation (4) was then used to determine the specimen's fracture toughness. Eight specimens were tested for each rubber coating thickness, and the average value for K_{Ic} was then calculated. These values were used to relate the rubber coating thickness to the resulting fracture toughness of the sample.

4.7 FIBER WEIGHT PERCENT CALCULATION

Because the fracture stress is dependent on the fiber content of the sample, it is important to determine the fiber weight percent for each sample tested. Each sample's fracture damage zone was cut out with a diamond saw. After cutting, the samples were wet from the water used to cool the saw blade, so the samples were blotted with paper towels and allowed to dry for a couple of days. Once dry, the samples were carefully weighed. Then, the polyester resin was burned off in a furnace. The glass fibers left after burn-off were allowed to cool to room temperature, and then weighed. These weight measurements were used to calculate the weight percentage of fiber in the damage zone area.

5. EXPERIMENTAL RESULTS/DISCUSSION

Table B2 shows the results of fracture toughness divided by weight percent of glass fibers versus percent rubber coating solution. These values were determined using the data found in Appendix C. The data show no significant difference in K_{Ic} values for varying coating thicknesses. These results were unexpected. There are several possible explanations for the results. The following examines these explanations and their relevance in this study.

5.1 FIBER CONTENT

One important factor in determining the fracture toughness is the amount of fiber contained in the sample. Increasing the amount of fibers present at the crack path tip leads to a higher fracture stress needed to induce crack propagation and specimen failure. Because of this fact, the fiber weight percent in the fracture damage zone was calculated, and then used to normalize the fracture toughness values. This should eliminate any influence of fiber content on the K_{Ic} values. However, it is important to have a large weight percent of fiber present in each sample to insure the change in fracture toughness due to changing the rubber coating thickness is detectable. If there is a small amount of fiber present, the magnitude of the change of fracture toughness would be too small to be measured. For the samples tested, the average fiber content was 27% by weight. Most fiber reinforced composites have a fiber content of greater than 40% by weight, so the fiber content could be too low. However, Gencorp's SMC composite material has an average fiber content of 28% by weight, so 27% can be considered reasonable.

5.2 RUBBER COATING METHODS

Another source of possible error is the consistency of the rubber coating. The method of spreading the tow of strands before dipping in the rubber solution is effective, but may not allow for complete coating at higher percent rubber solutions. At higher concentrations of rubber, the strands tended to clump together, and the coating did not seem completely uniform. This could lead to irregular fracture toughness readings, because some strands would have thicker coatings than others in the same sample. However, at lower rubber concentrations, the coatings appeared very uniform. Concentrations higher than 6% did not noticeably increase the coating thickness on the strands, and they clumped together to the point where they were unusable. Thus, the 6% rubber coating gives the thickest practical coating of the strands. If additional rubber is needed to affect the fracture toughness of the composite, then a new method of coating is needed in order to obtain thicker coatings.

5.3 DAMAGE ZONE MORPHOLOGY

By examining the damage zone of the DEN samples, it is possible to gain insight into the fracture mechanics of each sample's failure. For all the samples tested, the damage zone was quite large compared to the sample dimensions. The strands were mostly pulled out of the polyester with little fiber breakage. This suggests a weak interfacial bond between the polyester and the rubber. There was no significant difference in the damage zone morphology between the coated and uncoated samples.

5.4 LOAD-DISPLACEMENT CURVES

Typical Load-Displacement curves for each sample can be seen in Appendix C. The curves show a steady increase in load, followed by a dramatic drop at failure. This closely resembles the curve for a material with low toughness. A tough material typically is represented by a load-displacement curve that rises smoothly and then tends to level out with a saw-tooth form. [9] [10] The saw-tooth represents an increase in load followed by rapid crack propagation. Although some of the samples exhibited saw-tooth curves, the saw-tooth was not as jagged as would be expected from a tough material.

5.5 EMBRITTLEMENT OF RUBBER COATING

One possible explanation for the inability of the rubber coating to increase the fracture toughness is the possibility of styrene embrittlement of the rubber coating. It has been noted that styrene will be absorbed by rubber and then polymerizes to form polystyrene. The polystyrene regions would be very brittle, and would make the rubber coating ineffective. This would result in an unchanged fracture toughness value when the strands were coated with the rubber solution.

5.6 NOTCH-SENSITIVITY OF DEN SAMPLES

Table B2 also shows the notch-sensitivity of the various samples. Notch sensitivity is calculated by using the expression:

$$\text{notch-sensitivity factor} = 2.5\ (K_{Ic}/F_{ty})^2 \qquad (6)$$

in this equation F_{ty} represents the tensile yield force. [11] F_{ty} is defined as:

$$F_{ty} = W/(W-a)\ \sigma_f \qquad (7)$$

If the notch sensitivity factor exceeds the critical sample dimensions B, a, and (W-a) (B = thickness, W = width, a = crack length) then the sample is "notch-insensitive". [11] If a material is "notch-insensitive", it means that it does not obey linear elastic fracture mechanics and that there are not plane-strain conditions at the crack tip. This means that the measured K_{Ic} value is not necessarily a true material property. [4] For all of the samples, the notch-sensitivity value is much larger than the sample dimensions, and thus the fracture toughness values do not represent plane-strain conditions. However, this does not mean that the fracture toughness values are unusable; rather that these values should only be compared with samples of the same thickness and shape.

6. CONCLUSIONS

The effect of a rubber coating on strands in a fiber-reinforced composite is at best inconclusive. The data obtained in this study showed the fracture toughness to remain constant with increasing rubber coating thickness, within the variance of the samples. It is possible that the change in fracture toughness was not noticeable due to the relatively low fiber content in the samples, although 27% is comparable to the fiber content of typical SMC composite material. The load-displacement curves show a relatively low fracture toughness for all samples, supporting the ineffectiveness of the rubber coating in influencing fracture toughness. The fracture morphology shows mostly fiber pullout, suggesting a weak interface between the rubber and the polyester. Styrene embrittlement of the rubber coating could explain the inability of the rubber coating to increase the fracture toughness. The samples were also determined notch-insensitive, which means the data only applies to this particular sample geometry. Thus, it seems that coating with ATBN rubber does not have a significant effect on the fracture toughness of a fiber-reinforced polyester composite. In order to see an effect, it may be necessary to increase the fiber content, and either find a more suitable rubber or try to coat the ATBN rubber with epoxy to prevent styrene penetration.

7. SUGGESTIONS FOR FUTURE WORK

There are many different ways that this work could be developed further in the future. One of the most important would be to repeat the research, using different rubbers for coating the strands and determine if a more suitable rubber exists. The rubber could also be coated with a layer of material that is impenetrable to styrene, such as epoxy, to prevent possible embrittlement of the rubber coating. A larger specimen size might reduce the notch-sensitivity value, and therefore give plane-strain fracture toughness values. All of these changes should eliminate many of the possible sources of error in this work.

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APPENDIX A

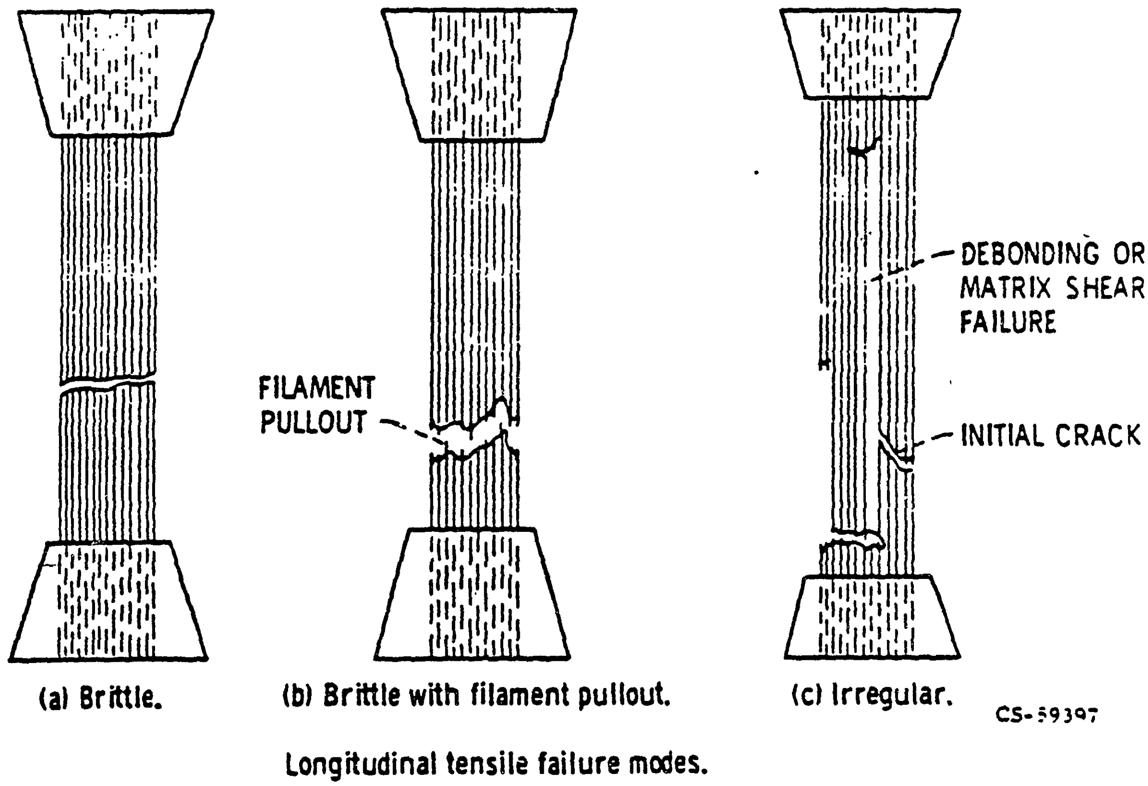


FIGURE A1: Fracture Morphology of Fiber Reinforced Composite [12]

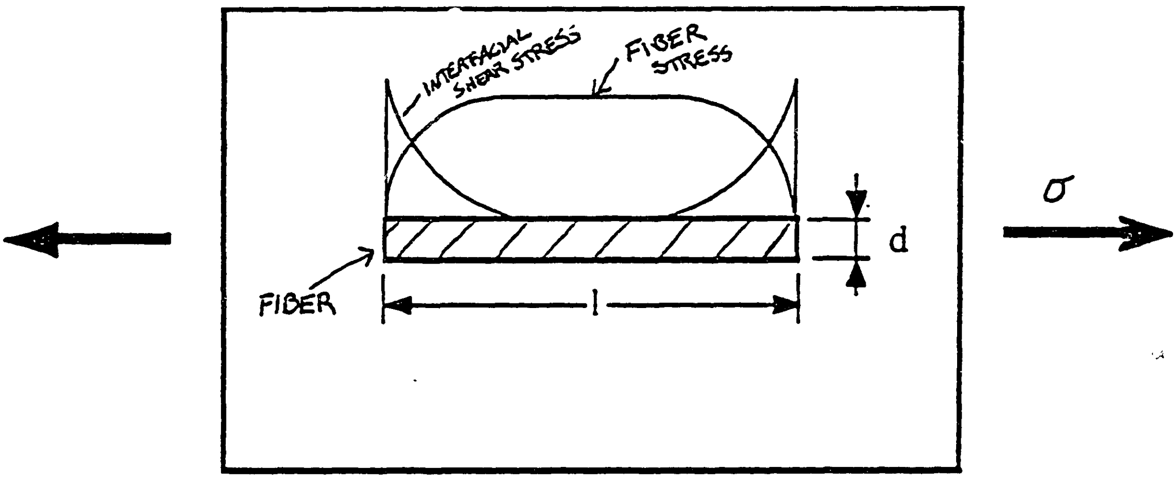


FIGURE A2: Stress Concentrations on Short Fibers

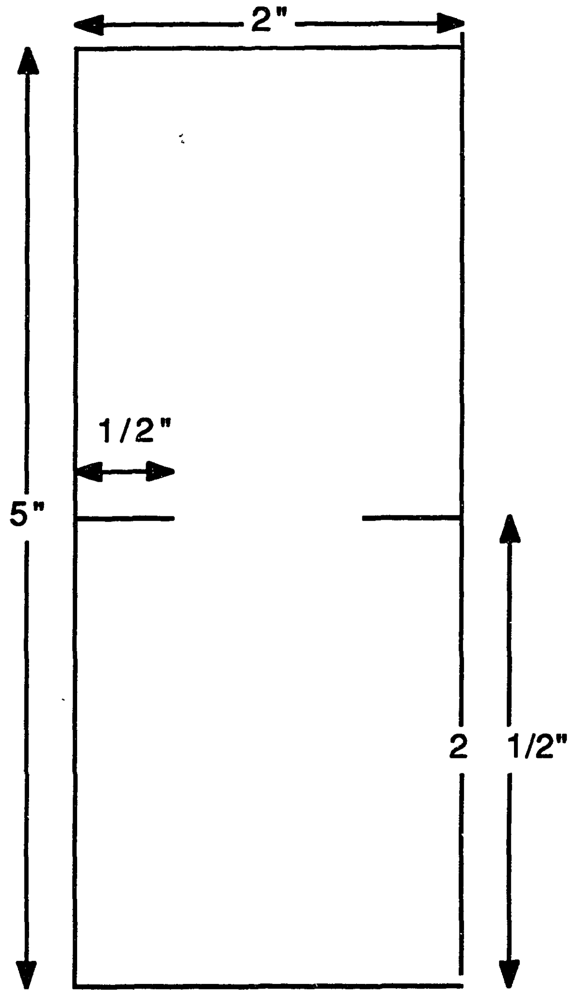
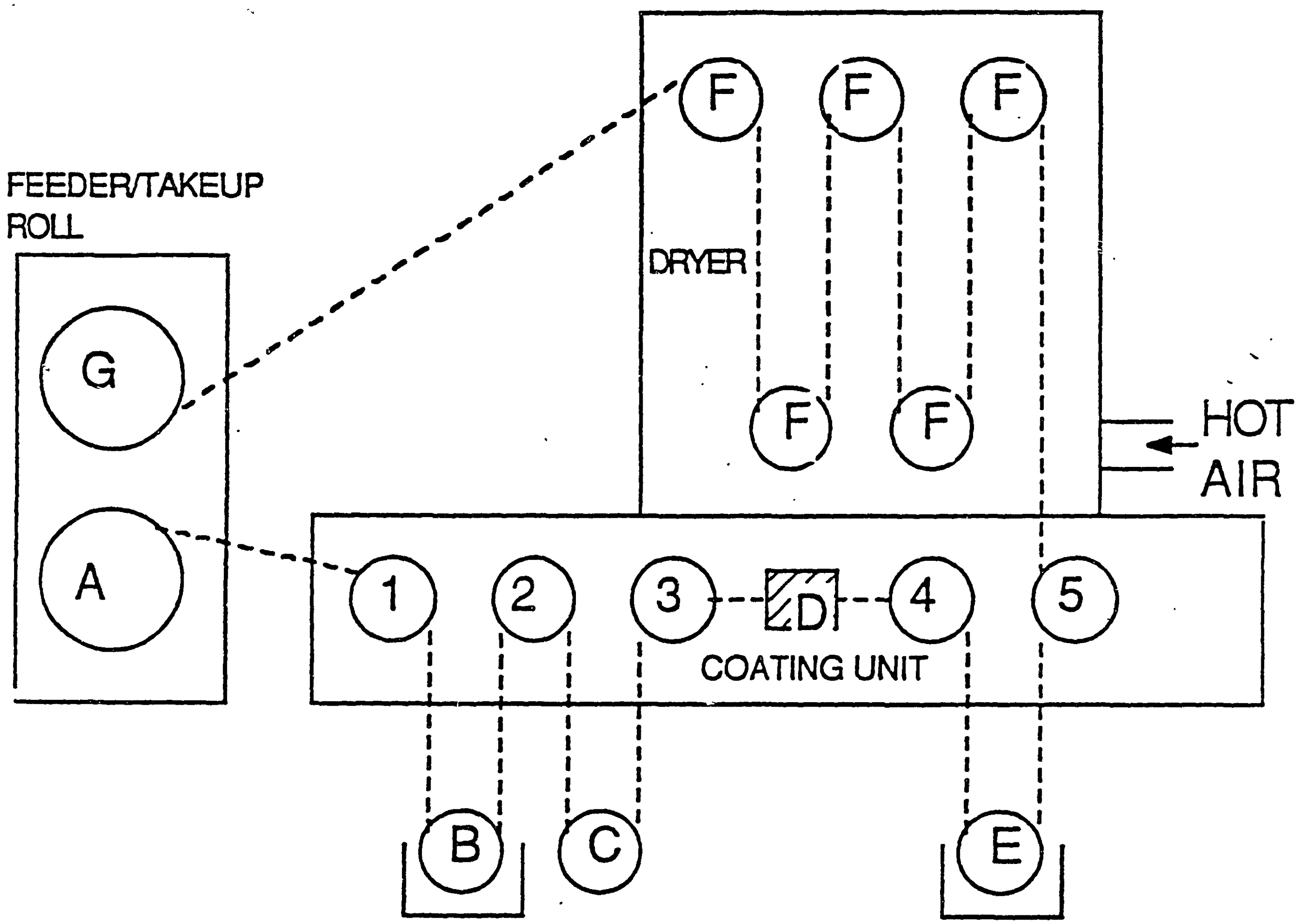


FIGURE A3: Doubled Edge Notch Sample Geometry (a = 0.5, W = 2.0)

COATING MACHINE



A : FEEDER ROLL
B : REMOVE SIZING
C : TENSION CONTROL
D : SPREADER
E : COATING BATH
F : DRYER
G : TAKE UP ROLL
: ROLLS

FIGURE A4: Fiber Coating Machine

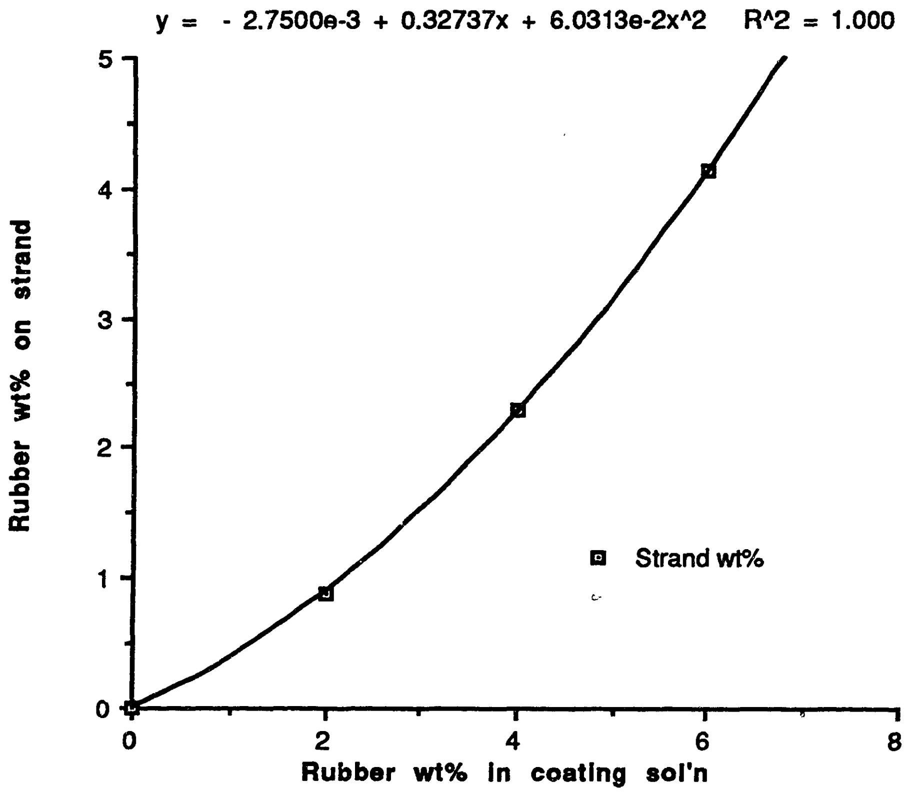


FIGURE A5: Weight %ATBN on Strand vs Weight %ATBN in Solution

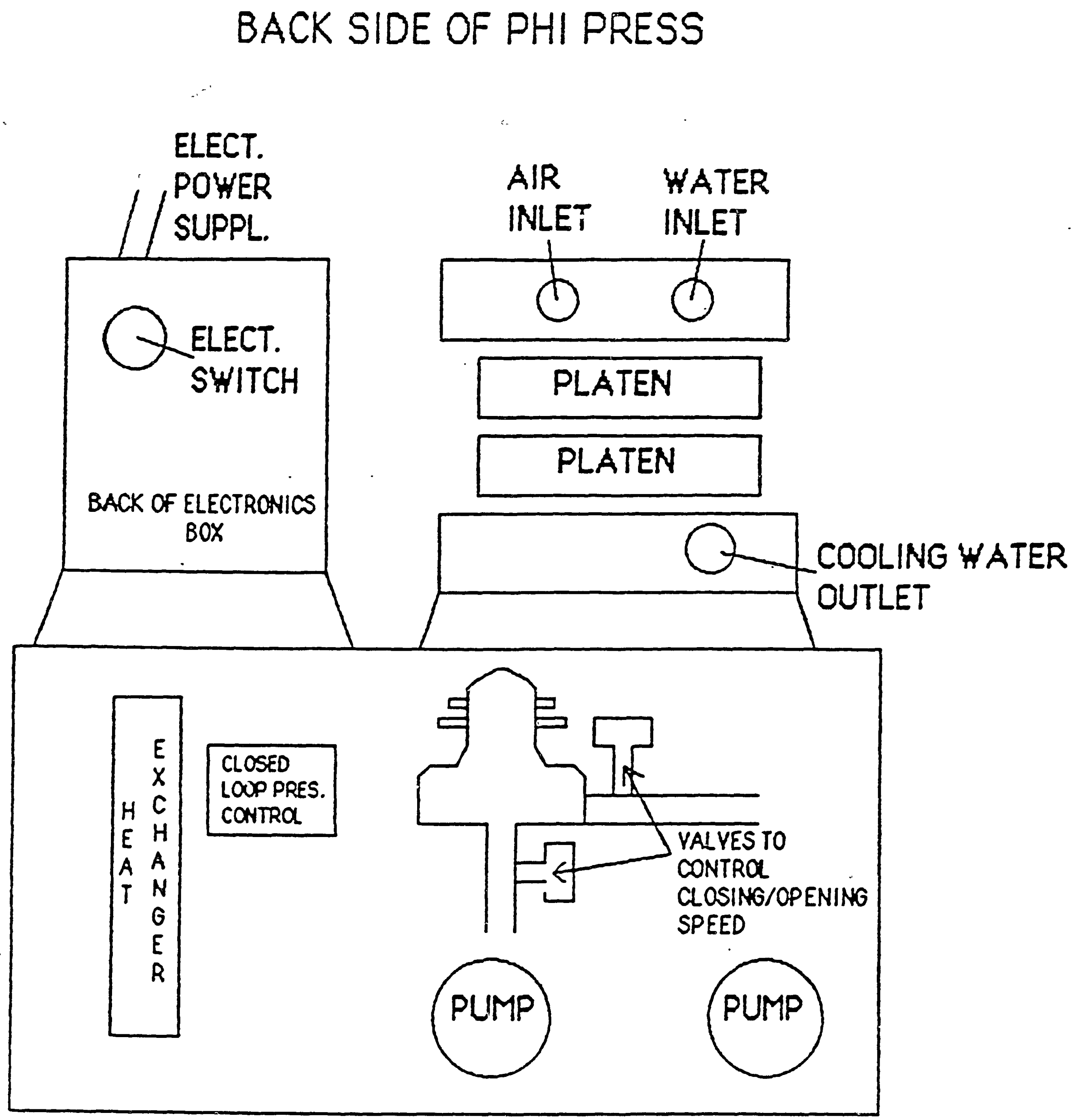


FIGURE A6: PHI Hot Press Machine

APPENDIX B

CHEMICAL	PART BY WEIGHT
POLYESTER	100
TBPB	4.5
CABOSIL	6.0

TABLE B1: Chemical Composition of Polyester Mixture

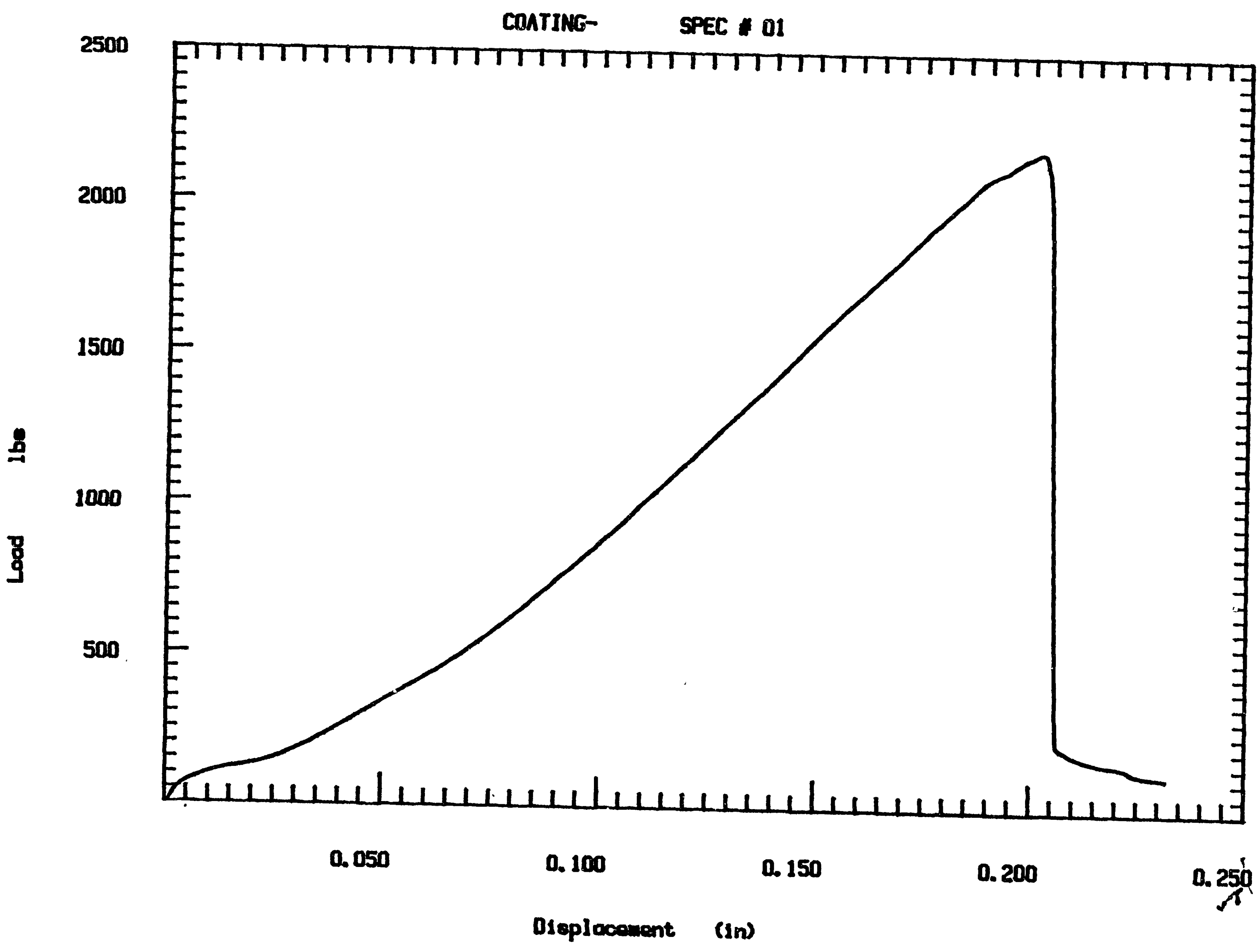
% RUBBER COATING	KIc/wgt % Fiber	$2.5(KIc/Fyt)^2$
0	327.4 ± 40.6	3.04
2	326.6 ± 44.1	3.05
4	339.8 ± 33.1	3.06
6	295.2 ± 34.8	3.03

TABLE B2: Percent Rubber Coating Versus Normalized Fracture Toughness and Notch-Sensitivity Values

APPENDIX C

SAMPLE #	Max Load (pounds)	Y	sf (Psi)	KIc (Psi (in)1/2)	wgt. % Fiber	KIc/wgt %
0-1	2181	2.0796	8768	1289[illegible]	34.3	375.9
0-2	1052	2.0639	4229	6047	24.0	252.0
0-3	1355	2.0775	5420	7962	26.8	297.1
0-4	1726	2.0775	6904	10142	29.2	347.3
0-5	1443	2.0775	5772	8479	27.0	314.0
0-6	1864	2.086	7456	11107	31.0	358.3
0-7	1186	2.0838	4720	7025	22.2	316.4
0-8	1773	2.0775	7092	10418	29.1	358.0
	Average =		6295	9259		327.4
	Standard Dev:		1524	2278		40.6
2-1	1576	2.0817	6242	9279	24.9	372.6
2-2	1527	2.0838	6078	9044	27.1	333.7
2-3	1126	2.0714	4527	6563	22.7	289.1
2-4	1988	2.0796	7992	11752	30.9	380.3
2-5	1103	2.0775	4412	6481	22.5	288.0
2-6 *	1244	2.0775	4976	7310	25.2	290.1
2-7	1120	2.0755	4458	6542	24.7	264.8
2-8	1416	2.0755	5636	8271	26.1	316.9
2-9	1632	2.0775	6528	9590	25.1	382.1
2-10	1381	2.0775	5524	8115	29.6	274.1
2-11	1204	2.0838	4792	7131	22.1	322.7
2-12	1715	2.0755	6826	10018	27.2	368.3
	Average (w/o *) =		5729	8435		326.6
	Standard Dev:		1143	1693		44.1
4-1	1863	2.0755	7415	10882	31.1	349.9
4-2	1701	2.0775	6804	9995	27.9	358.2
4-3 *	1052	2.0755	4187	6145	26.3	233.6
4-4	1922	2.0775	7688	11294	33.8	334.1
4-5	1057	2.0838	4207	6260	21.2	295.3
4-6	1768	2.0838	7037	10472	26.8	390.7
4-7	1612	2.0838	6416	9548	27.4	348.5
4-8	1160	2.0775	4640	6816	22.6	301.6
	Average (w/o *) =		6315	9324		339.8
	Standard Dev:		1361	1992		33.1
6-1	1140	2.0860	4560	6793	22.6	300.6
6-2	1642	2.0796	6601	9707	29.3	331.3
6-3	1444	2.0714	5805	8417	26.2	321.2
6-4	982	2.0796	3948	5806	25.0	232.2
6-5	1541	2.0755	6133	9001	30.2	298.0
6-6	1562	2.0796	6279	9233	32.1	287.6
6-7 *	969	2.0838	3857	5740	26.1	219.9
6-8 *	1222	2.0860	4888	7282	32.5	224.1
	Average (w/o *) =		5554	8160		295.2
	Standard Dev:		1057	1532		34.8

* = Irregular Fracure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Load lbs
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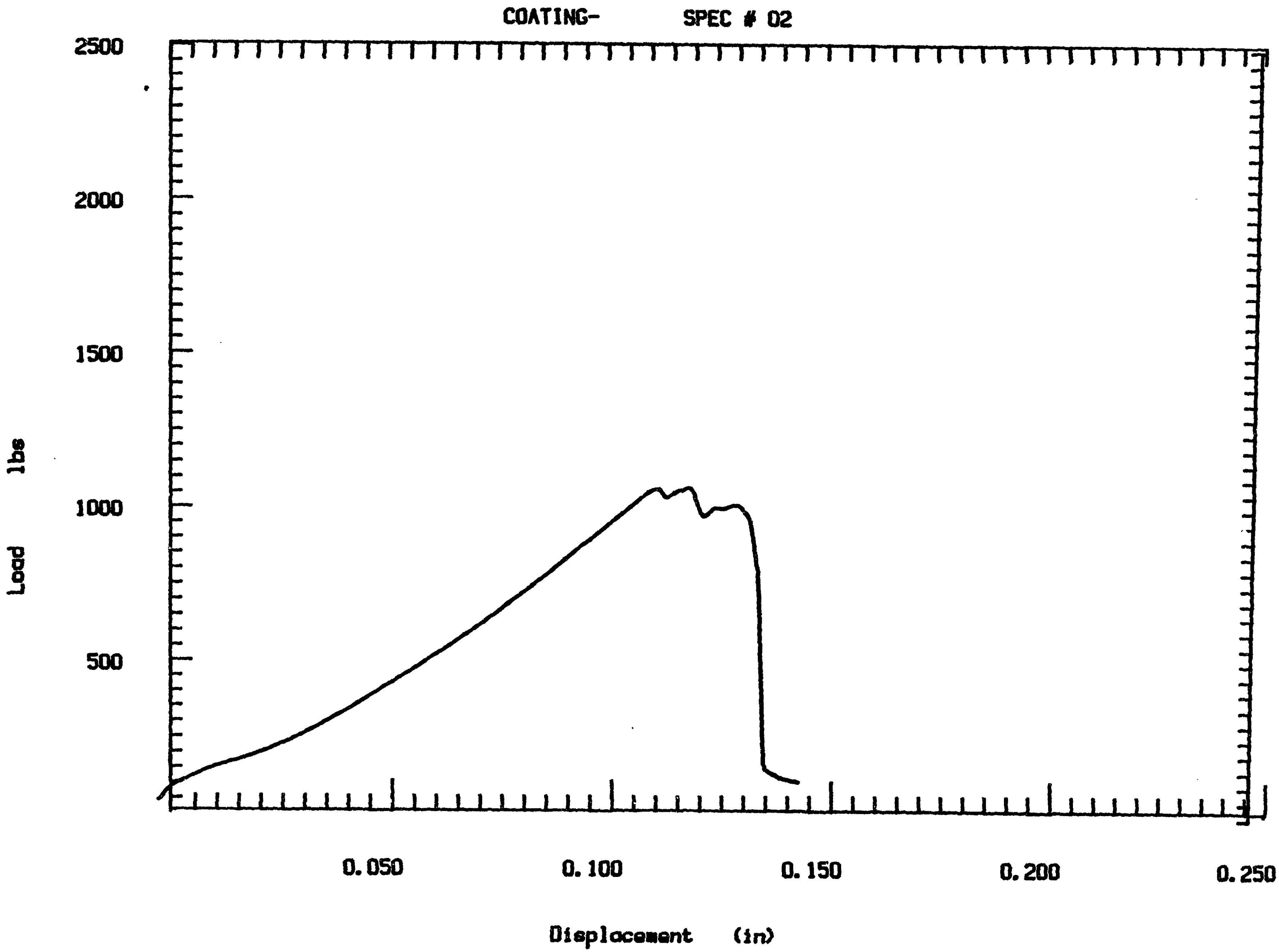
Displacement (in)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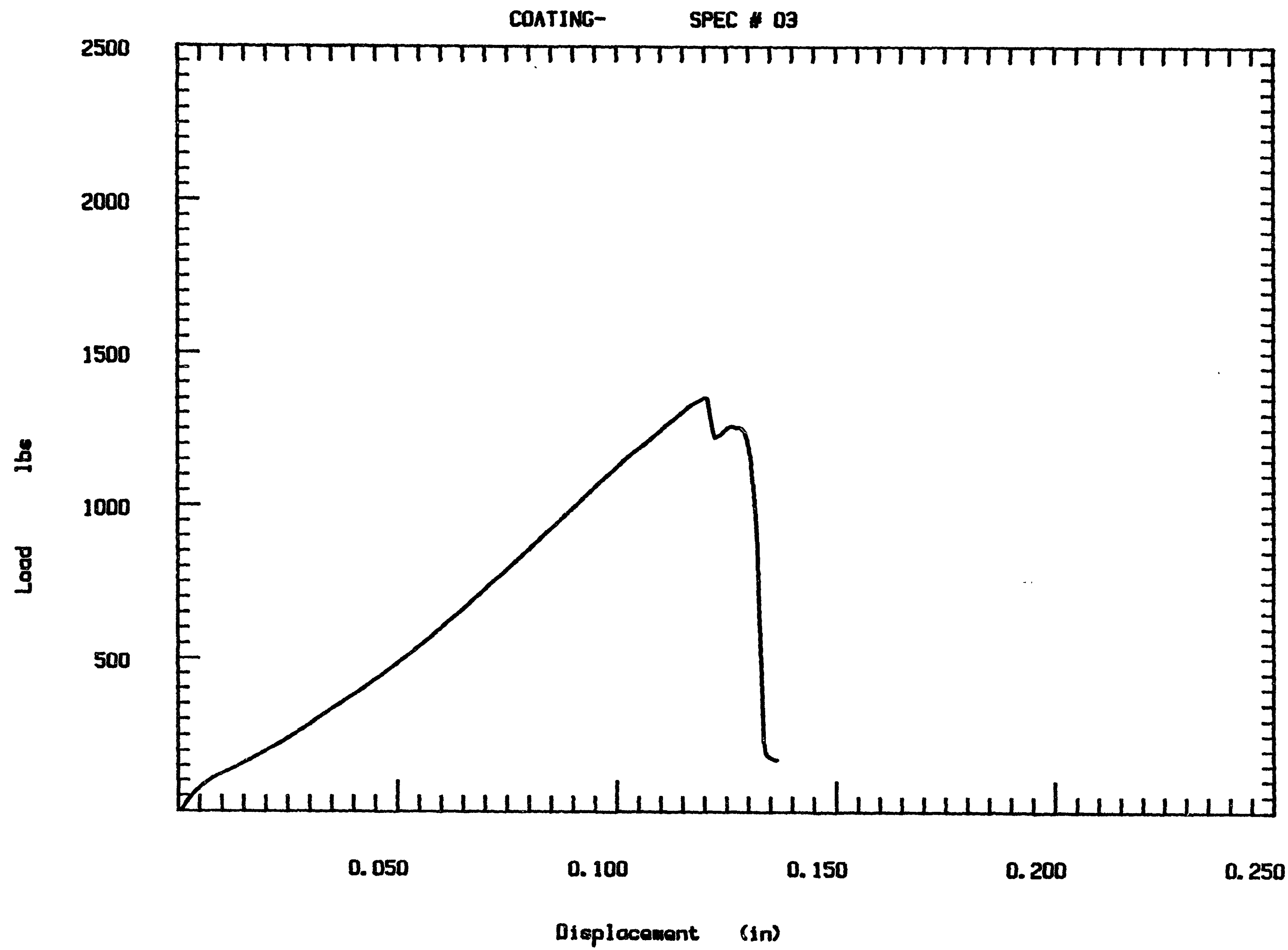
Displacement (in)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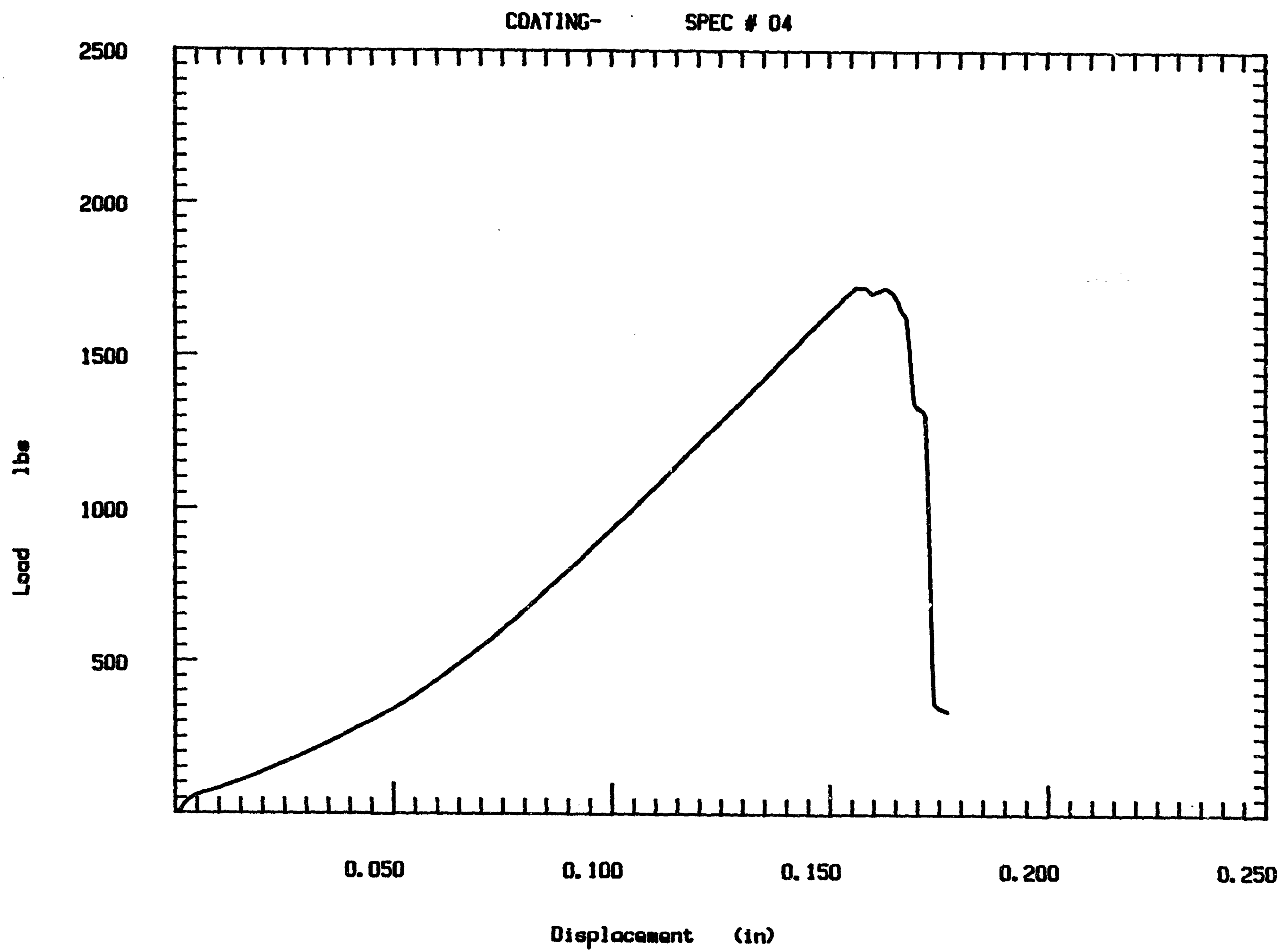
Displacement (in)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1000
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Load lbs
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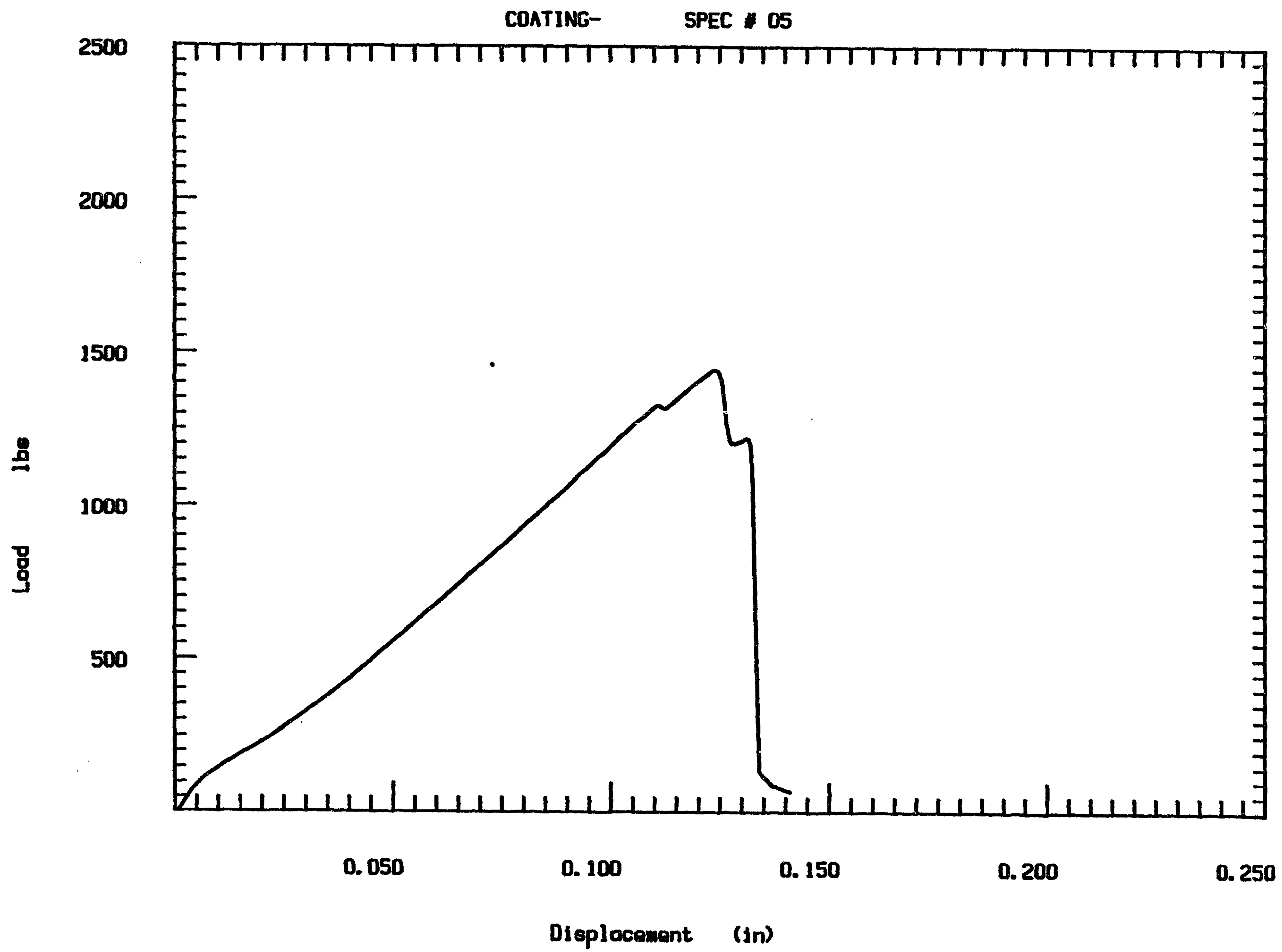
Displacement (in)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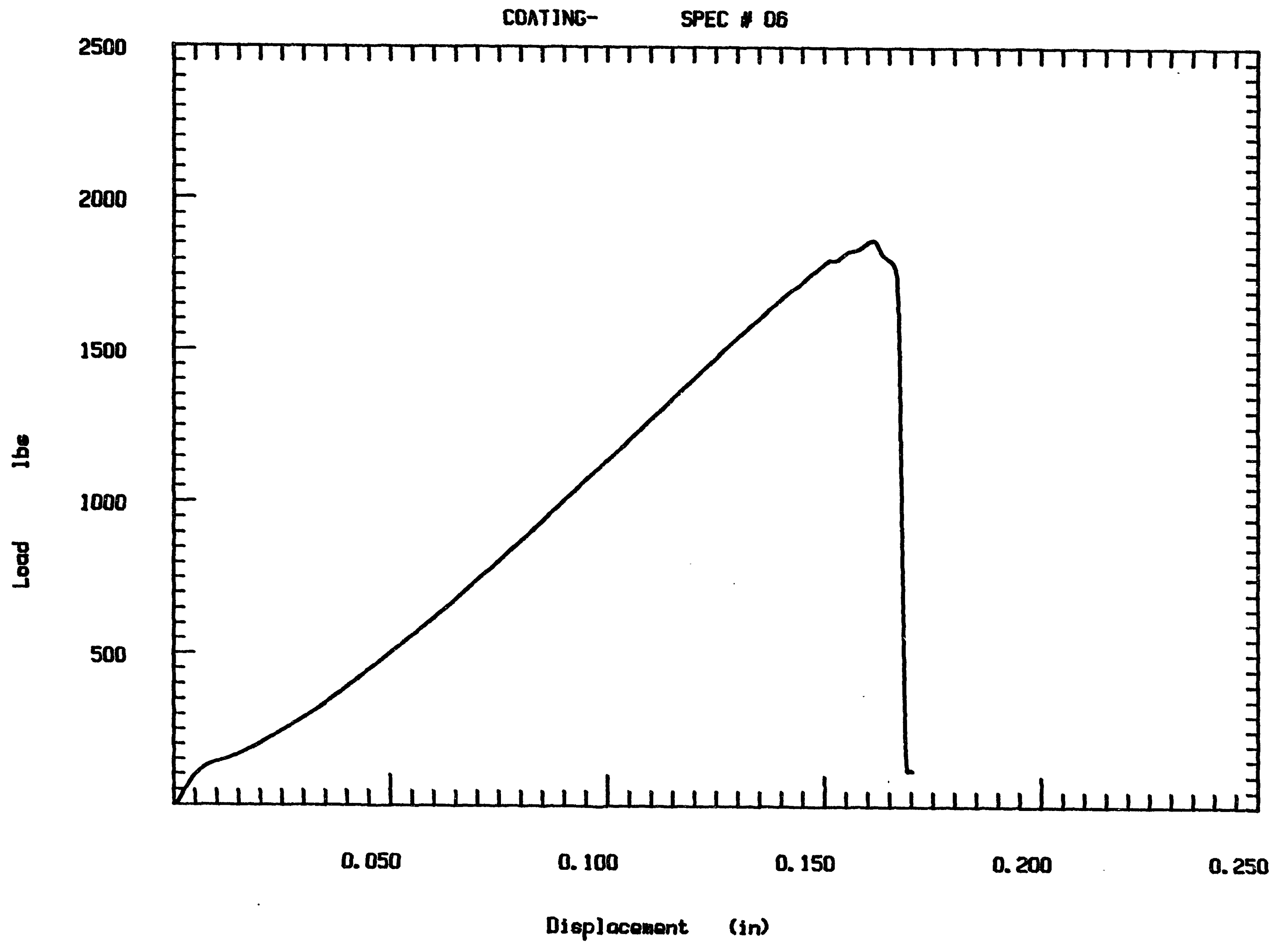
Displacement (in)



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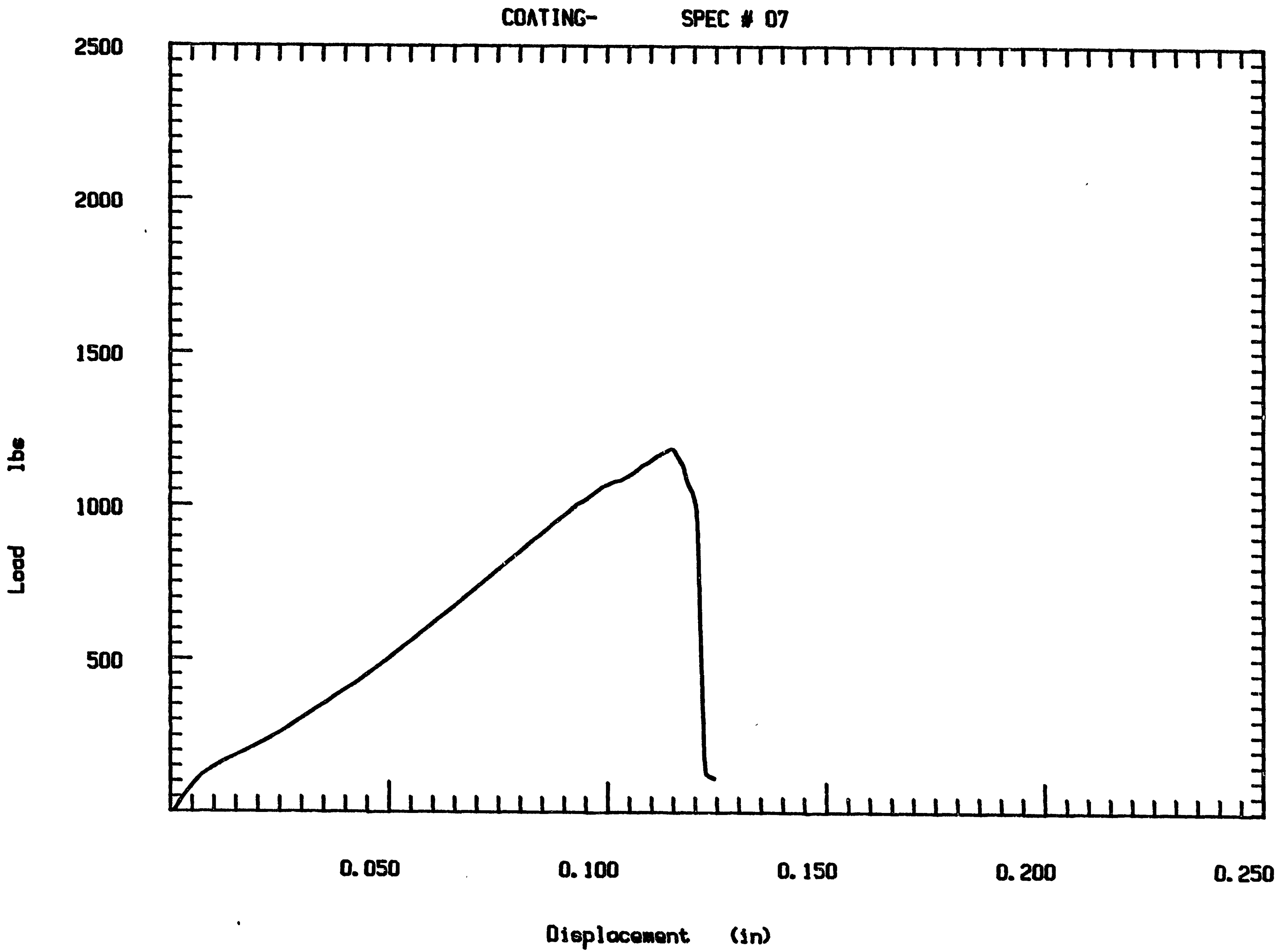
Displacement (in)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lbs
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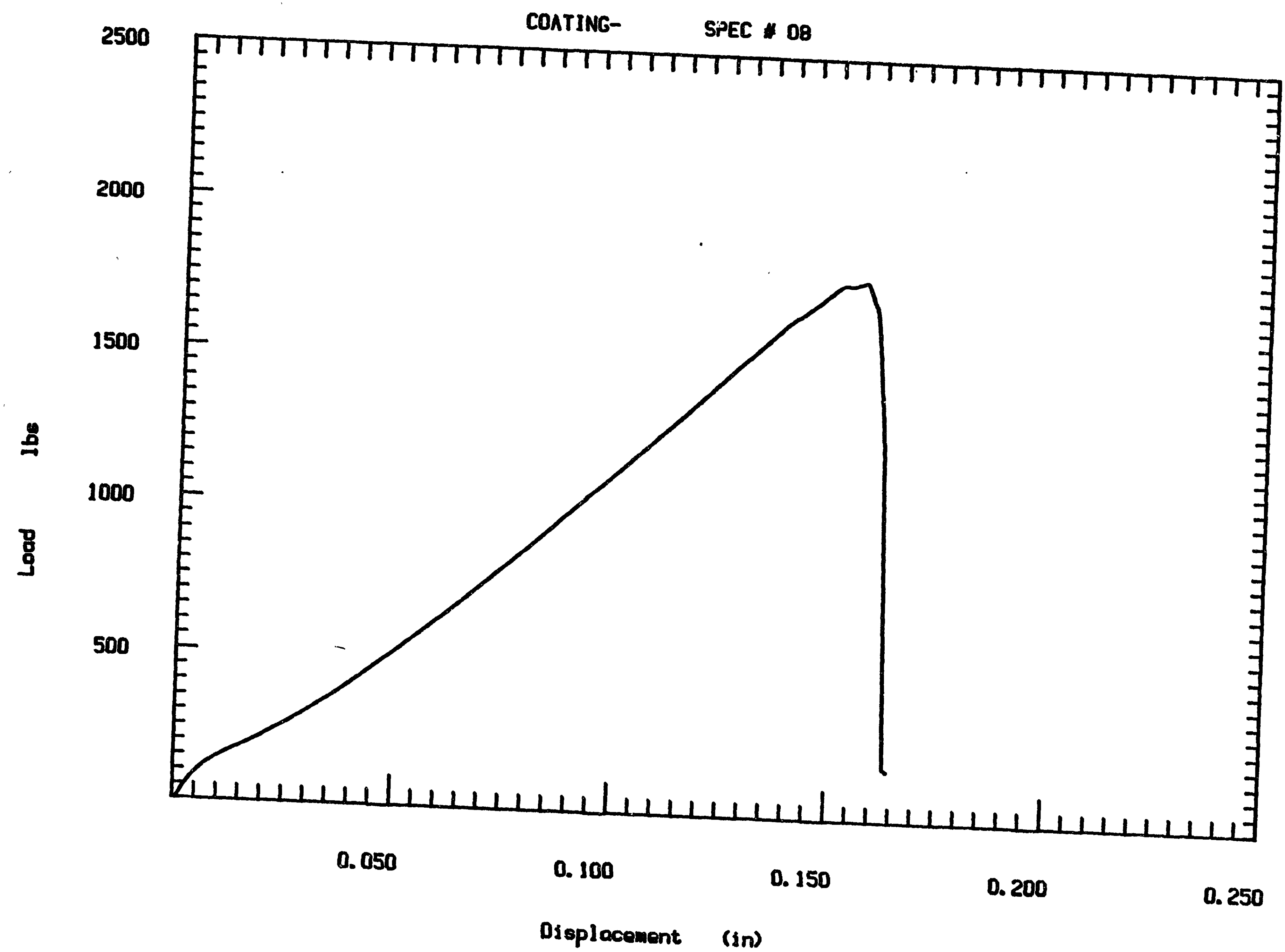
Displacement
(in)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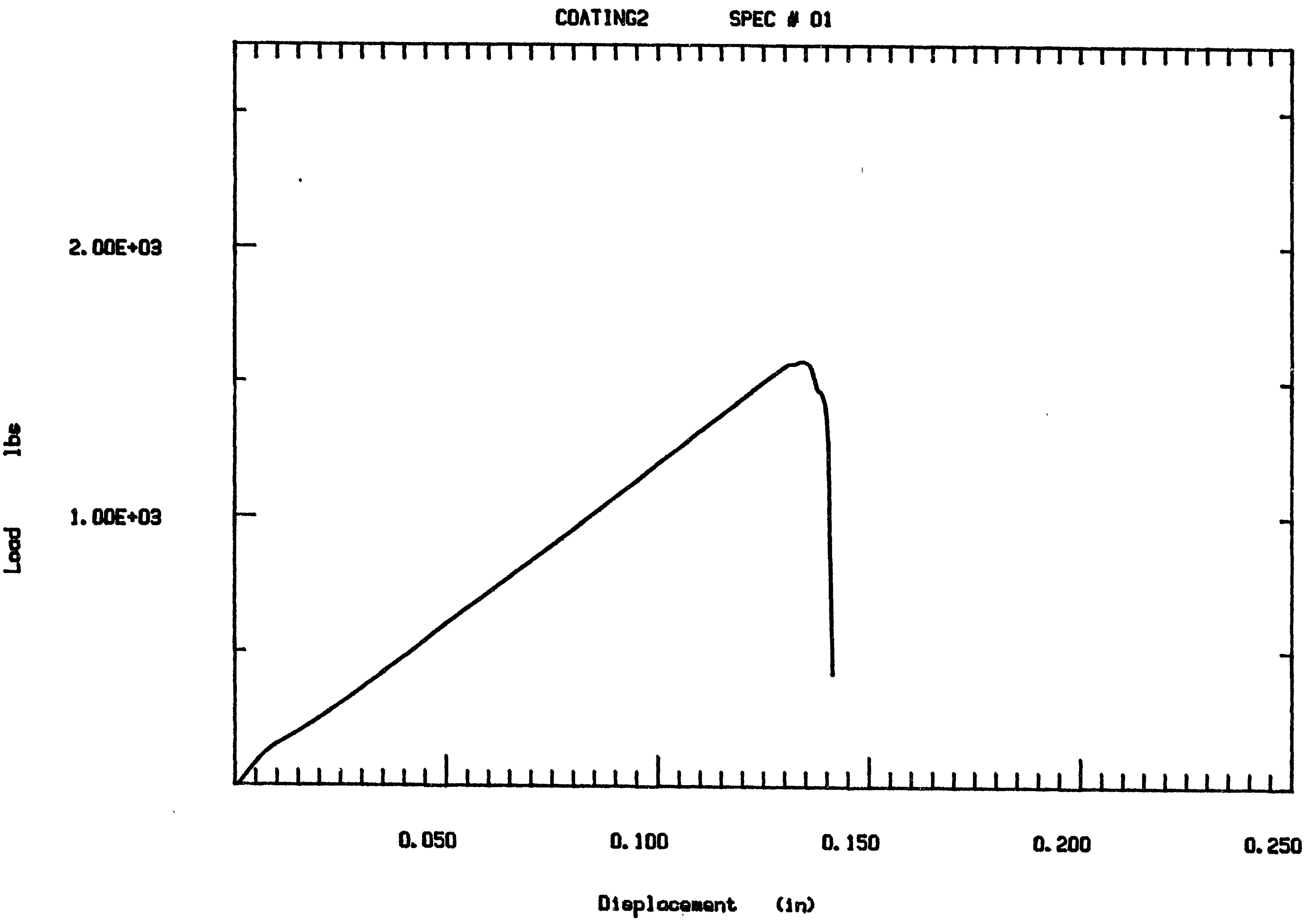
0.200
0.250
Displacement (in)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Load lbs
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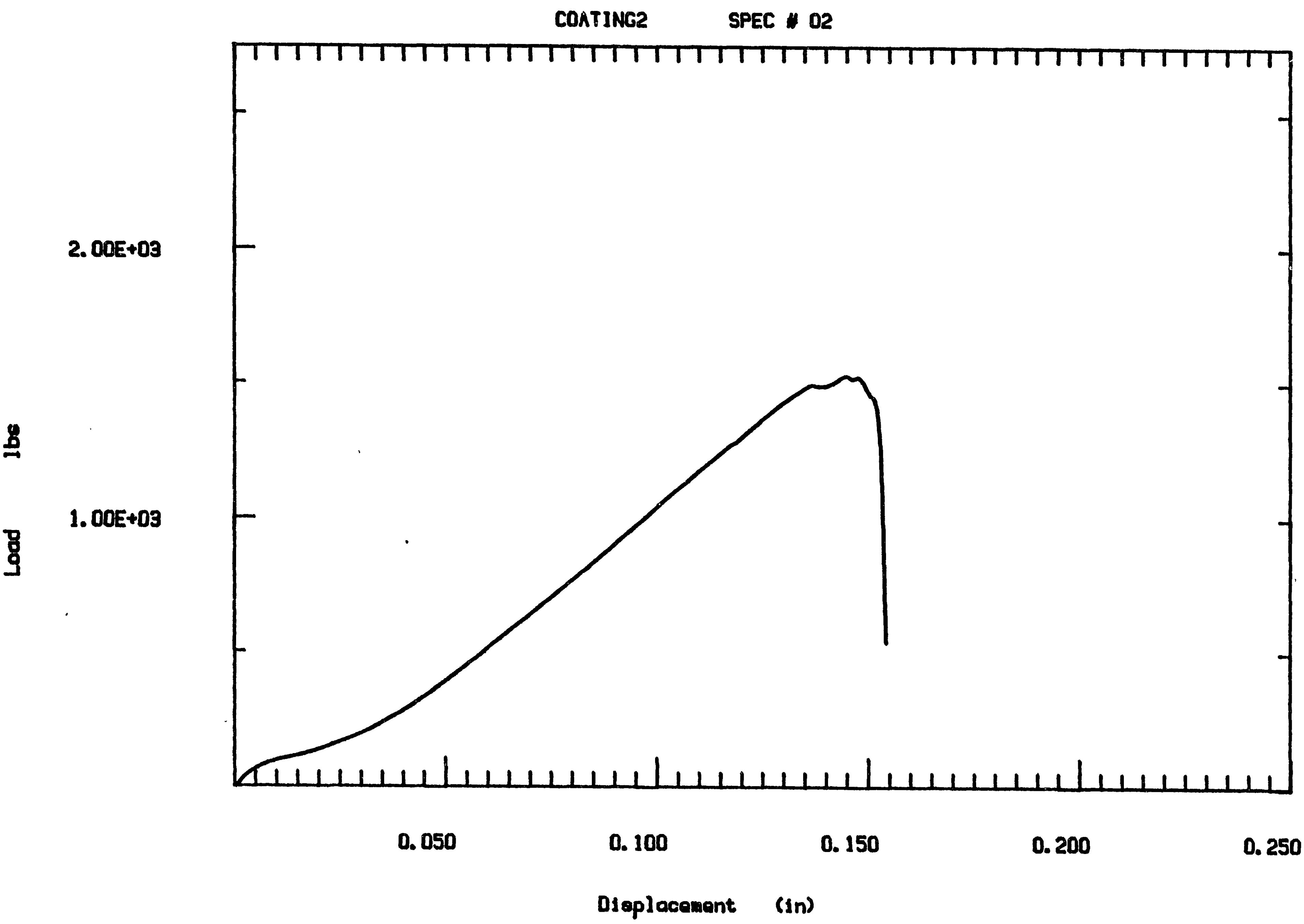
0.200
0.250
Displacement (in)



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Load lbs
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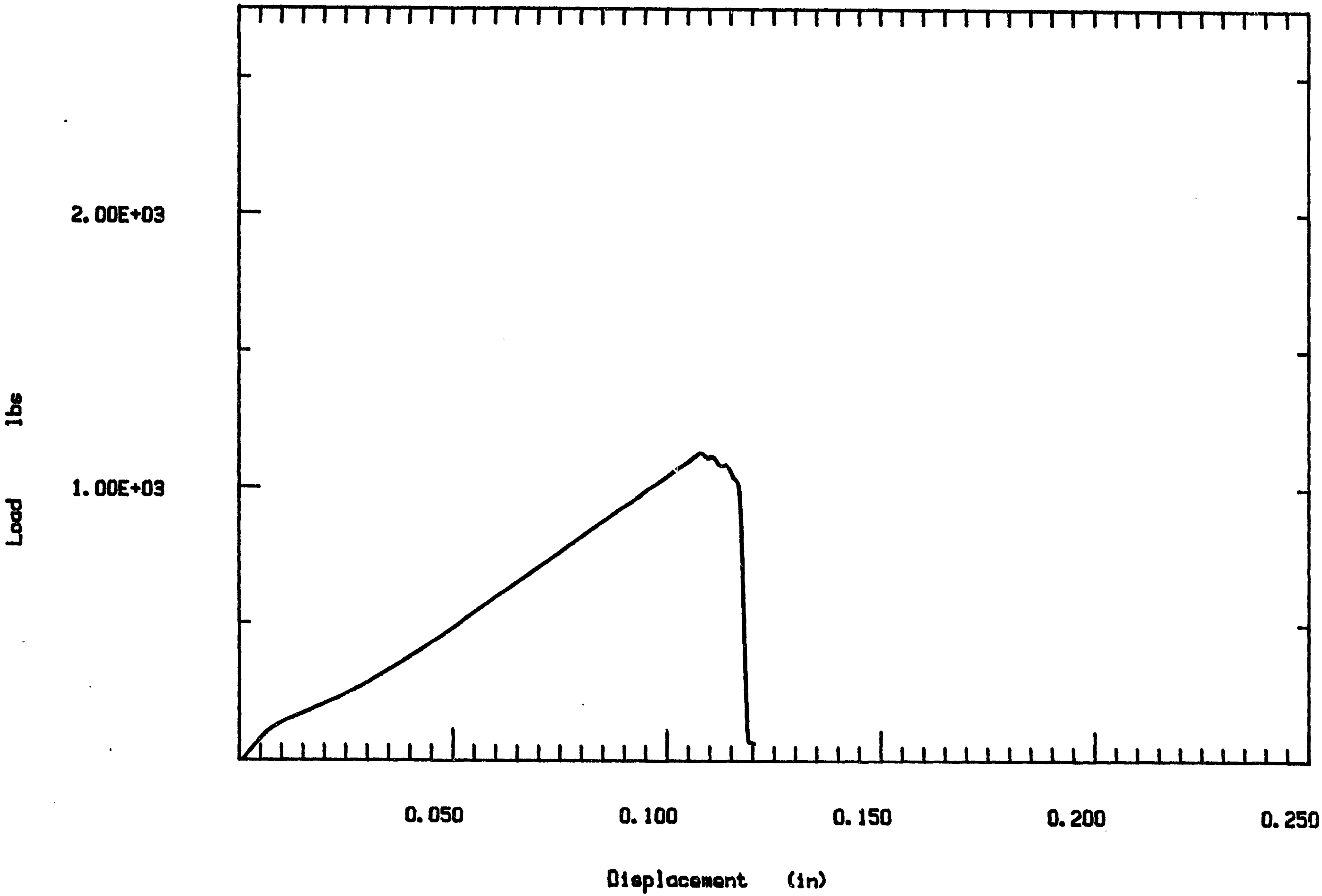
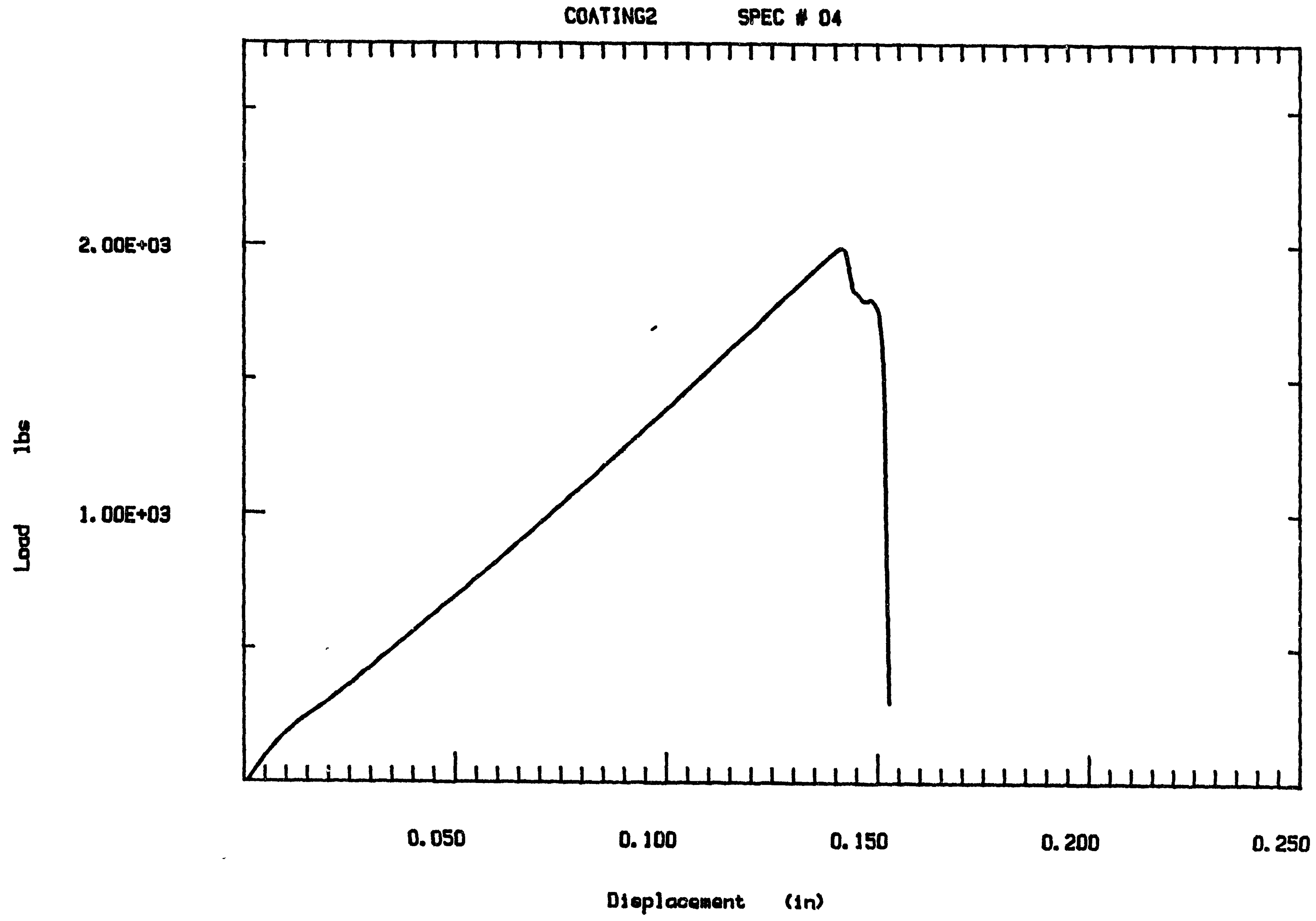
0.200
0.250
Displacement (in)

COATING2 SPEC # 03

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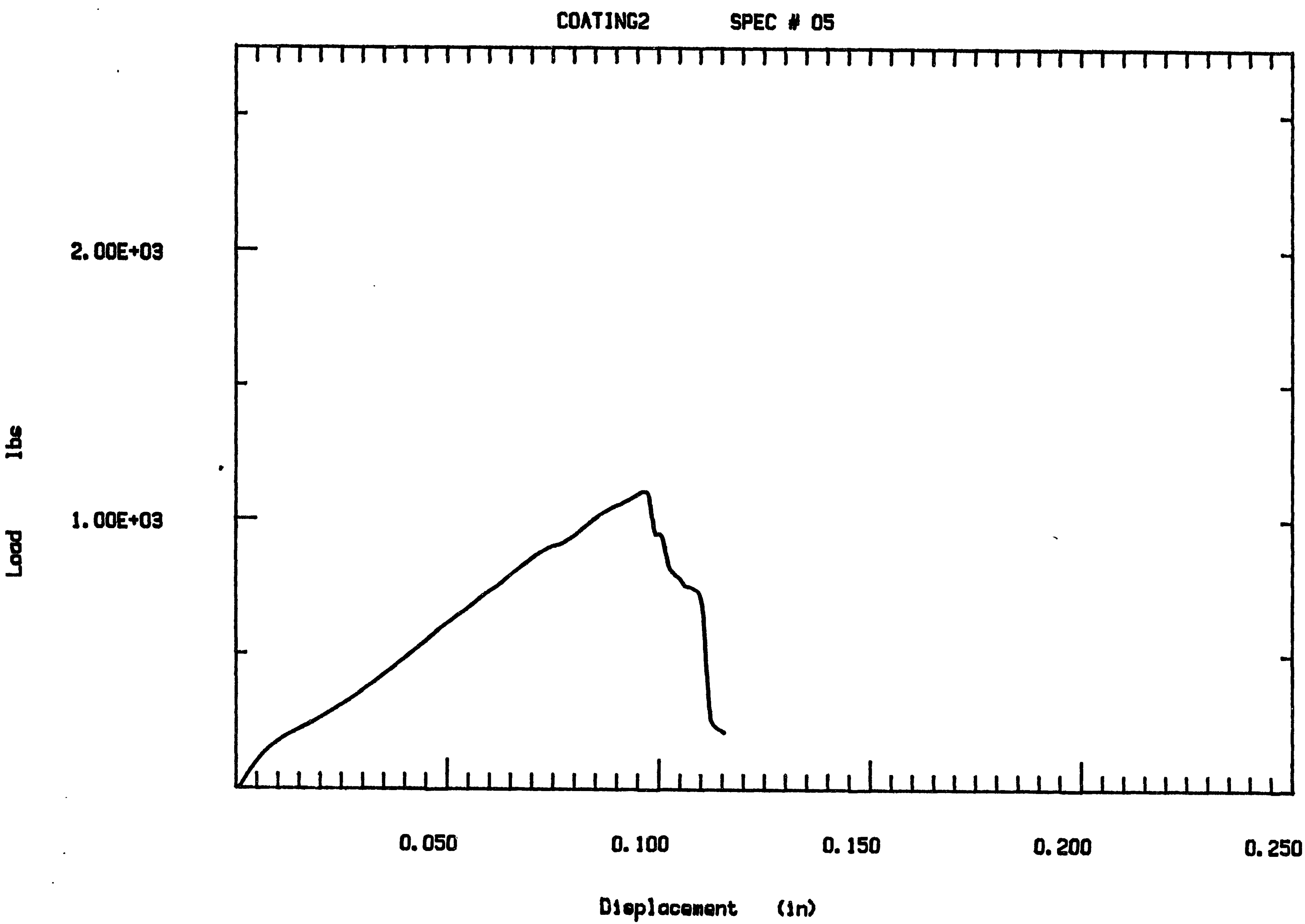
Displacement (in)



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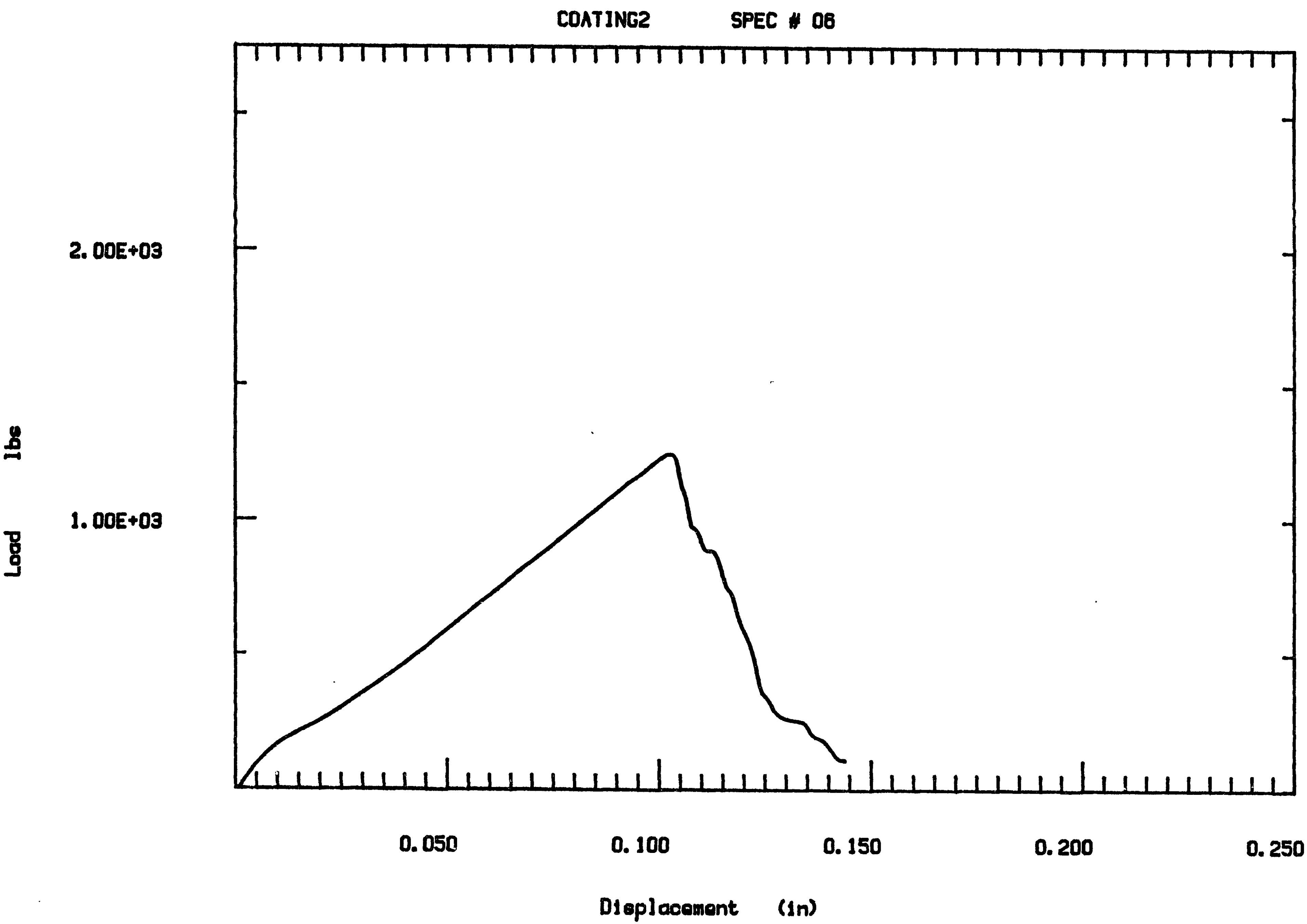
Displacement (in)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1.00E+03
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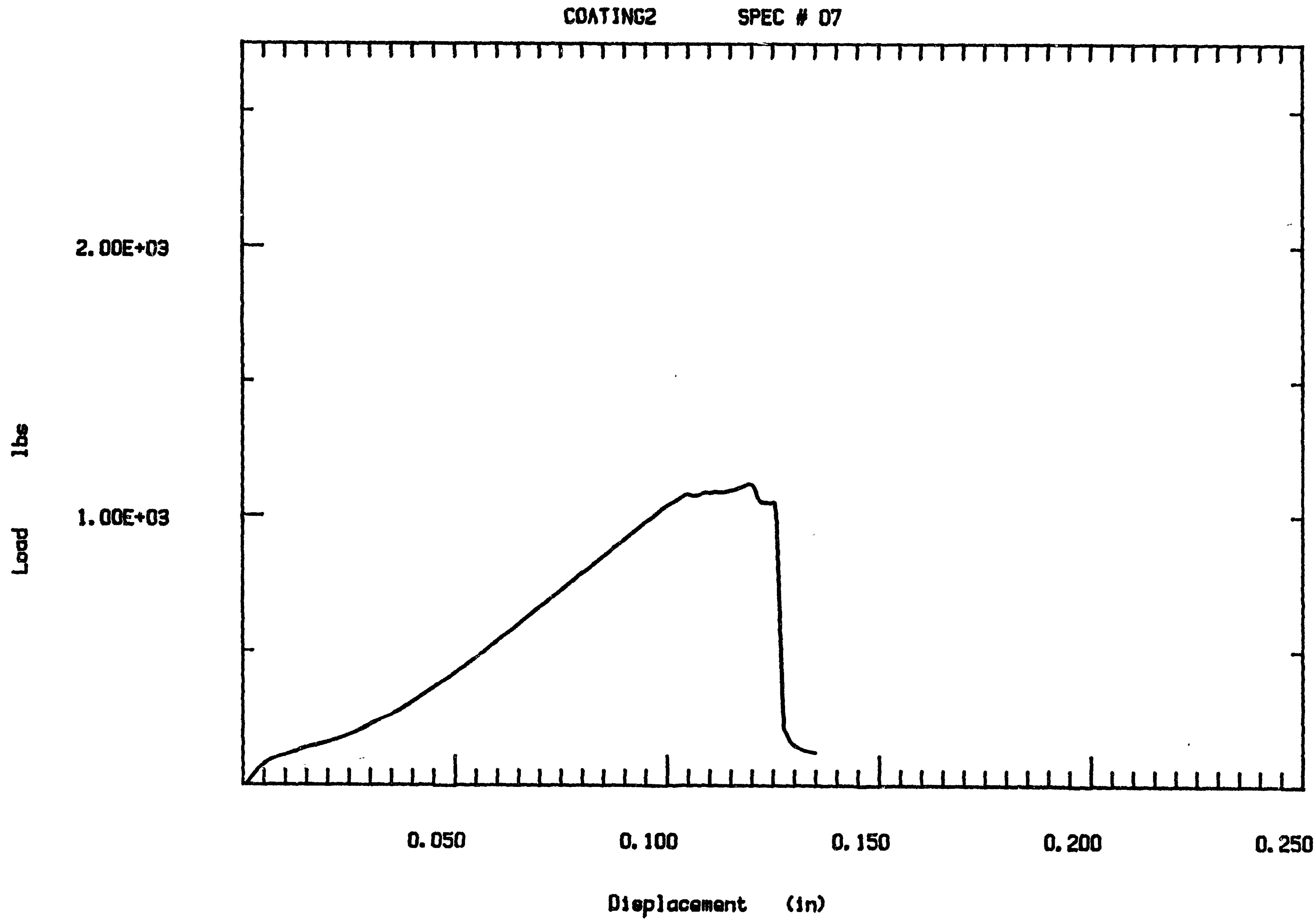
0.200
0.250
Displacement (in)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1.00E+03
Load lbs
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0.100
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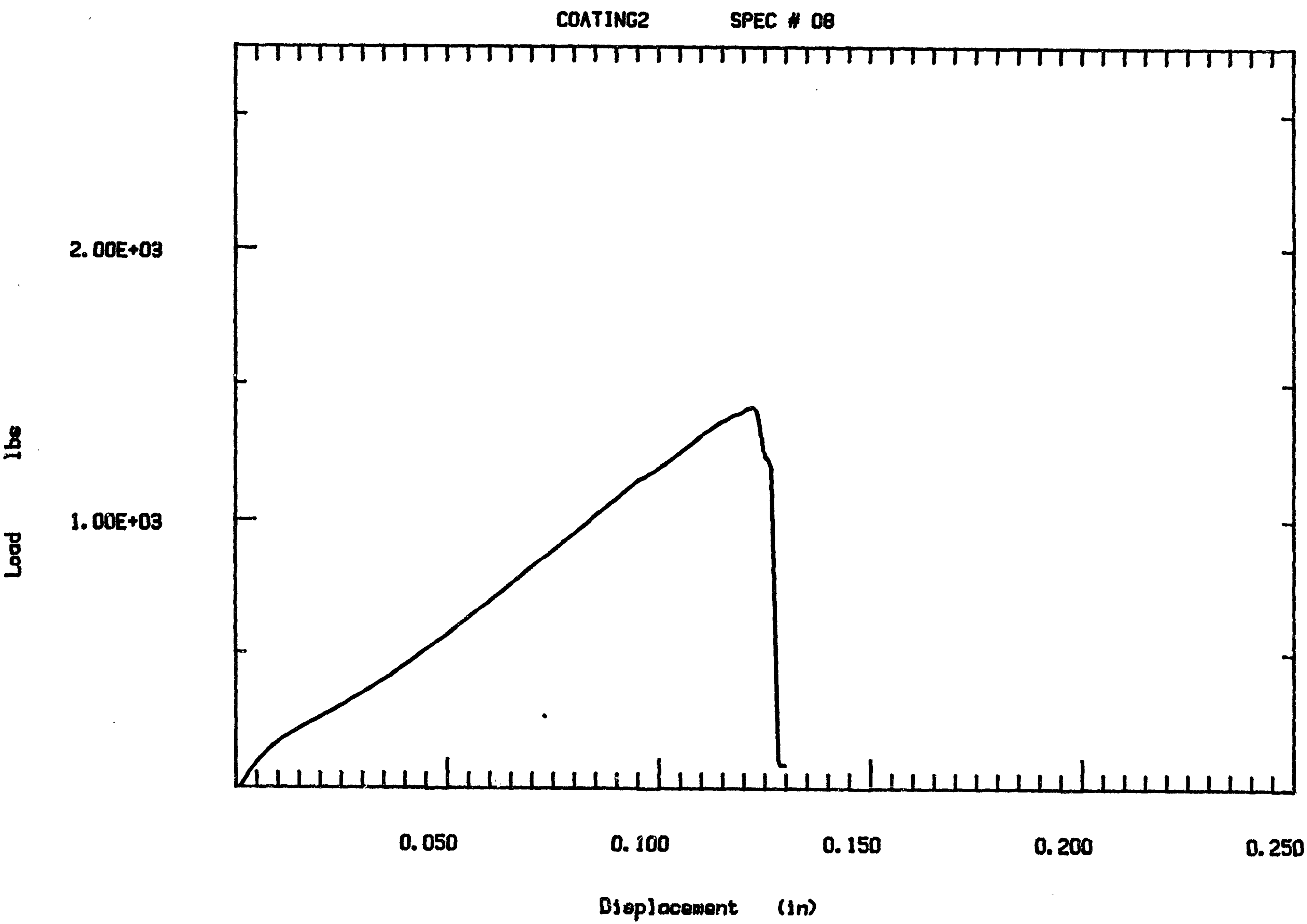
0.200
0.250
Displacement (in)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1.00E+03
Load lbs
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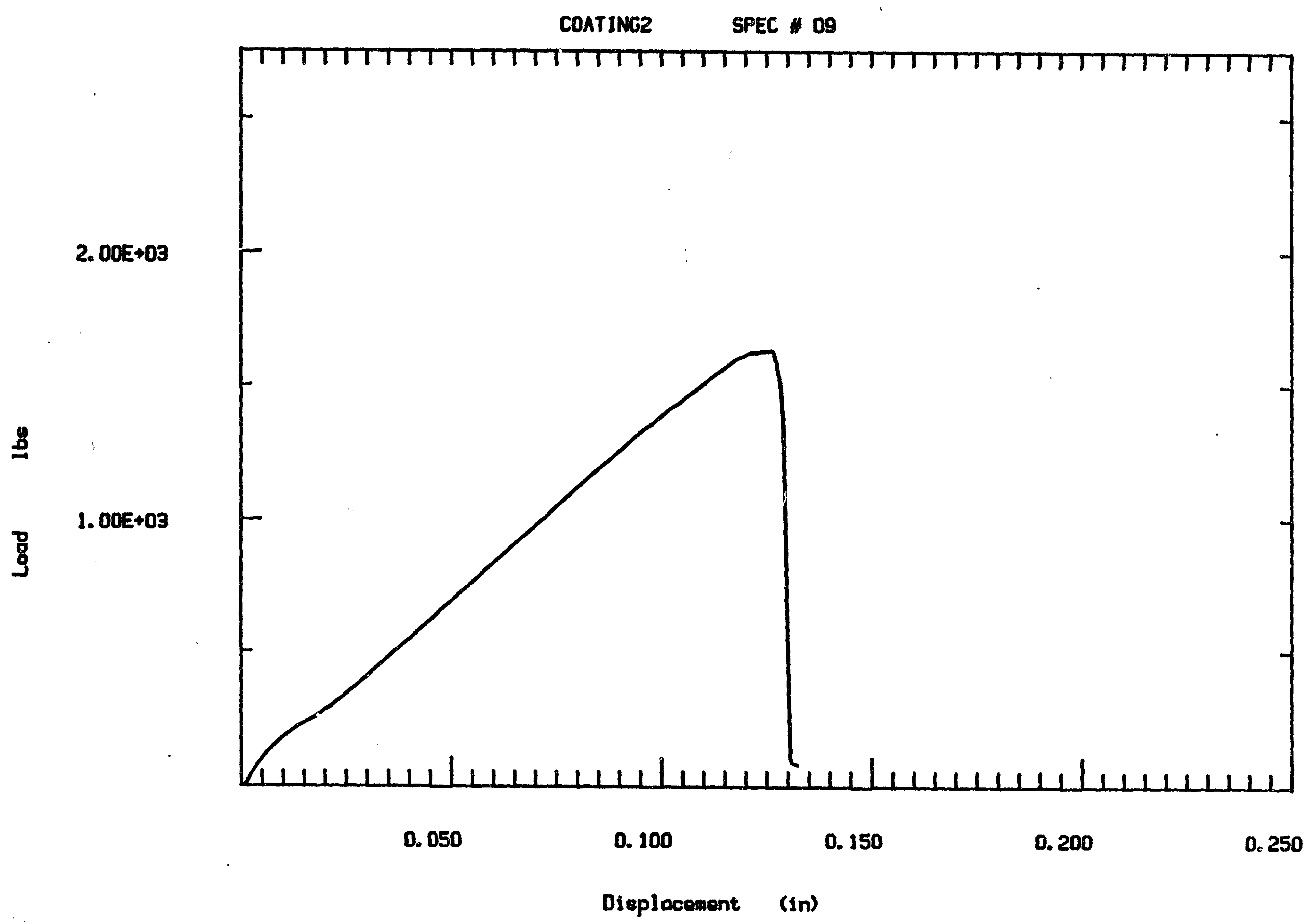
0.100
0.150
0.200
0.250
Displacement (in)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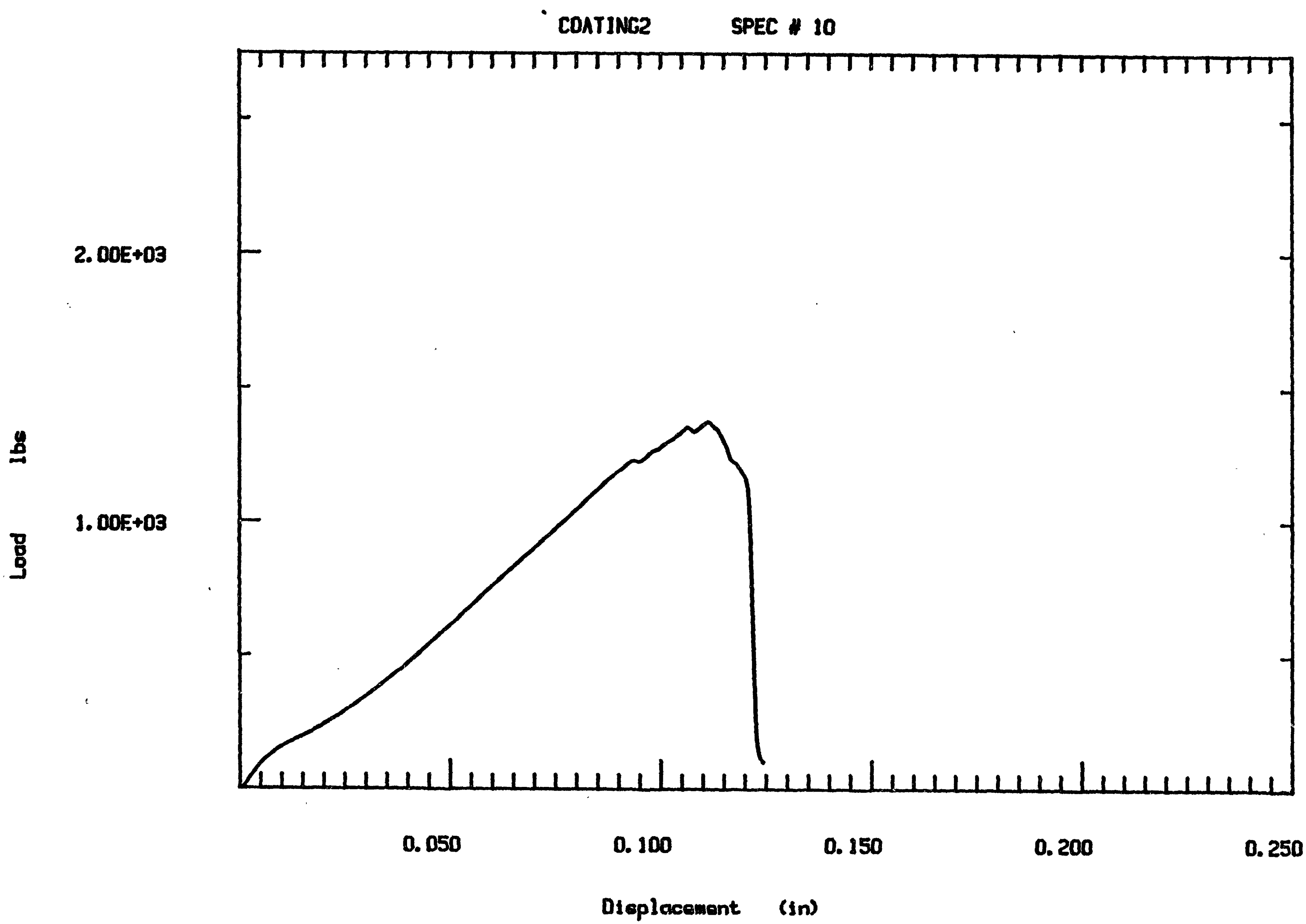
0.200
0.250
Displacement (in)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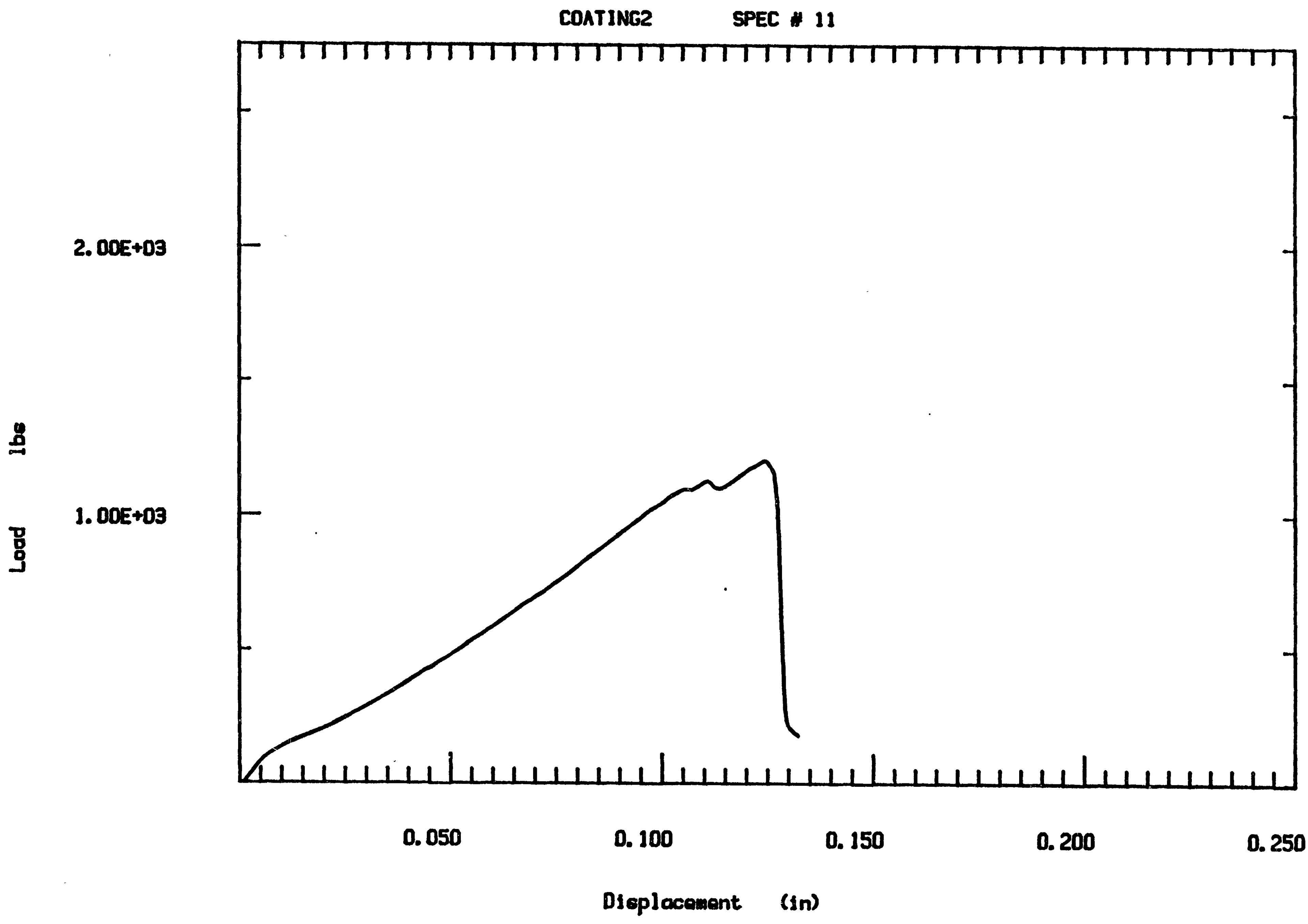
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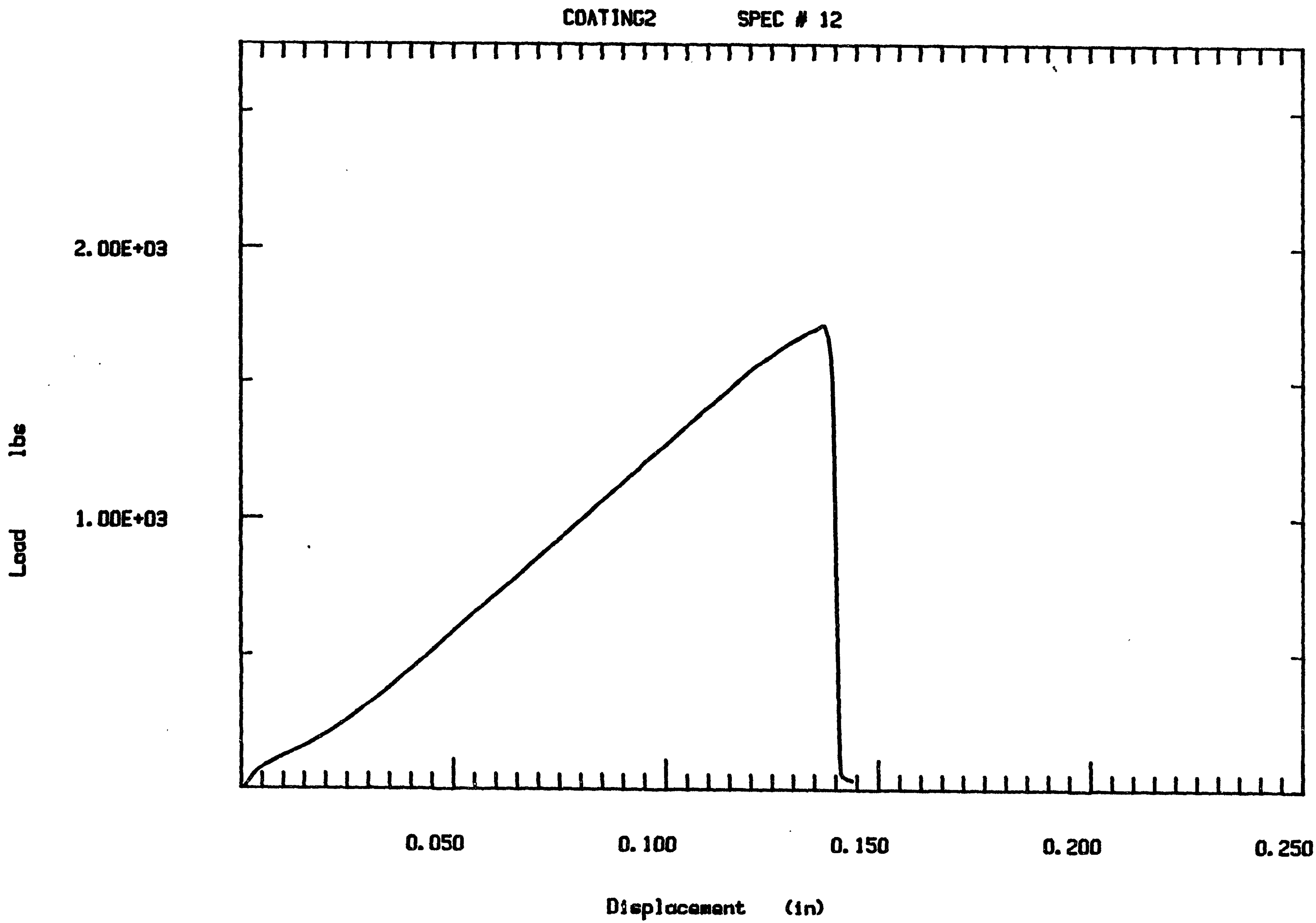
Displacement (in)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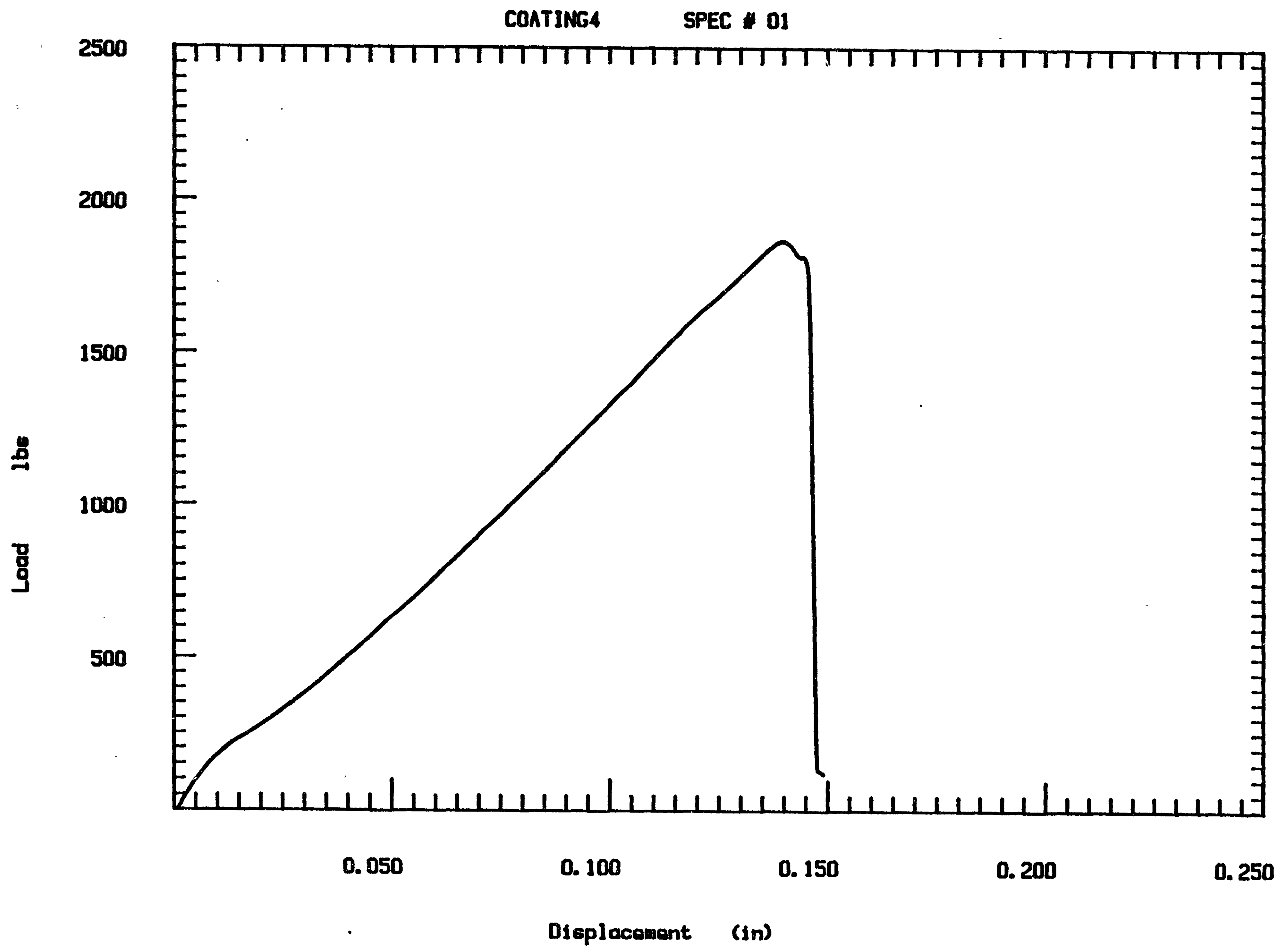
Displacement (in)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2000
1500
1000
500
Load lbs
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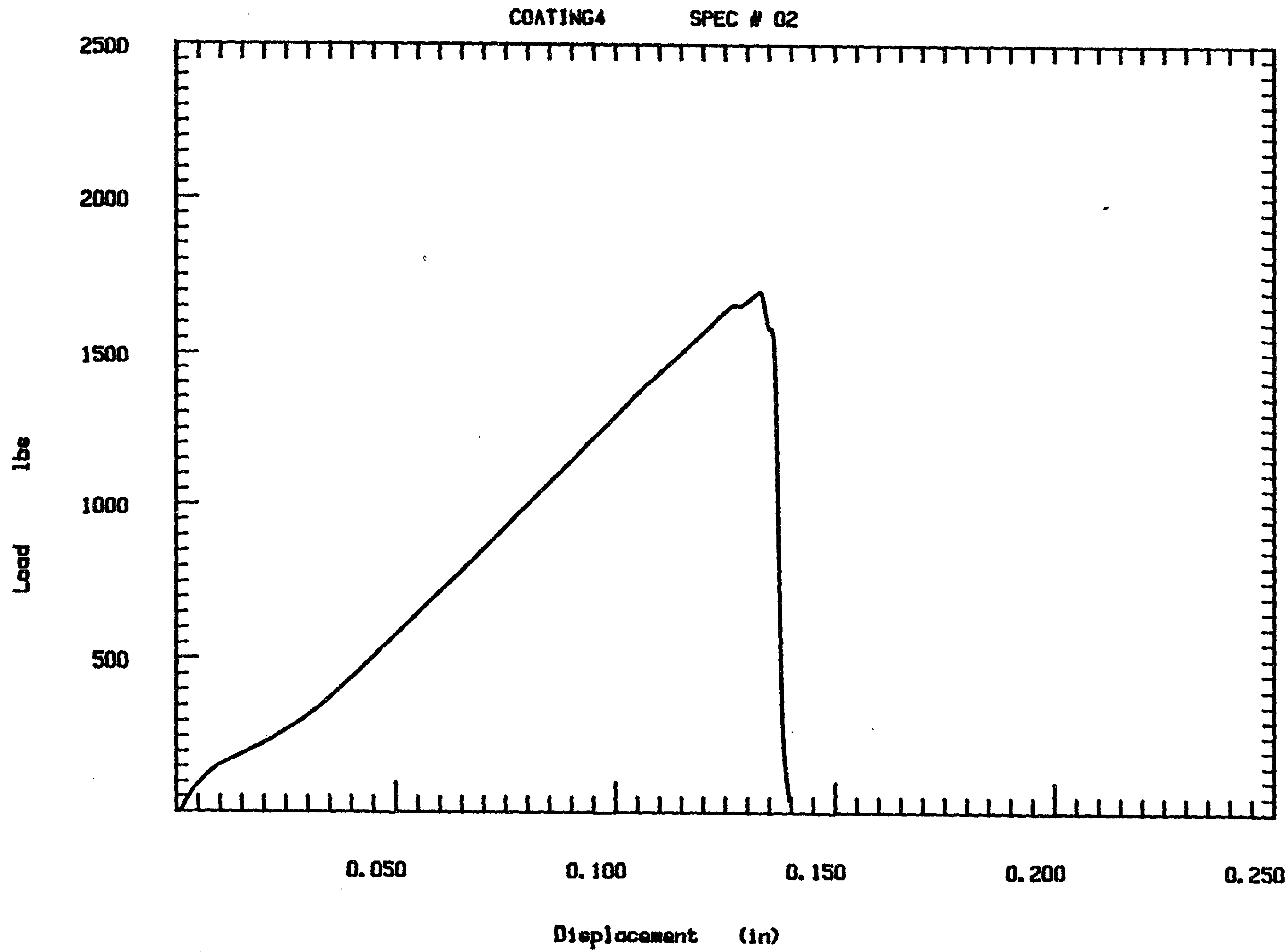
0.150
0.200
0.250
Displacement (in)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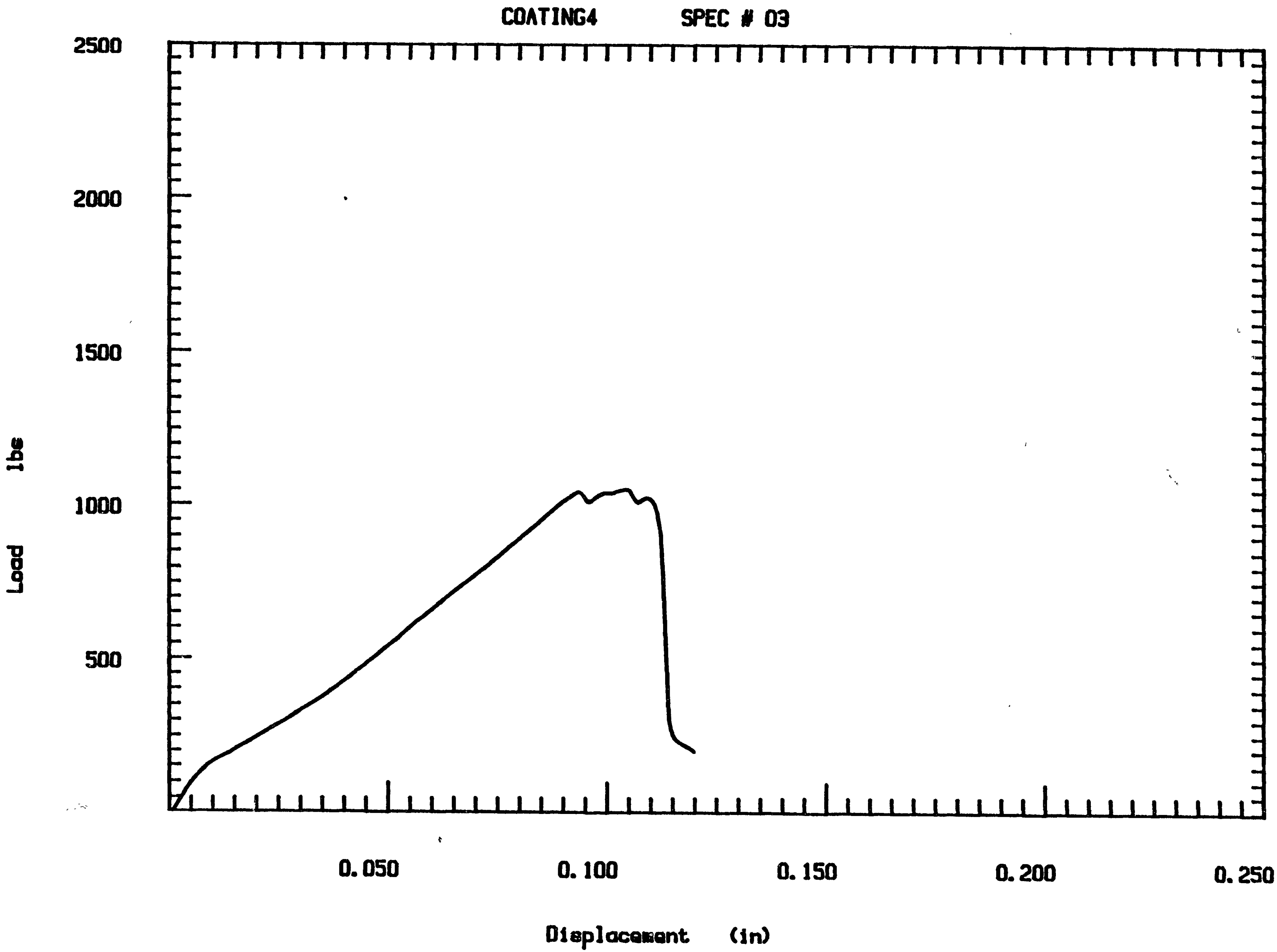
0.250
Displacement (in)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SPEC # 03
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2000
1500
1000
500
Load lbs
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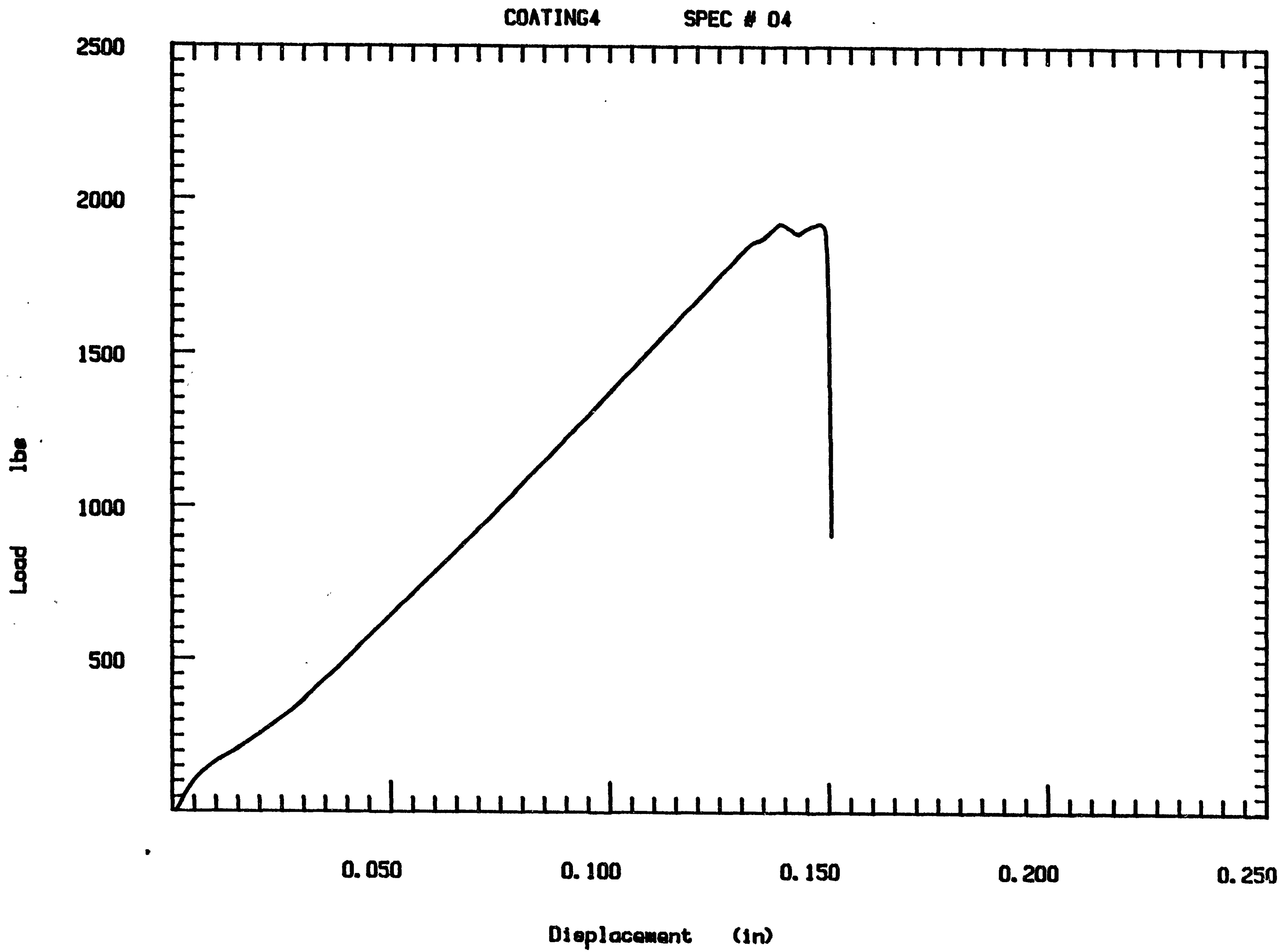
0.100
0.150
0.200
0.250
Displacement (in)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1000
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Load lbs
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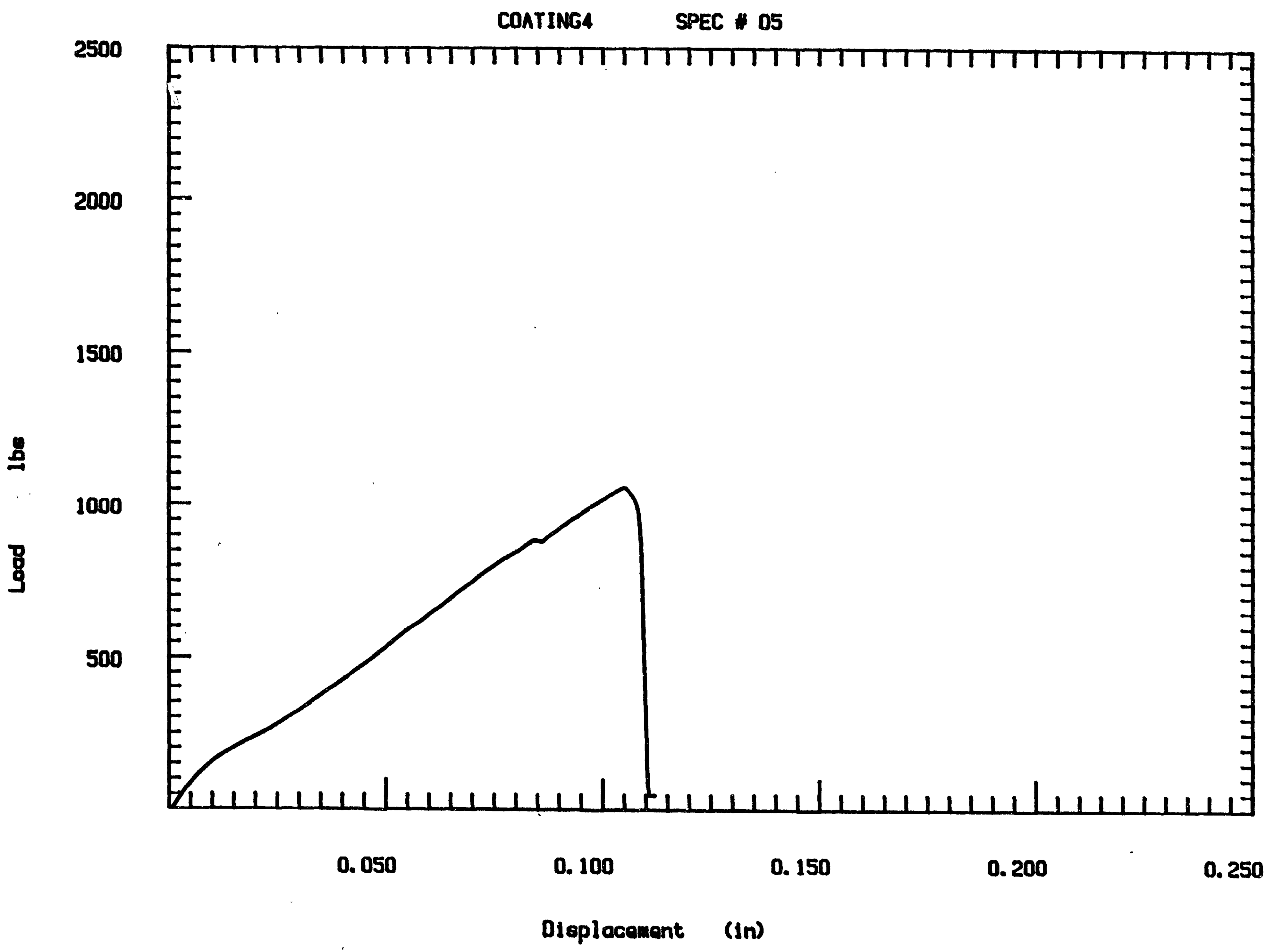
0.100
0.150
0.200
0.250
Displacement (in)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Load lbs
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0.100
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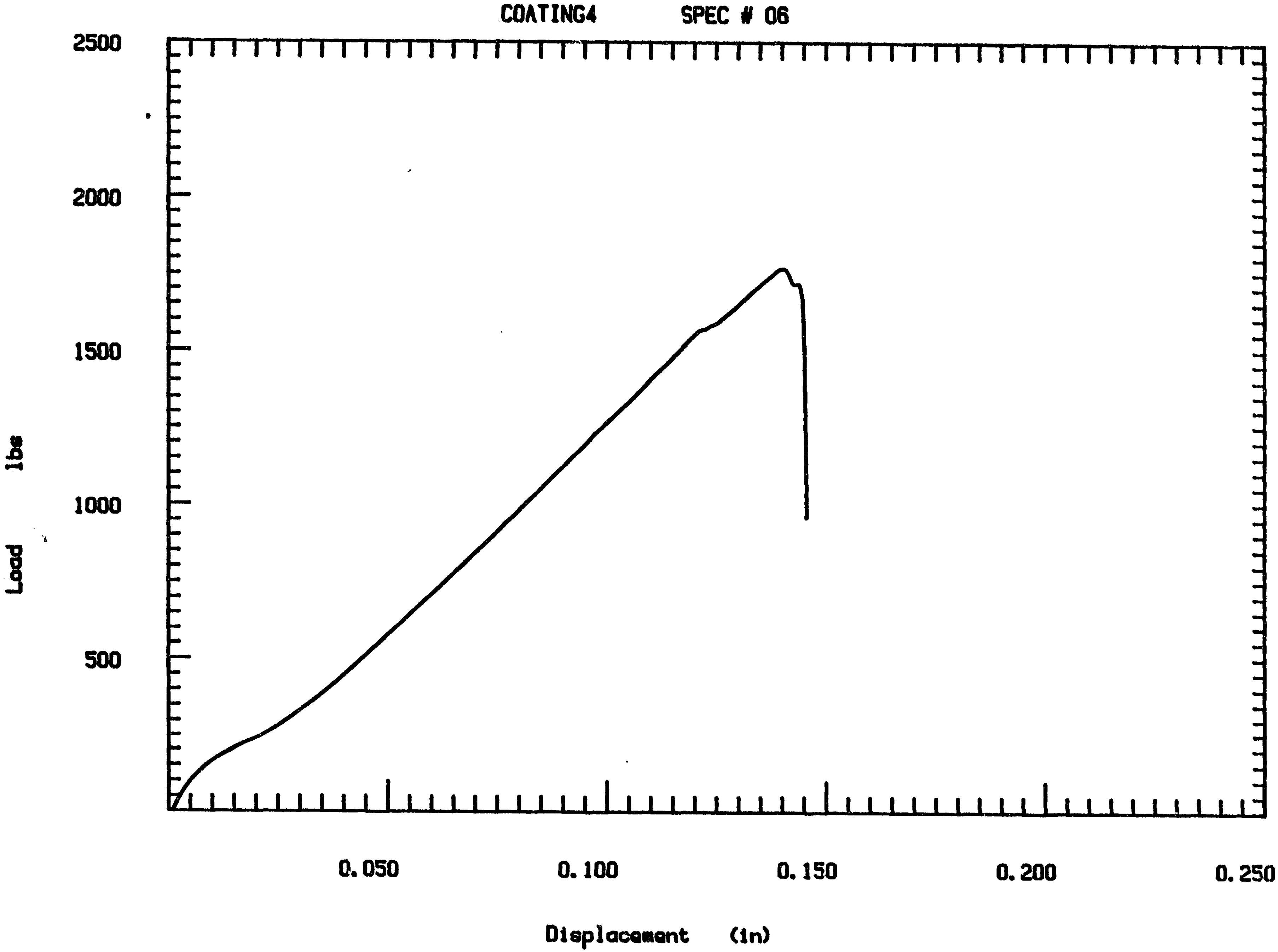
Displacement (in)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Load lbs
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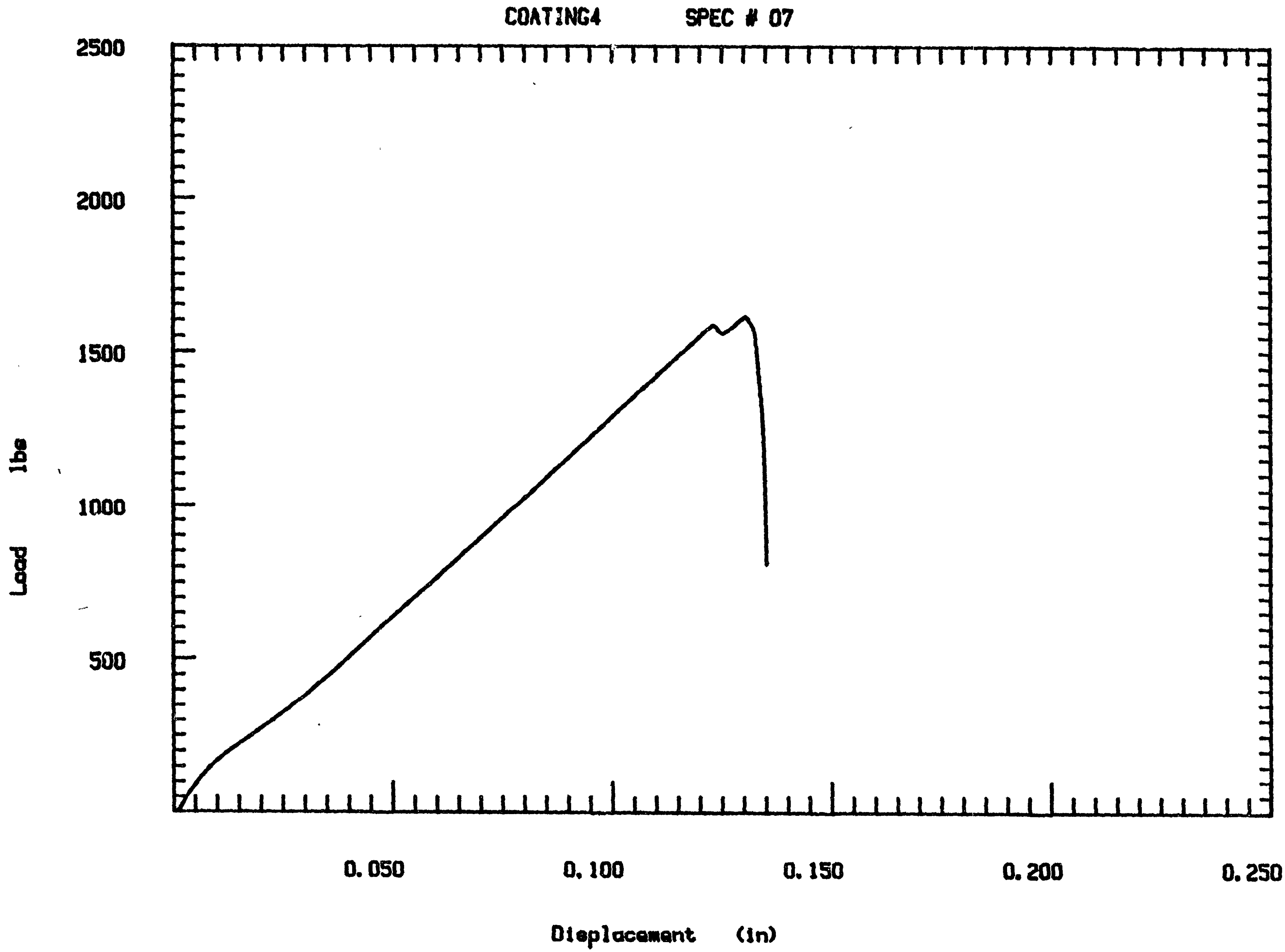
Displacement (in)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1000
500
Load lbs
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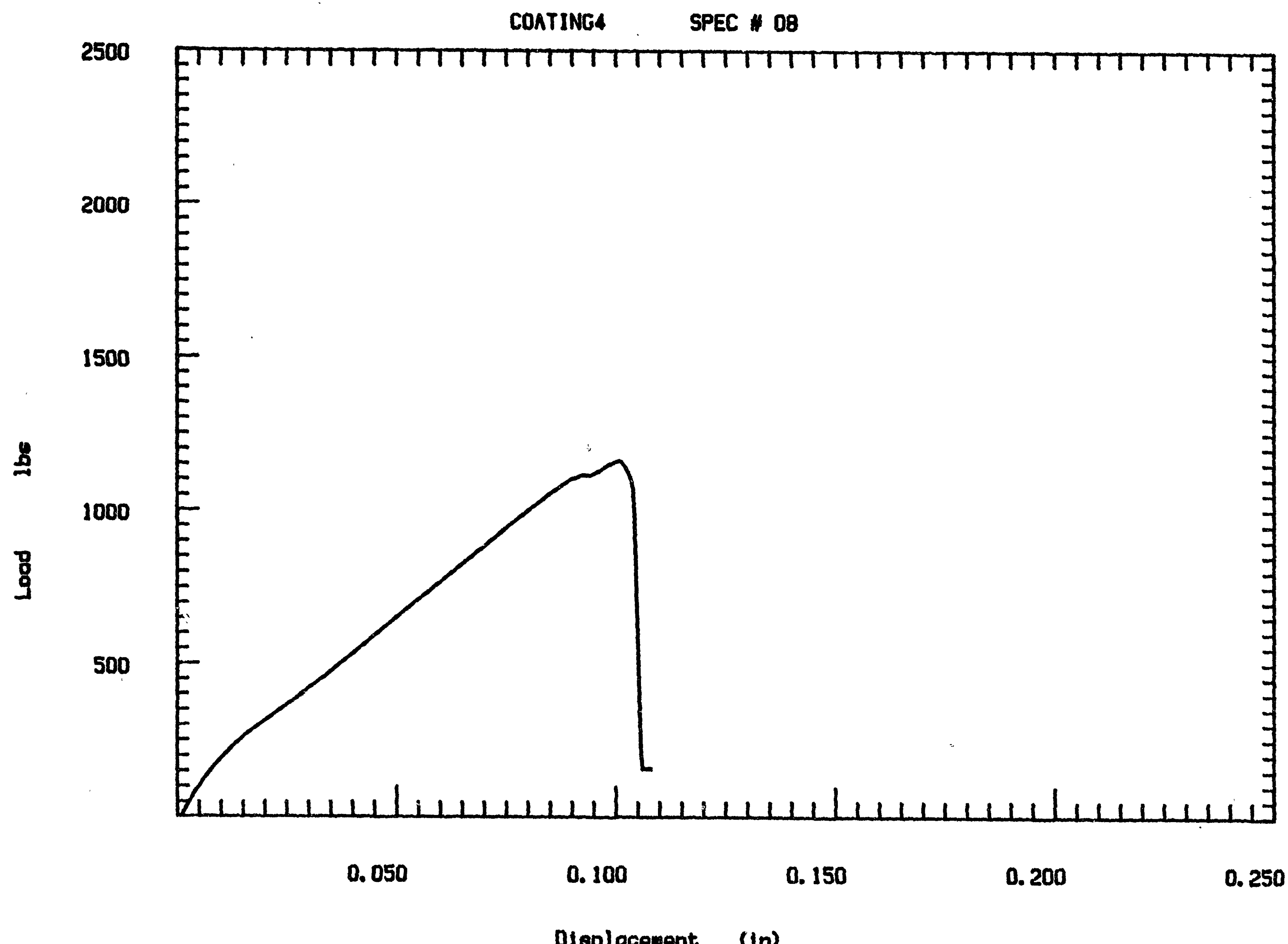
0.100
0.150
0.200
0.250
Displacement (in)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1000
500
Load lbs
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0.150
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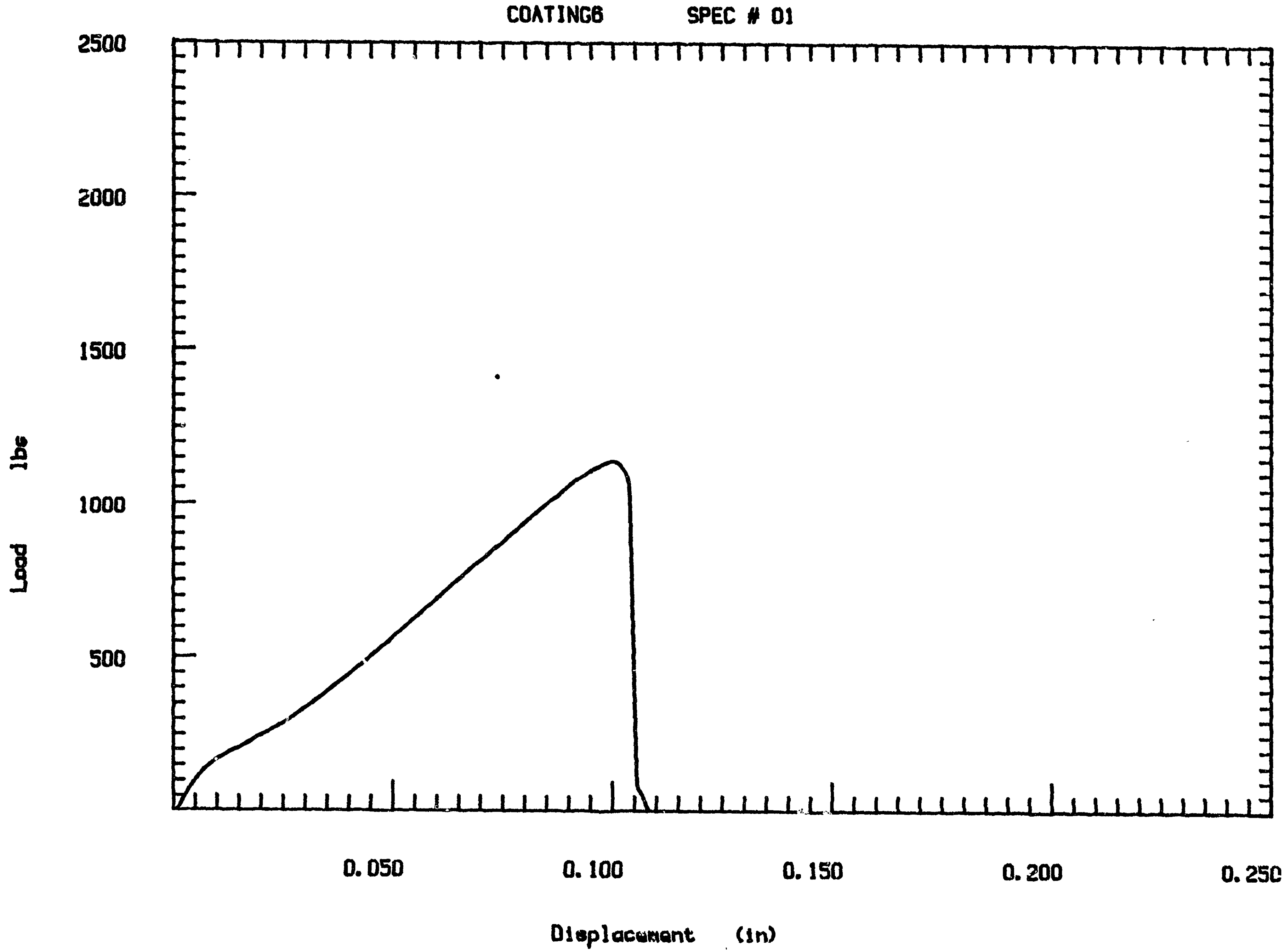
Displacement (in)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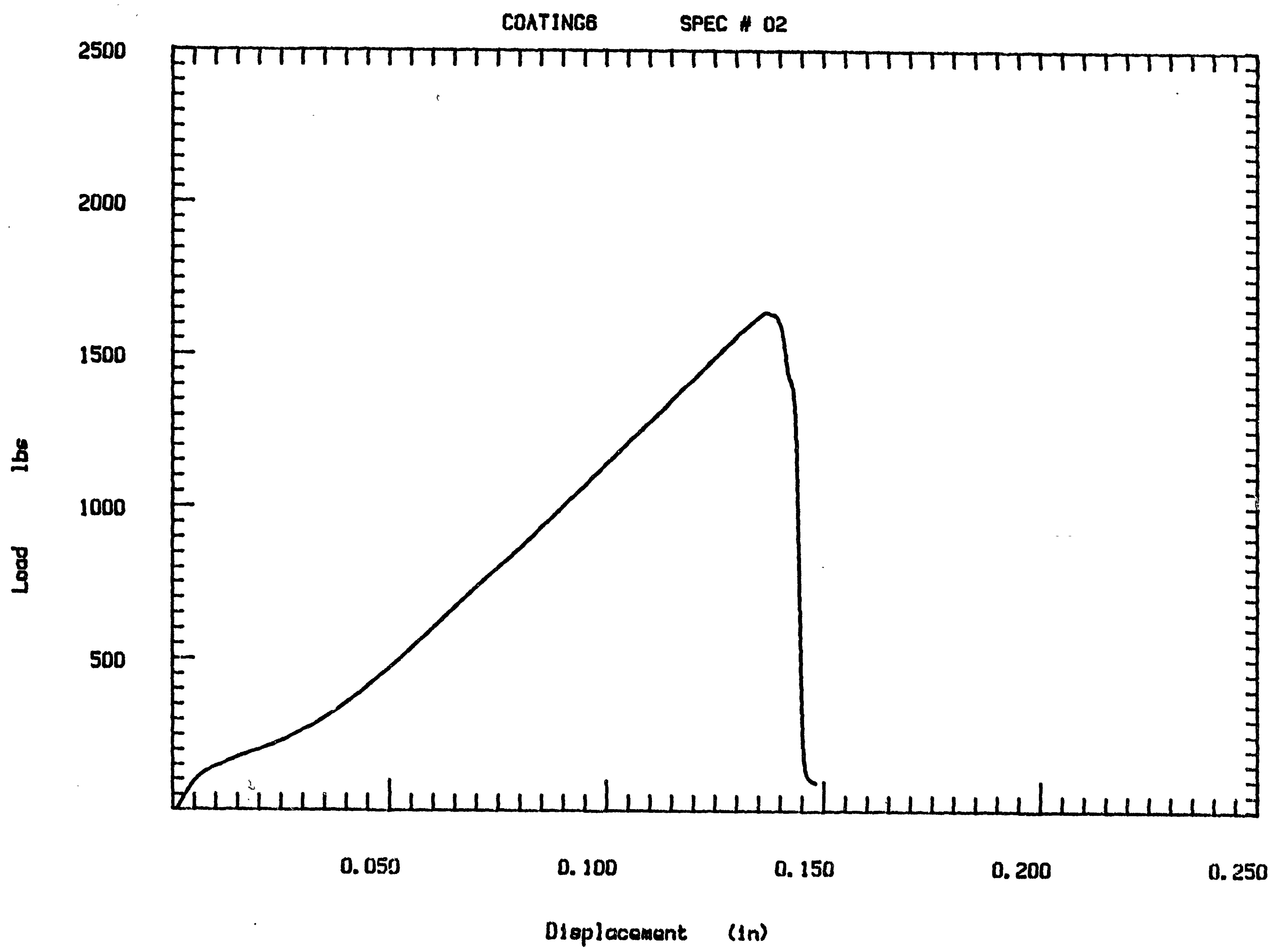
1500
1000
500
0.050
0.100
0.150
0.200
0.250
Displacement (in)



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1500
1000
500
Load lbs
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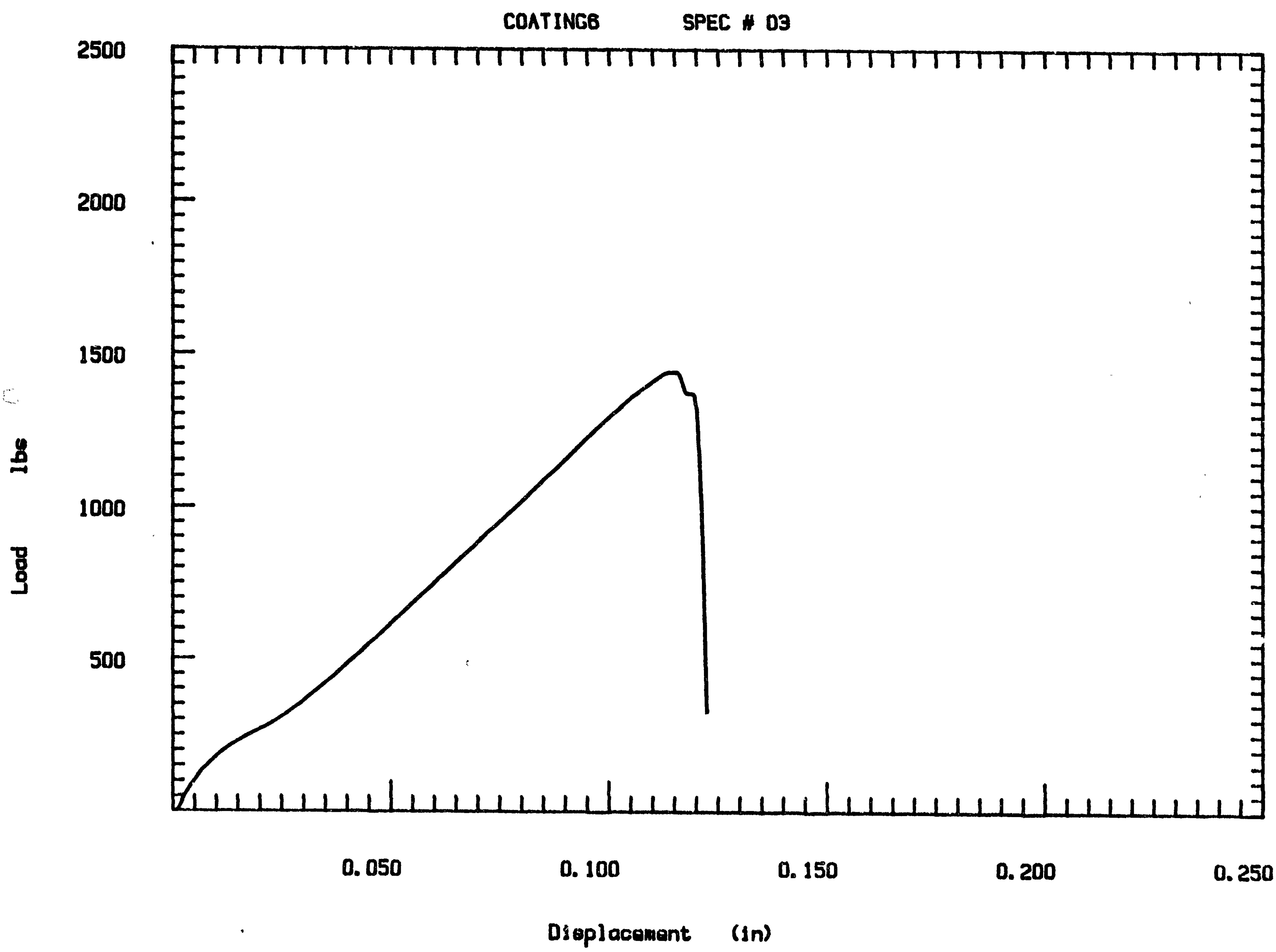
0.100
0.150
0.200
0.250
Displacement (in)



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1000
500
Load lbs
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0.150
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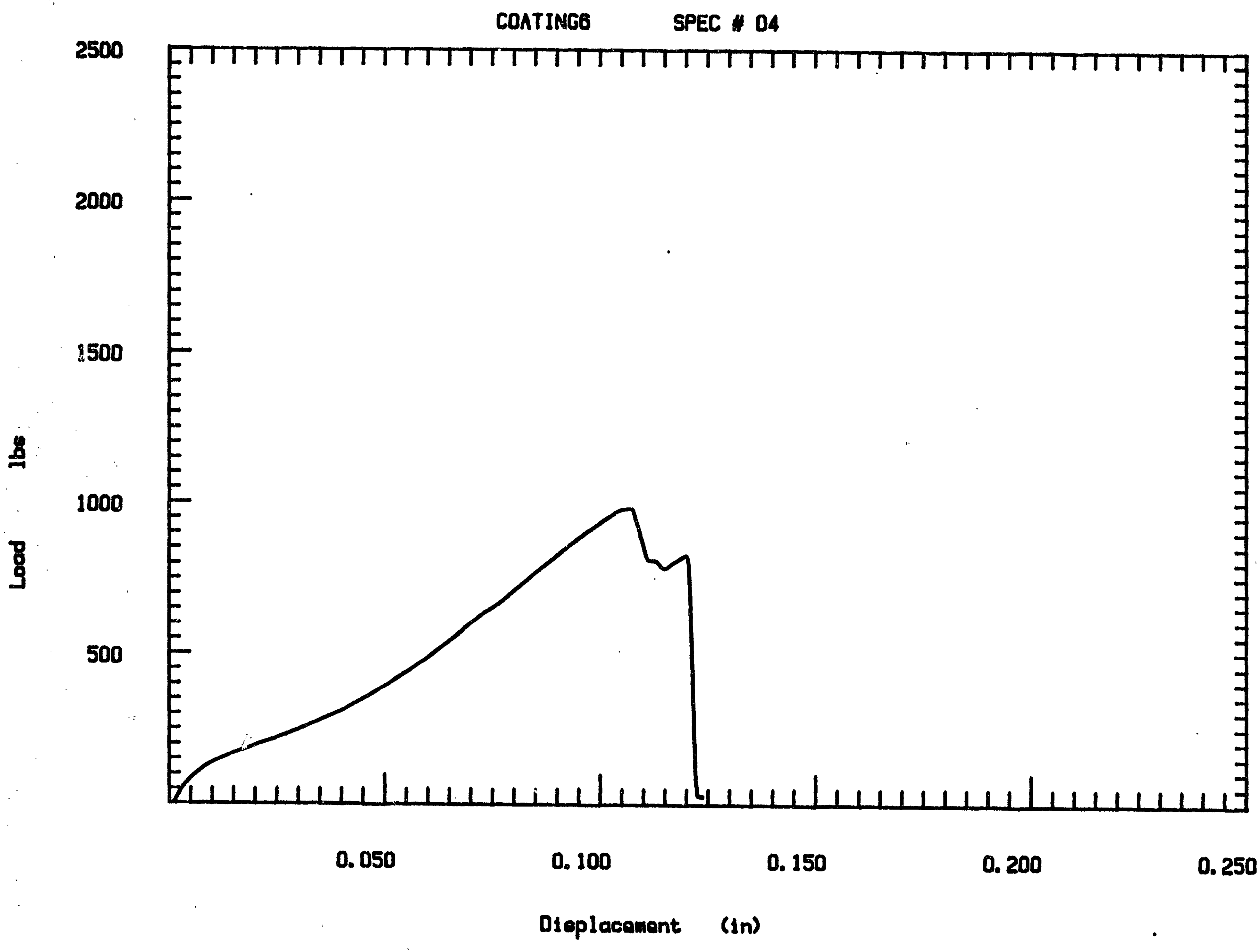
Displacement (in)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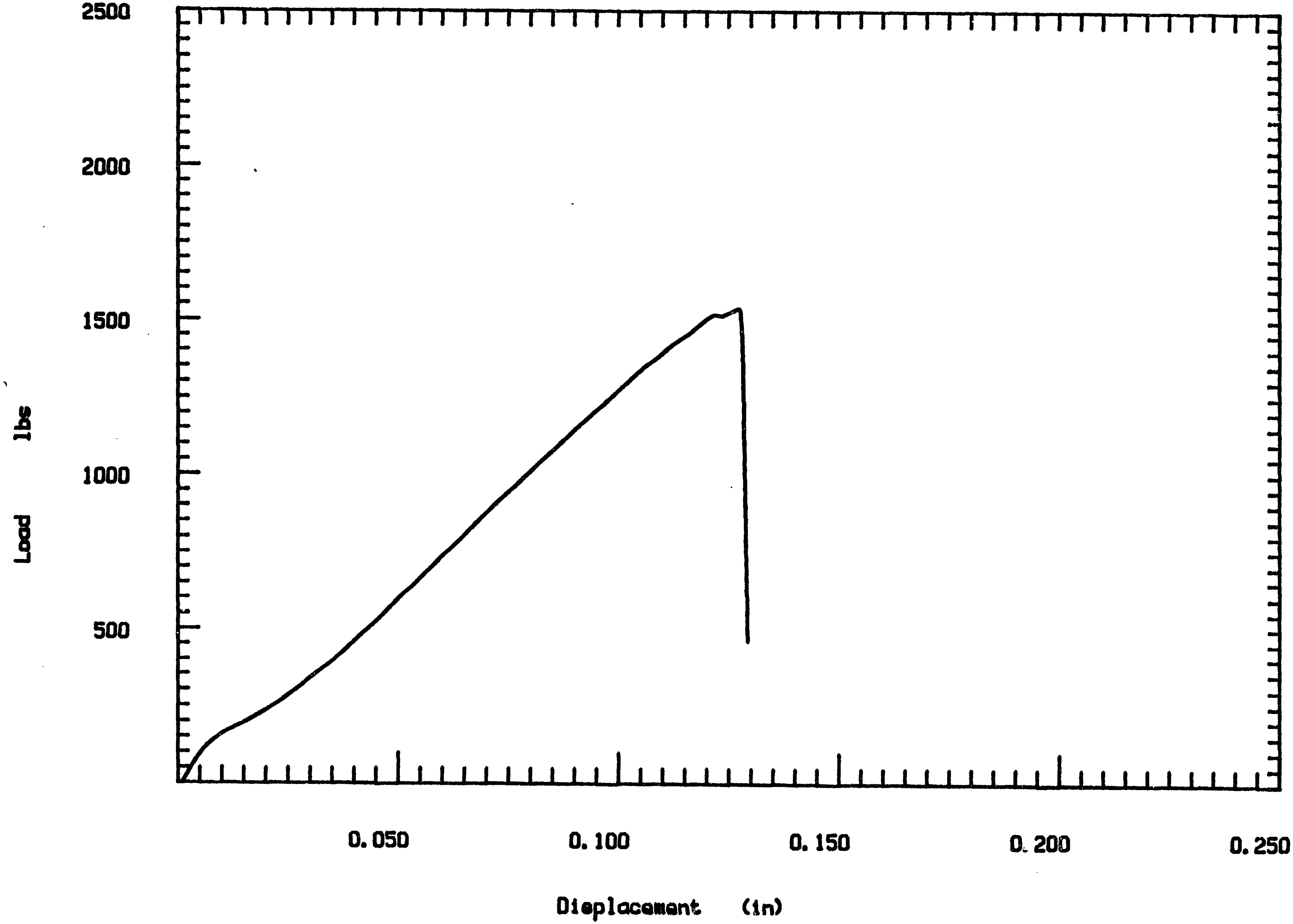
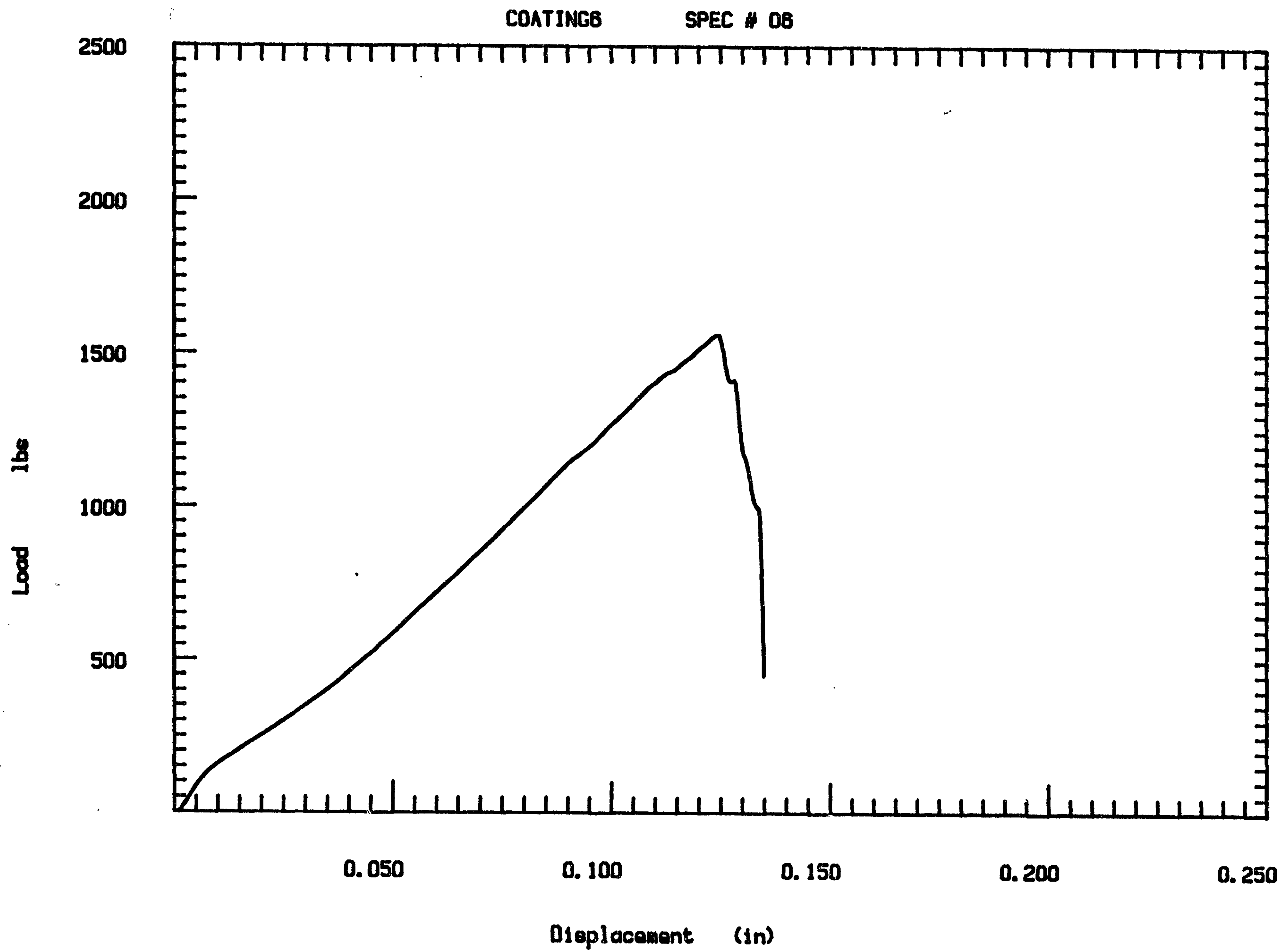
Displacement (in)

COATING6 SPEC # 05

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Load lbs
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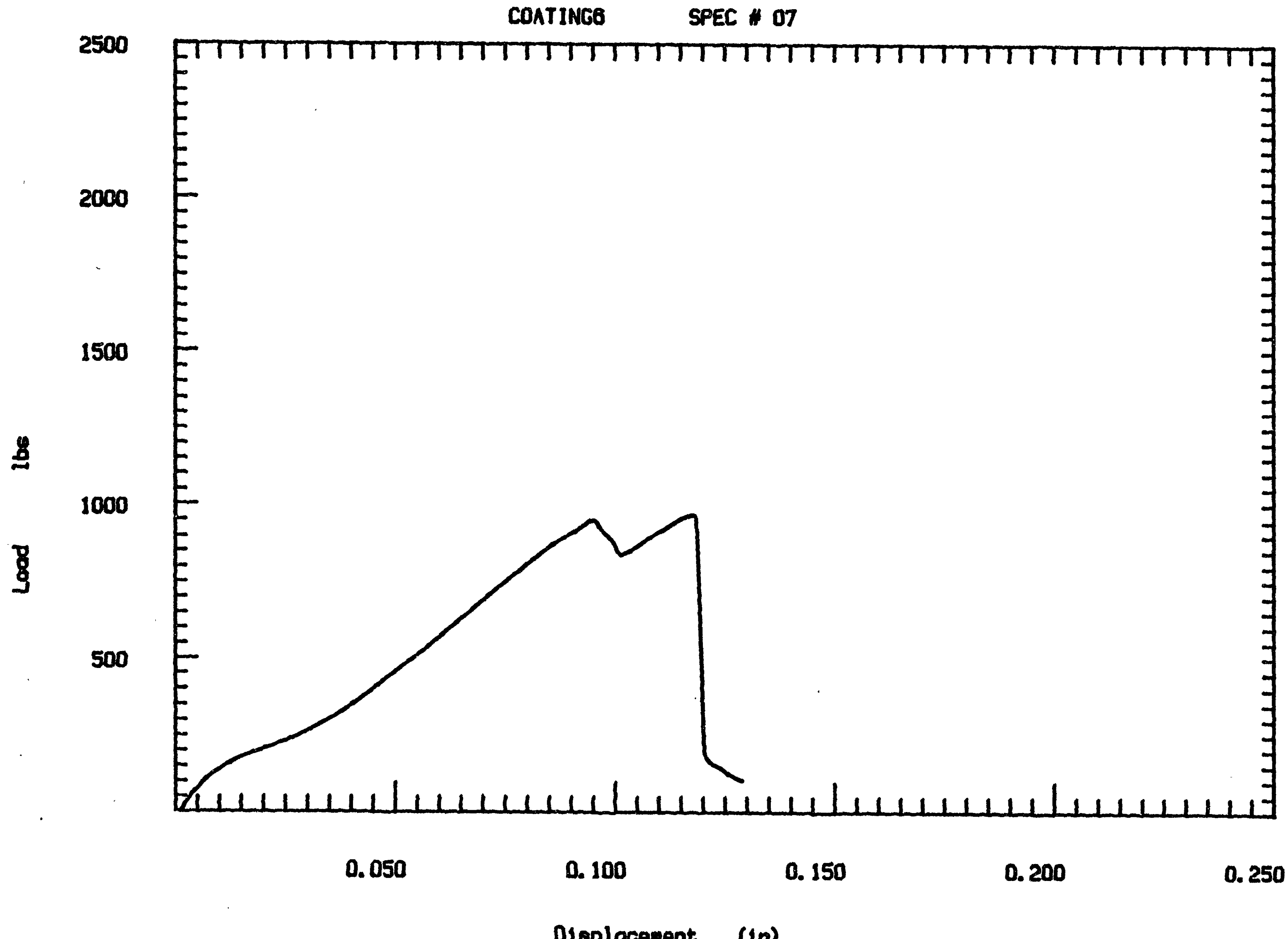
Displacement (in)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1000
500
Load lbs
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0.150
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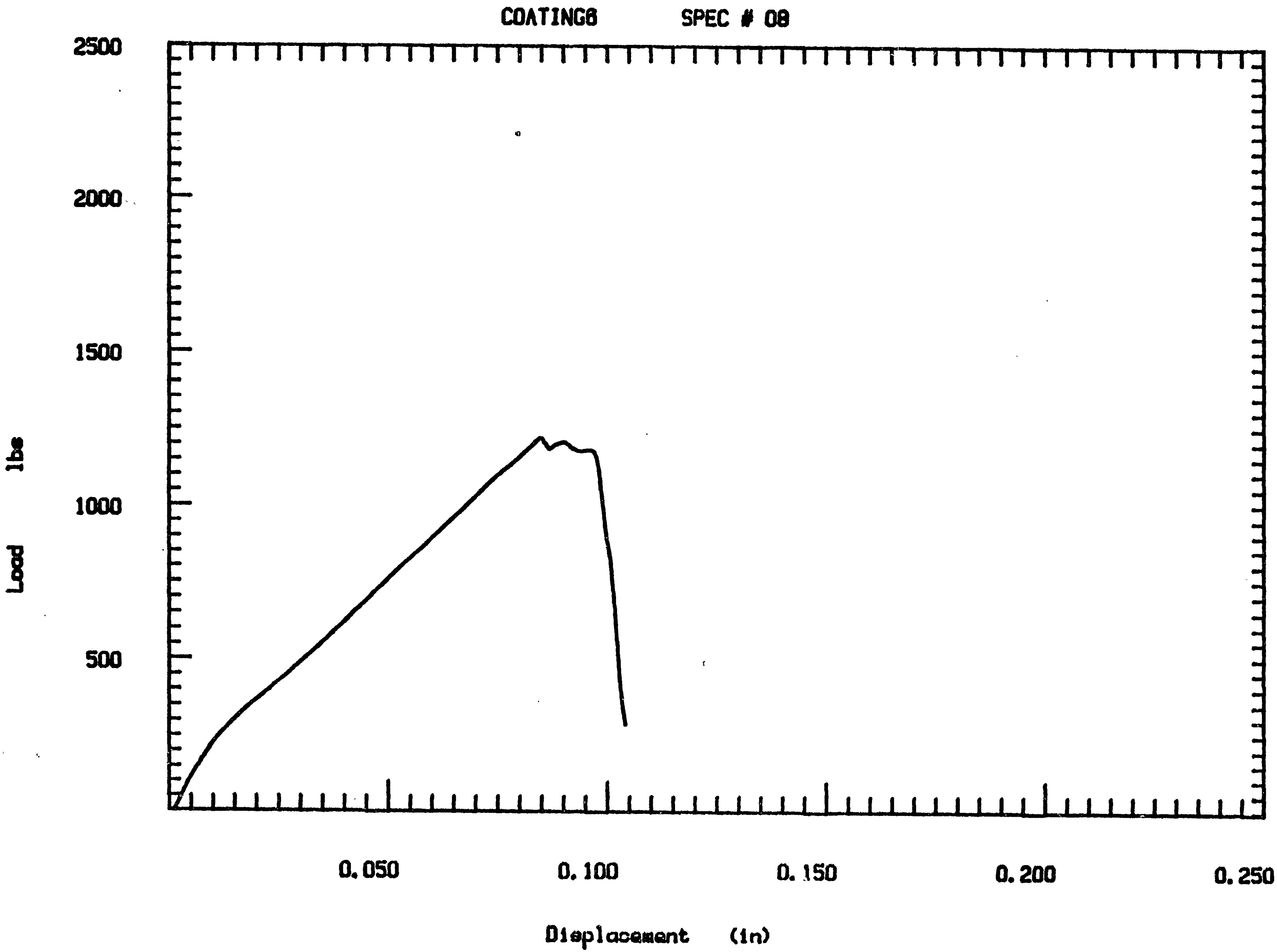
0.250
Displacement (in)



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1500
1000
500
Load lbs
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0.100
0.150
0.200
0.250
Displacement (in)